Jefferson's

WELDING ENCYCLOPEDIA

Eighteenth Edition

Edited by
ROBERT L. O'BRIEN

American Welding Society
550 N.W. LeJeune Road, Miami, FL 33126 USA

Reasonable care was applied in the compilation and publication of Jefferson's Welding Encyclopedia to ensure authenticity of the contents. The American Welding Society assumes no responsibility for use of the information contained in this publication. An independent, substantiating investigation should be made prior to the reliance on or use of such information.

Printed in the United States of America.

Library of Congress Catalog Card Number: 97-070432
International Standard Book Number: 0-87171-506-6

Photocopy Rights

Dedicated to the Welders of America

A tribute to welders was expressed by Jeff Weber, Publisher of the *Welding Journal*, Miami, Florida, in the May, 1993 issue:

WHAT MAKES A WELDER?

A recent phone conversation with an old friend got me thinking about what it takes to be a welder. The person I was talking to has been welding for 25 years, but he said he is between jobs again, waiting for startup of a new project. The fact that he is not currently working troubled me, considering that this guy is truly an artist with a GTAW torch, a magician with a stick electrode. He can lay down a bead that looks like a machine made it, time after time. And when joint fitup isn't all it should be, he can improvise in ways a computer would never even think of.

As editor of this magazine, I run into lots of capable people in the welding industry, but the ones who impress me most are the ones who can express themselves through a welding gun. These highly skilled men and women are independent, savvy and capable, yet they have to face challenges and conditions that would prove daunting to most people. Here are a few ways one might describe a welder:

A welder is the guy you'll find working on a high plains pipeline in January at twenty below, or inside a boiler in the California desert at 105 degrees. He might be asked to backweld a joint in a section of pipe hot enough to melt a hard hat, or to do repairs at the top of a box section where elbow room and visibility are near zero. At a construction site, the welder is sometimes expected to weld joints that were easy to design on paper, but are nearly impossible to reach in a real life situation. On especially tricky jobs, he may have to weld in a tiny pocket, watching his progress with a hand mirror and trying to read his reflected movements backwards. Sometimes, high on a structure, the welder has to put up with gusting winds that threaten to blow away his gas shield while he attempts to block the drafts with his body. Despite all this, he has to weld the joint right the first time. There are no second chances and no opportunity to fix mistakes. Every job a welder does, every second of arc-on time, is permanently etched in steel and visible to everyone who passes by.

Unlike most workers, many welders must continually prove their ability, recertifying on every new job and every welding procedure they will use on that job. Since there is no guarantee that he will pass a certification test, the welder must keep practicing everything he knows, while learning new techniques every chance he gets. Welders on big projects must often wait by the phone for jobs, and when the call finally comes, they frequently have to travel long distances and live away from home for extended periods. If hired in the middle of a project, they must meet existing deadlines without complaint. And, while wages are sometimes good, pay increases are often out of the question because of the short-term nature of the work.

Yes, it's often a tough job, but we've got a devoted group of people who are willing and eager to do it. That's why I take my hat off to the welders of America. They possess levels of skill, resolve and professionalism that are rare today in any work force, anywhere. And that is what makes them absolutely essential to the well-being of our country.

Photos by Renate Gaddis

Contents

Foreword

Jefferson's
WELDING ENCYCLOPEDIA

The first four editions of The Welding Encyclopedia were published annually from 1921 through 1924 by L. B. MacKenzie. Mr. MacKenzie was given editorial assistance in this endeavor by H. S. Card. Both were on the staff of *The Welding Engineer*, a monthly publication of the Welding Engineer Publishing Company in Chicago, Illinois.

In his preface to the Fifth Edition in 1926, Mr. Card advised of the death of L. B. MacKenzie. The four editions from 1926 to 1932 were edited by Mr. Card, with Stuart Plumley succeeding him as editor for the 8th, 9th and 10th editions.

Ted Jefferson, by then a principal of the Welding Engineer Publishing Company, revised the Encyclopedia in 1943. He edited and published the 11th through 17th editions over a period of 33 years. Ted Jefferson died on July 6, 1988, at the age of eighty.

The American Welding Society has obtained publication rights for the Welding Encyclopedia. Because of Jefferson's long association with this book and his dedication to continuing its publication, we are changing the name of this book to *Jefferson's Welding Encyclopedia.*

The following is an excerpt from Ted Jefferson's Preface to the 17th Edition of the Welding Encyclopedia in 1976:

> *"In 1921 the coverage of welding involved a discussion of only three very basic processes used principally for maintenance or repair applications. Down through the years, the ever-changing and expanding field of welding has grown to include more than fifty welding processes, capable of joining a wide variety of materials."*

In 1997, more than ninety welding and allied processes are listed in the literature, and the number continues to grow.

Acknowledgments

The Editor is indebted to the following for their contributions to this book:

B. J. BASTIAN, P.E., Consultant, Benmar Associates; Royal Oak, MI
H. H. CAMPBELL III, Senior Staff Engineer, American Welding Society; Miami, FL
L. P. CONNOR, Director of Standards Activities, American Welding Society; Miami, FL
M. V. DAVIS, Ph.D., Consultant, Miami, FL
R. J. DYBAS, Consultant; Schenectady, NY
J. M. GERKEN, Ph.D., Consultant; Chagrin Falls, OH
R. A. HUBER, Consultant; Oak Ridge, TN
L. G. KVIDAHL, Ingalls Shipbuilding; Pascagoula, MS
A. LESNEWICH, Ph.D., Welding and Metallurgical Consulting Services, Severna Park, MD
A. F. MANZ, Consultant, A. F. Manz Associates; Union, NJ
R. W. MESSLER, Jr., Ph.D., Associate Professor, Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, NY
E. P. NIPPES, Ph.D., Consultant; Vineyard Haven, MA

An associate in the production of this book was ANNETTE O'BRIEN, who prepared the text and served as copy editor. The Editor is grateful to L. G. KVIDAHL for his final review of the text.

ROBERT L. O'BRIEN
Editor

Preface

Eighteenth Edition

This edition represents a major revision of this encyclopedia, changing its orientation to the authoritative information base of the American Welding Society, and providing access to its resources.

Welding technology becomes more complex with every passing year, and has expanded to an extent that defies containment between the covers of a book. This encyclopedia presents as much information as is practical, but it is impossible to provide an exhaustive report on every welding process, variation, application, technique or material involved in the welding industry.

The Editor hopes Jefferson's Welding Encyclopedia will be a helpful resource to those who need authoritative welding information at their fingertips, and that it will be an effective starting point for those pursuing further scientific or engineering information. Following are some significant additions to the Eighteenth Edition:

Welding terms and definitions standardized by the American Welding Society are presented dictionary-style throughout the encyclopedia. They are identified by reference to Standard Welding Terms. Standard definitions are printed in italics.

Consensus standards, codes, specifications, recommended practices, classifications, methods, and guides for welding processes and applications documented by AWS are appropriately referenced. Standards of related organizations are referenced when applicable.

U.S. customary units are converted to the International System of Units (SI); conversion figures are appropriate to the application.

Nineteen appendixes have been included; most of these supply technical information from major American Welding Society documents. Appendix 1 contains historical notes of interest to the welding community.

A buyer's guide is provided; companies or organizations listed were exhibitors at the 1996 AWS International Welding and Fabricating Exposition in Chicago.

The primary editorial effort is directed to presenting new and updated material, although some of the basics of early welding processes are retained from previous editions, and much of the instructional material remains. An effort is made to meet the needs of persons associated with various areas of welding, and persons at many levels of expertise who are working with available equipment, old or new.

Most of the information available to the welding industry, and in this book, is the result of a continuous sharing of information involving every sector of the industry and spanning several generations. Contributors include research and development groups from manufacturers of welding equipment and consumables, universities, fabricators and job shops, as well as individual welders. All who are involved in the welding industry are grateful to those who have contributed and those who are continuing to develop and share technology. In that same spirit, we welcome comments, as well as contributions of further information.

ROBERT L. O'BRIEN
Editor

Guide to Using the Encyclopedia

The definition of an entry is presented in dictionary style. Terms and definitions standardized by the American Welding Society (AWS) are presented throughout the encyclopedia. Each AWS standard term is identified by reference to STANDARD WELDING TERMS. AWS standard definitions are printed in italics.

To find a specific consensus standard, code, specification, recommended practice, classification, method, or guide documented by AWS, refer to Appendix 16, Standards for Welding, Cutting, and Allied Processes. Refer also to the process, application, material or product involved. For example, to find standards or codes covering boilers, see BOILER CONSTRUCTION, as well as Appendix 16. To find AWS filler metal specifications, consult Appendix 17.

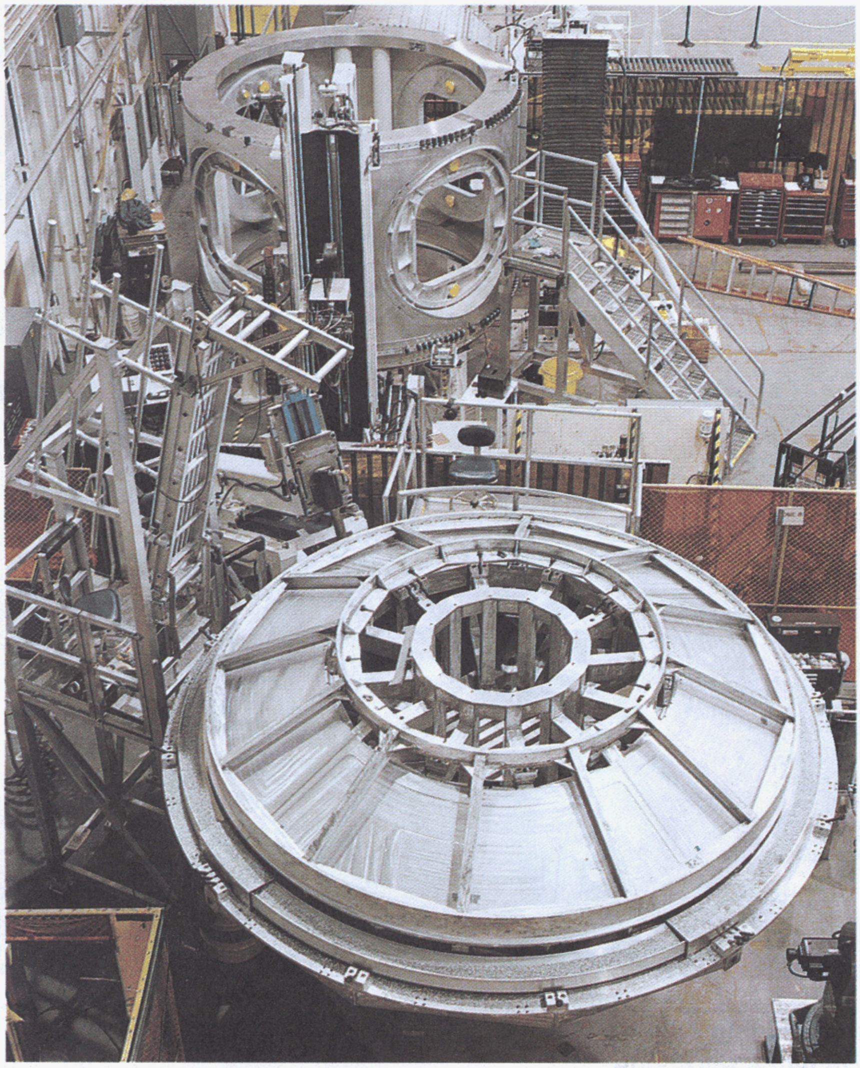
U.S. customary units are converted to the International System of Units (SI); conversion figures are appropriate to the application. For example, a postweld heat treat temperature of 1200°F converts exactly to 648.88°C, but the decimal figures are not meaningful. Therefore, the SI temperature is rounded off to 650°C. In critical cases, however, such as the melting point of an element or compound, the exact temperature in both scales is presented.

Appendixes 4 through 9, and Appendixes 11 and 12 have been designed to provide specific technical information about welds that is easy to find by consulting the appropriate appendix.

Welding and related processes are described in separate entries, for example, gas metal arc welding, laser beam welding, thermal spraying, or oxyfuel cutting. Refer also to the metal involved in a given project. Additional process information specific to the metal involved has been added to discussions under entries such as aluminum, cast iron, nickel, magnesium, and steel.

To use the Buyer's Guide, consult the product category, then refer to the alphabetical list of manufacturers and suppliers for a specific address, telephone or fax number. The Buyer's Guide is not all-inclusive; companies or organizations listed were exhibitors at the 1996 AWS International Welding and Fabricating Exposition in Chicago.

Structural Steel Welding Application
BP America Building, Cleveland



Vertical welding on Node 1, the first United States element of the International Space Station, at NASA's Marshall Space Center, Huntsville, Alabama

A

ABNORMAL GRAIN GROWTH

The formation of unusually large polycrystalline grains in a metal. This condition frequently occurs when a critical amount of strain (in the range of 2%) is present during heating to elevated temperatures.

ABRASION

A grinding action caused by abrasive solids sliding, rolling or rubbing against a surface; a scraped, ground, or worn area. Base plates are sometimes hardfaced to provide abrasion, or wear, resistance.

ABRASION SOLDERING

A soldering process variation during which the faying surface of the base metal is mechanically abraded. See STANDARD WELDING TERMS.

ABRASIVE

See GRINDING MATERIALS.

ABRASIVE BELT

A cloth or paper belt coated with abrasives used to rub, grind, or wear away by friction. The abrasive coating material may be sand or Carborundum, available in various grades and hardness factors.

ABRASIVE BELT GRINDER

A grinder which uses an abrasive belt for the removal of surplus material.

ABRASIVE BLASTING

A method of cleaning or surface roughening by a forcibly projected stream of abrasive particles. See STANDARD WELDING TERMS.

ABSORPTIONMETER

An instrument for measuring absorption of gases by liquids.

ABSORPTION BANDS

Dark bands in a spectrum produced by the selective absorption of light. The absorbing media are generally solids or liquids through which the light of the spectrum has been transmitted.

ABSORPTIVE LENS

A filter lens designed to attenuate the effects of glare and reflected and stray light. See STANDARD WELDING TERMS. *See also* FILTER PLATE.

AC or A-C

Abbreviation for alternating current. It is written *ac* when used as a noun and written as *a-c* when used as an adjective.

A-C ARC WELDING

An arc welding process using a power source that supplies an alternating current to the welding arc.

ACCELERATING POTENTIAL, Electron Beam Welding and Cutting

The potential that imparts velocity to electrons. See STANDARD WELDING TERMS.

ACCEPTABLE WELD

A weld that meets the applicable requirements. See STANDARD WELDING TERMS.

ACETONE

(C_3H_6O) A compound of carbon, hydrogen and oxygen; it is a volatile, flammable, liquid ketone used mainly as a solvent for such materials as resins, gums, oils, and cellulose.

Acetone is odorless and colorless; it evaporates rapidly. Acetone boils at 56°C (133°F). One liter of acetone weighs about 1 kg.

An important use for acetone is to stabilize acetylene gas. The safe, practical use of acetylene gas for welding and other applications would not be possible without acetone. Compressed acetylene itself is highly explosive; however, it can be safely compressed and stored in high-pressure cylinders if the cylinders are lined with absorbent material soaked with acetone. As a solvent agent for acetylene gas, acetone has an absorptive capacity of 25 volumes of acetylene per volume of acetone per atmosphere of pressure, or about 420 volumes of acetylene at 1724 kPa (250 psi) pressure.

Another important feature of the acetone-acetylene solution is that the exothermic properties of the acetone counteract the endothermic properties of the acetylene; consequently, the acetone-acetylene solution is, to a certain extent, immune from a complete dissociation in case an ignition or explosion is introduced into it. *See* ACETYLENE CYLINDERS.

ACETYLENE

Acetylene, a hydrocarbon (C_2H_2), is a colorless, flammable gas shipped dissolved in a solvent. It has a garlic-like odor. Acetylene is rated as a simple asphyxiant (ACGHI 1994–95). Users are cautioned not to discharge acetylene at pressures exceeding 103 kPa (15 psig), as noted by the red line on acetylene pressure gauges. Other specifications of acetylene are:

Molecular weight: 26.038
Specific Gravity (Air = 1): 0.91 at 0°C (32°F)
Specific Volume: 0.09 m^3/kg at 15.6°C (14.5 ft^3/lb at 60°F)
Critical Temperature: 35.2°C (95.3°F)
Critical Pressure: 6139.3 kPa (890.4 psia)

Acetylene is said to have an endothermic quality because it absorbs heat in formation and liberates it during combustion. In this respect, acetylene differs from most hydrocarbons: they are exothermic and give off heat during formation.

As a fuel gas, acetylene generates 1433 Btu per cu ft; 277 are derived from hydrogen combustion, 928 Btu result from the combustion of carbon into carbon dioxide, and 228 Btu result from its endothermic quality.

Chemical Characteristics

The chemical structure of acetylene is given in the formula C_2H_2, showing that two atoms of carbon (atomic weight 12) are combined with two atoms of hydrogen (atomic weight 1.008), which can be expressed as 92.3% carbon and 7.7% hydrogen. The nearest gaseous hydrocarbon is ethylene (C_2H_4), which consists of 85% carbon and 15% hydrogen.

Acetylene contains the highest percentage of carbon of all the gaseous hydrocarbons and is the only one of the unsaturated hydrocarbons with endothermic properties (viz: absorbs heat during its production, and liberates heat when it is decomposed). Because of these characteristics, the oxyacetylene flame creates intense heat. The theoretical maximum for the oxyacetylene flame is 4359°C (7878°F), although the working temperature is about 3316°C (6000°F). The temperature of the oxyacetylene flame cannot be approached by any other gas, and is only exceeded by the heat produced in the electric arc or electron beam and laser processes.

Metalworking with Acetylene

Acetylene is usually combined with oxygen to intensify the heat of the acetylene flame for welding. It can also be combined with air, but with a much lower flame temperature. The principal application for the air-acetylene mixture is in soldering operations.

Mixed in equal amounts and burned at the tip of a welding torch, oxygen and acetylene create the so-called neutral flame. This flame can be identified by the luminous, well-defined white cone at the torch tip, and by a fairly long, almost colorless outer envelope that is blue or orange at its leading edge. See Figure A-1. The neutral flame is the correct flame with which to weld many metals. *See* OXYACETYLENE FLAME.

If excess oxygen is fed into the torch, an oxidizing flame results. This flame is characterized by a short inner cone and a short outer envelope. The flame is hotter than a neutral flame, burning acetylene at the same rate.

When this situation is reversed and an excess of acetylene is used, the resulting flame is termed *carburizing*. This flame appears as a greenish feather-shaped form between the inner cone and outer envelope. There are white-hot carbon particles in this feather which are dissolved to some extent in molten metal during welding.

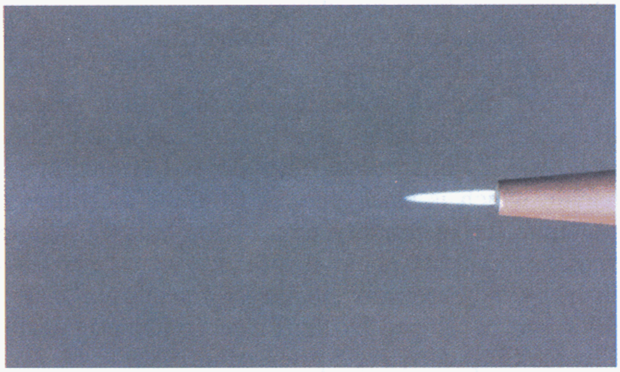
Applications

Because of its intense heat, and because it can be accurately controlled, the oxyacetylene flame can be applied to literally hundreds of welding and cutting operations, including hardfacing, brazing, beveling, gouging, and scarfing. The heating capability of acetylene is utilized extensively in bending, straightening, forming, hardening, softening, and strengthening many types of metals.

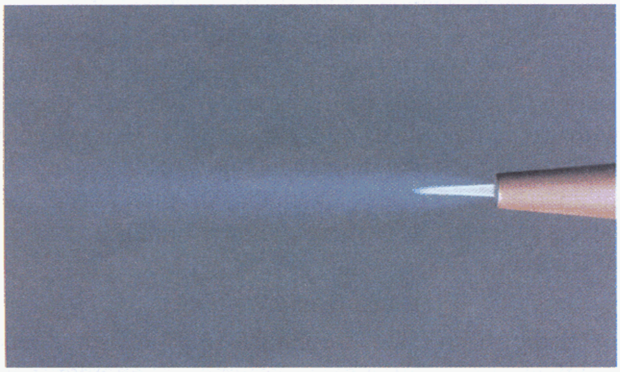
Historical Background

Acetylene gas was discovered by Edmund Davy in 1836, but it was not until 1862 when Woehler's discovery that acetylene gas could be produced from calcium carbide that the gas became well known. These developments were of little consequence, however, until 1892, when Thomas L. Wilson, of Spray, N. C., invented a process for producing calcium carbide and established facilities to produce it. He and James Morehead devised an economical commercial production method, and by 1895 acetylene gas was becoming recognized as a valuable gas for lighting.

(A) Carburizing



(B) Neutral



(C) Oxidizing

Figure A-1—Types of Oxyacetylene Flames

However, acetylene producers' hopes for widespread use of acetylene for illumination of streets and buildings were dashed by the growing use of incandescent lamps. Acetylene's potential in metalworking became apparent in World War I, when welding was adopted as the most effective and expedient method of constructing and repairing war ships and merchant vessels.

Producing Acetylene

Acetylene is produced either in generators, by the reaction of calcium carbide and water, or by the cracking of hydrocarbons in a chemical plant.

In the generator method, water is allowed to react with calcium carbide (CaC_2), a chemical compound produced by fusing lime and coke in an electric furnace. The reaction between water and carbide is instantaneous, and as a result, the carbon in the carbide combines with the hydrogen in the water, forming acetylene, while the calcium combines with the oxygen and water, forming slaked lime, or calcium hydrate.

There are two methods of generating acetylene: (1) carbide-to-water, and (2) water-to-carbide. The carbide-to-water method is generally used in the United States, while the water-to-carbide method is favored to a large extent in Europe.

A carbide-to-water generator operates on a "batch" basis, with a ratio of one gallon (8.3 lb) of water to one pound of carbide. This mixture is designed, in some generator models, to produce one cubic foot of acetylene per hour per pound of carbide hopper capacity. Some stationary generators are "double-rated" for capacities of 2 ft^3/hr per pound of carbide hopper capacity.

There are two further classifications for acetylene generators: low pressure and medium pressure. The low-pressure generator carries out the calcium carbide-to-water reaction process at pressures below 7 kPa (1 psi). A medium-pressure generator produces acetylene at between 7 and 103 kPa (1 and 15 psi).

Calcium carbide used for acetylene generation in the U. S. normally produces gas containing less than 0.4% impurities other than water vapor. Because of this favorable factor, there is no need for further purification of acetylene used for welding and cutting.

The welding supply distributor receives and resells acetylene in its most common form: dissolved in acetone and compressed in cylinders. These rugged acetylene cylinders have nominal capacities of 0.28, 1.1, 2.8, 6.4, or 8.5 m^3 (10, 40, 100, 225 or 300 cu ft) and hold the gas at a pressure of 1724 kPa (250 psi). See

ACETYLENE CYLINDERS, ACETYLENE CYLINDERS, Safe Handling, *and* ACETYLENE GENERATORS.

ACETYLENE CUTTING

See OXYFUEL GAS CUTTING.

ACETYLENE CYLINDERS

Because of the characteristics of acetylene gas, acetylene cylinders are constructed in an entirely different manner from those made to contain other gases.

Historical Background

Until 1904, no suitable acetylene container had been developed. The gas was used mainly for illumination and was generally piped directly from generators to the area to be served. In that year in Indiana, P. C. Avery displayed to two of his home state's most famous promoters, James Allison and Carl Fisher, a portable cylinder containing acetylene gas designed to power auto headlights. Then engaged in auto sales, Allison and Fisher were immediately interested, and with Avery, set up a small factory in Indianapolis to fabricate this "tank."

The shop was known as Concentrated Acetylene Company, until Avery withdrew in 1906. The company then became the Prest-O-Lite Company, the forerunner of the Linde Division of Union Carbide Corporation.

Allison and Fisher devoted much of their time relocating their plant into progressively larger quarters. Not until 1910 did they build one of sufficient size in what was then suburban Indianapolis, across the street from the site of the famed motor speedway they later constructed.

Carbide production continued to increase, and in 1913, a much improved acetylene cylinder similar to that used today was introduced. With these two major achievements, gas welding began replacing other metal joining methods.

Cylinder Stabilizing Fillers

The need for a porous substance in a cylinder to stabilize compressed acetylene was realized by the French scientist Fouche, one of the men responsible for the oxyacetylene mixture. The size of the filler, however, left very little room for gas in the cylinder. One filler was a magnesium oxychloride cement type; another was made of asbestos discs. The charcoal-cement filler was not developed until 1919, and in 1950 a sand-lime material became popular.

In 1897 a French team, Claude and Hess, demonstrated the value of acetone. This colorless, flammable liquid, when added to the porous material, is capable of absorbing 25 times its own volume of acetylene for each atmosphere 101 kPa (14.7 psi) of pressure applied. Thus, at full cylinder pressure of 1724 kPa (250 psi at 70°F), it can absorb over 400 times its own volume of acetylene.

In 1958, cylinder manufacturers announced a lightweight calcium-silicate filler with 92% porosity. This new filler lessened cylinder weight by 30%, increased cylinder capacity, and improved charging and discharging characteristics. Although only 8% solid, this filler had extraordinary strength, longer life, no deterioration, and could be charged and discharged much faster.

The calcium silicate filler, composed of sand, lime and asbestos, lined the cylinder and conformed to its shape. Its crushing strength, an indication of cylinder life, is 6205 kPa (900 psi).

When medical research indicated that asbestos fibers are carcinogenic due to the size of the fibers (less than 3.5 microns in diameter and 10 microns in length, which is small enough to allow the fibers to penetrate the respiratory tract of the lungs), cylinder manufacturers set about to produce an asbestos-free filler. A non-asbestos alkaline-resistant glass fiber filler was developed by the Linde Division of Union Carbide Corporation and patented in 1982.

A cut-away view of a modern acetylene cylinder is shown in Figure A-2.

How Acetylene Cylinders are Manufactured

Cylinder production and testing is a step-by-step procedure which insures ultimate quality and safety. Seamless shells are cold drawn in hydraulic presses with capacities up to 454 000 kg (500 tons). Center seams and footring attachments are welded using the submerged arc process. Cylinders are then normalized (stress relieved) to increase cylinder life and corrosion resistance.

Measure and Weight

In the filling area, cylinders are measured and weighed to determine exact volume. At another location, filler is mixed to correct proportions in hoppers, weighed, and mixed with water in agitators. Before each new batch of filler is used, a sample containing one cubic foot is weighed and examined to ensure correct mixture.

Cylinders are then filled automatically and weighed again. Factoring in the weight and volume of the cylinder confirms that it is accurately filled to specification. The cylinders are then oven-baked at 315°C (600°F) to

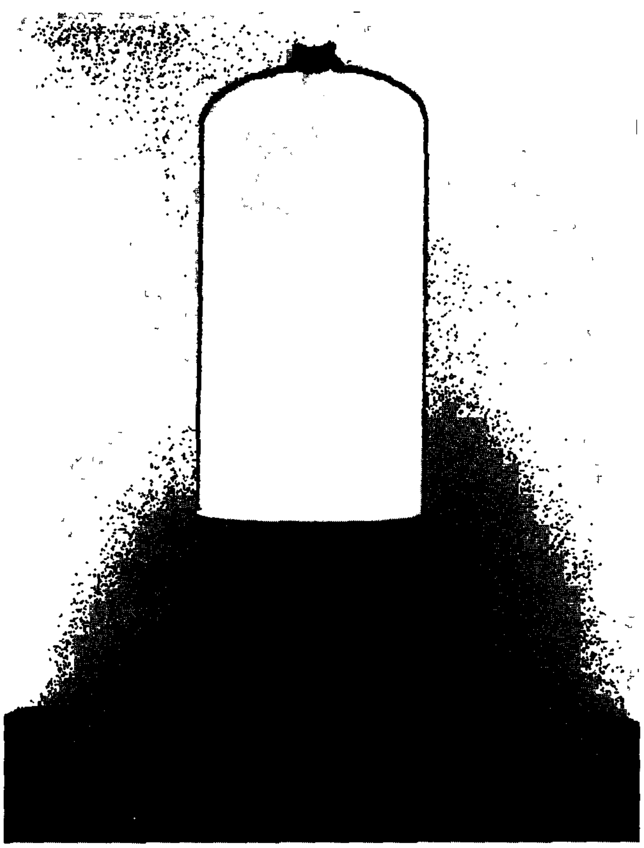


Figure A-2—Cross Section of an Acetylene Cylinder Showing the Filler Material

Photo courtesy of Norris Cylinder Company

eliminate the water. Baking time ranges from 40 to 120 hours, depending on cylinder size. After baking, another weight check is made to determine if any water remains. Since 1% moisture in the filler will affect ultimate performance, cylinders are baked again if only a slight moisture content is detected.

Fuse plugs and valves are installed, and cylinders are shot-blasted and painted. (Fuse plugs are small steel machine bolts with holes filled with a low-melting alloy designed to release gas in case of fire, and to lessen the acetylene pressure to reduce the possibility of an explosion).

Finally, strength proof tests at 4140 kPa (600 psi) are run. Pressure is then reduced to 2070 kPa (300 psi), and the cylinders are immersed in water to check for leaks. Drawn to a vacuum, they are charged with acetone and weighed again to determine if they are fully charged.

Cylinders are checked after each procedure during the manufacturing process. Those not meeting the rigid requirements of federal law and company rules are rejected regardless of the stage of manufacture. For example, a number of cylinders are selected from each completed lot, charged with acetylene, and tested to ensure proper discharge. If the cylinders do not meet specifications, the entire lot is rejected.

Basic Tests

A *bonfire test* is designed to check cylinder performance under conditions similar to a fire in a building. A fully charged cylinder is placed horizontally on racks, and specified sizes and amounts of wood strips are ignited around it. The cylinder passes the test if there is no appreciable shell bulge, no penetration of filler by decomposition, and no breakup of the filler.

The *flashback test* simulates torch flashback entering the cylinder, assumed to be at full pressure when the operator closes the valve immediately afterward. If the flash is immediately quenched in the cylinder with only a minimum of decomposition and without release of fusible plugs, the cylinder passes the test.

A *hot spot test* simulates negligent impinging of a torch flame against the cylinder. Flame is directed at the cylinder sidewall until a 3 to 20 mm (1/8 to 3/4 in.) bulge develops. If filler decomposition is limited to the area closely adjacent to the resulting cavity, performance is satisfactory.

The *bump test* determines the filler's resistance to mechanical shock received during normal service. The cylinder is mounted on a foundry mold-bumper and subjected to minimum 200 000 bumping cycles. At the conclusion of the test, satisfactory performance is indicated when there is no attrition, sagging, or cracking of the filler.

ACETYLENE CYLINDERS, Safe Handling

At ambient conditions, increased pressure and decreased temperature can liquefy acetylene. At extremely low temperatures, acetylene can solidify. The danger at the point of liquefaction or solidification (and the major reason why acetylene cannot be distributed in this form) is that the necessarily high pressures create a very unstable product. At the slightest provocation, compressed acetylene will dissociate into its chemical components, carbon and hydrogen. This dissociation is accompanied by drastic increases in both temperature and pressure, and results in an explosion.

The acetylene distributor, as well as the user, must observe important precautions:

(1) Slings, hooks or magnets cannot be used to move cylinders. Cylinders of acetylene must be kept in an upright position. Cylinders cannot be dragged, and can never be used or stored in a horizontal position.

(2) A hand truck should be used when an acetylene cylinder must be moved, or the cylinder should be tilted slightly and rolled it on its bottom edge.

(3) A cylinder storage area should be chosen that is well removed from any heat sources, and the area should be posted with conspicuous signs forbidding smoking or the use of open flames or lights.

(4) If cylinders are stored outdoors, dirt, snow or ice should not be allowed to accumulate on valves or safety devices.

(5) The cylinders should be secured with chains or heavy rope so that they cannot be accidentally tipped over.

(6) A leaking cylinder must be handled with extreme care; it should be removed immediately from the storage area after checking to be sure that no sources of ignition are brought near it. The supplier should be notified immediately.

(7) One cylinder should not be recharged from another, or other gases mixed in an acetylene cylinder.

(8) Copper tubing should never be used to convey acetylene. Acetylene will react with the copper to form copper acetylide, an unstable compound which can explode spontaneously.

ACETYLENE FEATHER

The intense white, feathery-edged portion adjacent to the cone of a carburizing oxyacetylene flame. See STANDARD WELDING TERMS. *See also* Figure A-1.

ACETYLENE GENERATOR

In the United States, common practice has established a preference for the carbide-to-water machines, and they are almost universally used. There is another type of generator using calcium carbide molded into cakes, in which the water drops into the calcium carbide. This type of generator, while common in Europe, is almost unknown in the United States.

Insurance Regulations

The Underwriters' Laboratories is an organization maintained by the insurance companies of the United States which provides for the inspection and testing of all types of equipment which may be considered a fire or accident hazard, including welding and cutting equipment and acetylene generators. There are established sets of rules governing the design, construction, and installation of acetylene generators, including acetylene pipe lines.

Another insurance authority which publishes rules for acetylene generators is the Factory Mutual Engineering Organization, Norwood, Mass. Regulations of the American Insurance Service Group, New York, N.Y. and the National Fire Protection Association, Quincy, Mass. are also followed. See GAS SYSTEMS.

ACETYLENE WELDING

See OXYACETYLENE WELDING *and* OXYFUEL GAS WELDING.

ACID BRITTLENESS

Brittleness induced in steel, especially wire or sheet, by pickling in dilute acid for the purpose of removing scale. This brittleness is commonly attributed to the absorption of hydrogen.

ACID CORE SOLDER

A solder wire or bar containing acid flux as a core. See STANDARD WELDING TERMS.

ACID STEEL

See STEEL, ACID.

ACTIVATED ROSIN FLUX

A rosin base flux containing an additive that increases wetting by the solder. See STANDARD WELDING TERMS.

ACTIVE FLUX, Submerged Arc Welding

A flux from which the amount of elements deposited in the weld metal is dependent on the welding conditions, primarily on the arc voltage. See STANDARD WELDING TERMS. *See also* NEUTRAL FLUX.

ACTUAL THROAT

The shortest distance between the weld root and the face of a fillet weld. See STANDARD WELDING TERMS. See Appendix 11, Figure A, B. *See also* THROAT OF A FILLET WELD, EFFECTIVE THROAT, *and* THEORETICAL THROAT.

ADAMS, COMFORT A.

Founder and first president of the American Welding Society.

ADAPTER

A device for connecting two parts (i.e., of different diameters) of an apparatus, or for adapting apparatus for uses not originally intended. An adapter is sometimes used to connect a regulator to a tank which has a valve threaded differently from the inlet connection of the regulator. **This practice is not recommended.**

ADAPTIVE CONTROL

Pertaining to process control that automatically determines changes in process conditions and directs the equipment to take appropriate action. See STANDARD WELDING TERMS. *See also* AUTOMATIC WELDING, MANUAL WELDING, MECHANIZED WELDING, ROBOTIC WELDING, *and* SEMIAUTOMATIC WELDING.

ADAPTIVE CONTROL BRAZING.

See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING.

ADAPTIVE CONTROL SOLDERING

See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING.

ADAPTIVE CONTROL THERMAL CUTTING

See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING.

ADAPTIVE CONTROL THERMAL SPRAYING

See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING.

ADAPTIVE CONTROL WELDING

Welding with a process control system that automatically determines changes in welding conditions and directs the equipment to take appropriate action. Variations of this term are adaptive control brazing, adaptive control soldering, adaptive control thermal cutting, and adaptive control thermal spraying. See STANDARD WELDING TERMS.

Adaptive (feedback) control systems are automatic welding systems which make corrections to welding variables based on information gathered during welding. The objective is to maintain weld quality at a constant level in the presence of changing welding conditions. Automatic adjustment of individual weld variables, such as arc current or arc length, is made by monitoring a weld characteristic, such as pool width. Other feedback control systems are available to provide electrode guidance and constant joint fill. *See also* AUTOMATIC WELDING, MANUAL WELDING, MECHANIZED WELDING, ROBOTIC WELDING, *and* SEMIAUTOMATIC WELDING.

ADDED METAL

A term sometimes used to describe the metal added to the base metal during arc, gas, or thermite welding.

ADHESIVE BONDING

Adhesive bonding is a materials joining process in which a nonmetallic adhesive material is placed between the faying surfaces of the parts or bodies, called *adherends.* The adhesive then solidifies or hardens by physical or chemical property changes to produce a bonded joint with useful strength between the adherends.

Adhesive is a general term that includes such materials as cement, glue, mucilage, and paste. (Terms relating to adhesives are defined in ANSI/ASTM D907.) Although natural organic and inorganic adhesives are available, synthetic organic polymers are usually used to join metal assemblies. Various descriptive adjectives are applied to the term adhesive to indicate certain characteristics, as follows:

(1) Physical form: liquid adhesive, tape adhesive

(2) Chemical type: silicate adhesive, epoxy adhesive, phenolic adhesive

(3) Materials bonded: paper adhesive, metal-plastic adhesive, can labeling adhesive

(4) Application method: hot-setting adhesive, sprayable adhesive.

Although adhesive bonding is used to join many nonmetallic materials, the following paragraphs refer only to the bonding of metals to themselves or to nonmetallic structural materials.

Adhesive bonding is similar to soldering and brazing of metals in some respects, but a metallurgical bond does not take place. The surfaces being joined are not melted, although they may be heated. An adhesive in the form of a liquid, paste, or tacky solid is placed between the faying surfaces of the joint. After the faying surfaces are mated with the adhesive in between, heat or pressure, or both, are applied to accomplish the bond.

An adhesive system must have the following characteristics:

(1) At the time the bond is formed, the adhesive must become fluid so that it wets and comes into close contact with the surface of the metal adherends.

(2) In general, the adhesive cures, cools, dries, or otherwise hardens during the time the bond is formed or soon thereafter.

(3) The adhesive must have good mutual attraction with the metal surfaces, and have adequate strength

and toughness to resist failure along the adhesive-to-metal interface under service conditions.

(4) As the adhesive cures, cools, or dries, it must not shrink excessively. Otherwise, undesirable internal stresses may develop in the joint.

(5) To develop a strong bond, the metal surfaces must be clean and free of dust, loose oxides, oil, grease, or other foreign materials.

(6) Air, moisture, solvents, and other gases which may tend to be trapped at the interface between the adhesive and metal must have a way of escaping from the joint.

(7) The joint design and cured adhesive must be suitable to withstand the intended service.

A variety of adhesives can be used. Thermoplastic adhesives develop a bond through the evaporation of a solvent or the application of heat. The pressure-sensitive adhesives produce a bond when pressure is applied to the joint. Other adhesives, usually used for metals, react chemically with curing agents or catalysts. Some epoxy-based adhesives can produce joint strengths up to 70 MPa (10 000 psi) when cured at 175°C (350°F) for a few hours under pressures of about 1030 kPa (150 psi). The types of polymeric adhesives used to bond metal are listed in Table A-1.

Table A-1
Types of Polymeric Adhesives Used to Bond Metals

Solvent	Neoprene Nitrile Urethane (thermoplastic) Block copolymer Styrene-butadiene
Hot Melt	Ethylene vinyl acetate Block copolymer Polyester Polyamide
Pressure Sensitive	Block copolymer Acrylic
Chemically Reactive	Epoxy Phenolic Structural acrylic Anaerobic Cyanoacrylate Urethane

Advantages and Applications

Adhesive bonding has several advantages for joining metals when compared to resistance spot welding, brazing, soldering, or mechanical fasteners such as rivets or screws. Adhesive bonding is also capable of joining dissimilar materials, for example, metals to plastics; bonding very thin sections without distortion and very thin sections to thick sections; joining heat-sensitive alloys; and producing bonds with unbroken surface contours.

The adhesive that bonds the component may serve as a sealant or protective coating. Adhesives can provide thermal or electrical insulating layers between the two surfaces being joined, and different formulations of the adhesive can make the bonding agent electrically conductive. These properties are highly adaptable to mass-produced printed circuit boards, and to the electrical and electronic components industry.

Smooth, unbroken surfaces without protrusions, gaps, or holes can be achieved with adhesive bonding. Typical examples of applications are the vinyl-to-metal laminate used in the production of television cabinets and housings for electronic equipment. Other examples are automotive trim, hood and door panels, and roof stiffeners.

The ability of flexible adhesives to absorb shock and vibration gives the joint good fatigue life and sound-dampening properties. A specific example is the improved fatigue life of adhesive-bonded helicopter rotor blades.

A combination of adhesives and rivets for joints in very large aircraft structures has increased the fatigue life of joints from 2×10^5 cycles for rivets alone to 1.5×10^6 cycles for bonded and riveted joints. The large bonded area also dampens vibration and sound.

Adhesive bonding may be combined with resistance welding or mechanical fasteners to improve the load-carrying capacity of the joint. The adhesive is applied to the adherents first. Then the components are joined together with spot welds or mechanical fasteners to hold the joints rigid while the adhesive cures. Figure A-3 illustrates typical design combinations. These techniques significantly reduce or eliminate fixturing requirements and decrease assembly time when compared to conventional adhesive bonding methods.

Adhesive bonding may permit significant weight savings in the finished product by utilizing lightweight fabrications. Honeycomb panel assemblies, used extensively in the aircraft industry and the construction field are excellent examples of lightweight fabrications. Although weight reduction can be important in the function of the product, adhesive bonding of products may also provide considerable labor and cost savings in packing, shipping, and installation.

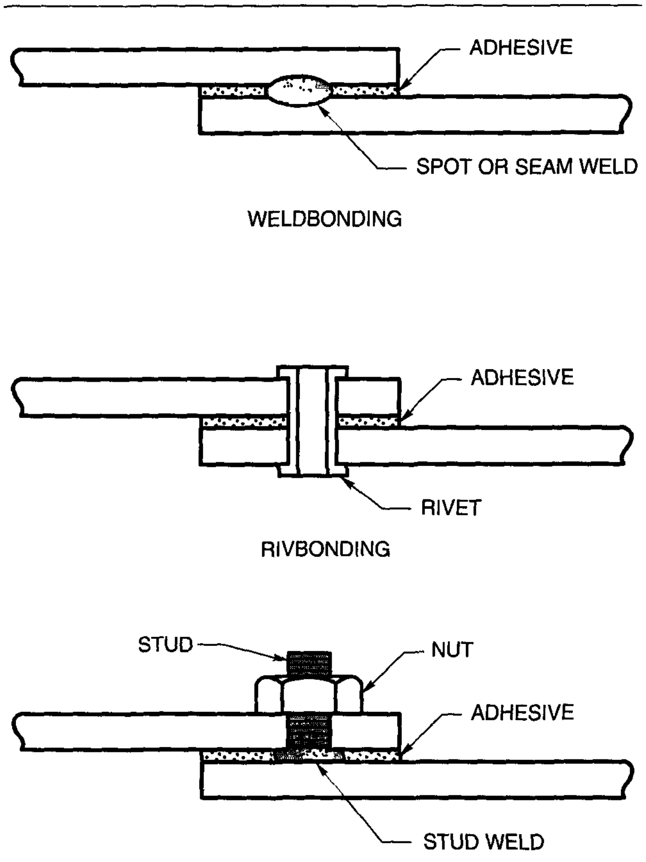


Figure A-3—Adhesive Bonding in Combination with Resistance Welds and Mechanical Fasteners

Limitations

Adhesive bonding has certain limitations which should be considered in its application. Joints made by adhesive bonding may not support shear or impact loads.These joints must have an adhesive layer less than 0.13 mm (0.005 in.) thick, and must be designed to develop a uniform load distribution in pure shear or tension. The joints cannot sustain operational temperatures exceeding 260°C (500°F).

Capital investment for autoclaves, presses, and other tooling is essential to achieve adequate bond strengths. Process control costs may be higher than those for other joining processes. In critical structural bonding applications, surface preparation can range from a simple solvent wipe to multi-step cleaning, etching, anodizing, rinsing and drying procedures; and joints must be fixtured and cured at temperature for some time to achieve full bond strength. Some adhesives must be used quickly after mixing. Nondestructive testing methods normally used for other joining methods are not generally applicable to evaluation of adhesive bonds. Both destructive and nondestructive testing must be used with process controls to establish the quality and reliability of bonded joints.

Service conditions may be restrictive. Many adhesive systems degrade rapidly when the joint is both highly stressed and exposed to a hot, humid environment.

Safe Practices

Corrosive materials, flammable liquids, and toxic substances are commonly used in adhesive bonding. Manufacturing operations should be carefully supervised to ensure that proper safety procedures, protective devices, and protective clothing are being used. All federal, state and local regulations should be complied with, including OSHA Regulation 29CRF 1900.1000, Air Contaminants. The material safety data sheet of the adhesive should be carefully examined before the adhesive is handled to ensure that the appropriate safety precautions are being followed.

References: American Welding Society. *Welding Handbook*, 8th Edition, Vol.1. Miami, Florida: American Welding Society, 1987; and American Welding Society. *Welding Handbook,* 8th Edition, Vol. 2. Miami, Florida: American Welding Society, 1991.

ADMIRALTY BRASS

An alloy which is 70% copper, 29% zinc and 1% tin, commonly used for condenser and heat exchanger tubing. *See* COPPER ALLOY WELDING.

AGE HARDENING

A term applied to a property exhibited by some of the light alloys, such as aluminum or magnesium, of hardening at ordinary temperatures after solution treatment or cold work. The controlling factors in age hardening are the composition of the material, degree of dispersion of the soluble phase, solution time and temperature, and aging time and temperature.

AGGLOMERATED FLUX, Submerged Arc Welding

A type of flux produced with a ceramic binding agent requiring a higher drying temperature that limits the addition of deoxidizers and alloying elements. This is followed by processing to produce the desired particle size. See STANDARD WELDING TERMS.

AGING

A term applied to metals and particular alloys which show changes in physical properties on exposure to ordinary or elevated temperatures.

AGRICULTURAL WELDING

See FARM IMPLEMENT REPAIR.

AIR-ACETYLENE TORCH

A torch which produces a flame by burning a mixture of acetylene and air. The flame is as easily controlled and manipulated as the oxyacetylene flame, but has a lower temperature.

The air-acetylene torch operates on the same principle as the Bunsen burner, that is, the acetylene flowing under pressure through a Bunsen jet draws in the appropriate amount of air from the atmosphere to provide combustion. The flame is adjusted by controlling the amount of air admitted to the Bunsen jet. The mixer on the torch must be carefully adjusted to draw the correct volume of air to produce an efficient, clean flame. The air-acetylene flame ignites at 480°C (896°F) and produces a maximum temperature of 1875°C (3407°F).

The air-acetylene torch is used for brazing, soldering, and heating applications, but the flame temperature is not sufficient for welding, except for joining materials with a low melting point, like lead. It is widely used for soldering copper plumbing fittings up to 25 mm (10 in.) in diameter.

AIR ACETYLENE WELDING (AAW)

An oxyfuel gas welding process that uses an air-acetylene flame. The process is used without the application of pressure. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

AIR CAP

A nonstandard term for the nozzle of a flame spraying gun for wire or ceramic rod.

AIR CARBON ARC CUTTING (CAC-A)

A carbon arc cutting process variation that removes molten metal with a jet of air. See STANDARD WELDING TERMS.

The air carbon arc cutting process uses an arc to melt metal which is blown away by a high-velocity jet of compressed air. The electrodes are rods made from a mixture of graphite and carbon, and most are coated with a layer of copper to increase their current-carrying capacity. Standard welding power sources are used to provide the current. Air is supplied by conventional shop compressors, and most applications require about 550 kPa (80 psi) at between 560 to 840 liters/min (20 to 30 cubic feet per minute). Manual rod holders are very similar in appearance to shielded metal arc welding electrode holders, and supply both compressed air and current.

In gouging operations, the depth and contour of the groove are controlled by the electrode angle, travel speed, and current. Grooves up to 16 mm (5/8 in.) deep can be made in a single pass. In severing operations, the electrode is held at a steeper angle, and is directed at a point that will permit the tip of the electrode to pierce the metal being severed.

In manual work, the geometry of grooves is dependent on the cutting operator's skill. To provide uniform groove geometry, semiautomatic or fully automatic torches are used to cut "U" grooves in joints for welding. When removing weld defects or severing excess metal from castings, manual techniques are most suitable.

Voltage controlled automatic torches and control units are used for very precise gouging, with tolerances of less than 0.8 mm (1/32 in.), and are generally mounted on standard travel carriages.

Reference: American Welding Society. *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

AIR CARBON ARC CUTTING TORCH

A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of air. See STANDARD WELDING TERMS.

AIRCRAFT WELDING

The character of welding changes in aircraft construction with each technological advancement that affects any aircraft component. Because the materials and joining techniques and processes utilized in the aircraft industry are constantly changing and improving, it is vital that the most recent standards and current literature on the subject be used for reference.

While airplanes were largely hand-made metallic structures in the past, only the lighter planes have the welded steel fuselage that was once popular. High-speed transports and military jets have a metallic skin to provide a monococque fuselage. Although rivets have been used to fasten the skin to the cell rings, spot welding also has an important role in the construction of this type of aircraft.

Welding is the method that has the versatility to meet the varying conditions of joining members of varying sizes and weights which make up aircraft structures. The aircraft structure, with its multiplicity of joints, must be light in weight and sufficiently strong to withstand severe conditions of service.

The welded joint offers rigidity, simplicity, low weight, approximately full-strength joints, low corrosion possibilities, and relatively low-cost production equipment. Because of these advantages, welding is used for building all classes of airplanes, from light two-place pleasure planes to giant supersonic jets.

Welded tubular structures form the framework for the landing gear and the engine mounts. Requirements of the jet engine have introduced many areas in which welding plays an important role.

Modern jet transports contain extremely high quality welds in the miles of duct work found in every jet plane. The welds are made by highly skilled gas tungsten arc welders in 5052 and 6061 aluminum, Inconel® 625 and 718 nickel-base alloys, and 6Al-4V titanium.

AIR CUSHION

A pneumatic pressure device, sometimes adjustable, incorporated in the air-operating mechanism of a resistance welding machine to provide a deceleration of a mechanical motion.

AIR FEED

A thermal spraying process variation in which an air stream carries the powdered surfacing material through the gun and into the heat source. See STANDARD WELDING TERMS.

ALIGNED DISCONTINUITIES

Three or more discontinuities aligned approximately parallel to the weld axis, spaced sufficiently close together to be considered a single intermittent discontinuity. See STANDARD WELDING TERMS.

ALIGNED POROSITY

A localized array of porosity oriented in a line. See STANDARD WELDING TERMS.

ALIGNMENT

Arrangement or position in line. To produce an accurate and serviceable weld when several parts are involved, an alignment jig is a necessity. *See* JIG, FIXTURE, *and* POSITIONER.

ALLOTROPY

The reversible phenomenon by which certain metals may exist with more than one crystal structure. For example, alpha, gamma and delta iron are three allotropic forms of iron with different crystal structures.

ALLOY

A substance with metallic properties and composed of two or more chemical elements of which at least one is a metal. See STANDARD WELDING TERMS.

The added element may be metallic or nonmetallic. *See also* STEEL, ALLOY; ALUMINUM ALLOYS; MONEL; COPPER ALLOY WELDING.

ALLOY POWDER

Powder prepared from a homogeneous molten alloy or from the solidification product of such an alloy. See STANDARD WELDING TERMS. *See also* POWDER BLEND.

ALLOY STEEL

See STEEL, ALLOY.

ALLOYING ELEMENTS

The chemical elements comprising an alloy. In steel it is usually limited to the metallic elements added to steel to modify its properties. For example, the addition of copper, nickel, or chromium individually or in combination produces alloys or special steels.

ALL-WELD-METAL TEST SPECIMEN

A test specimen in which the portion being tested is composed wholly of weld metal.

ALNICO ALLOYS

A series of alloys developed for use as permanent magnets. With the exception of Alnico III, all of these iron-base alloys contain aluminum, nickel, and cobalt as the principle alloying elements (as the name *Alnico* indicates). Most also contain 3% or 6% copper. Because these alloys are available only in the cast or sintered condition, they are difficult to fabricate by welding.

ALPHA BRASS

A copper-zinc alloy with a copper content greater than approximately 64%. "Yellow brass" is the name used in metallurgical literature.

ALPHA IRON

The body-centered cubic form of pure iron. *See* METALLURGY.

ALTERNATING CURRENT (ac or a-c)

(Abbreviation: ac, when used as a noun; a-c when used as an adjective). A current which reverses directions at regularly recurring intervals. Unless otherwise distinctly specified, the term alternating current refers to a periodically varying current with successive half waves of the same shape and area.

ALTERNATING CURRENT ARC WELDING

An arc welding process in which the power supply provides alternating current to the arc.

ALUMINOTHERMIC PROCESS

A method of welding which makes use of the exothermic reaction which occurs when a mixture of aluminum and iron oxide powders is ignited. When ignited, this mixture produces superheated liquid steel and aluminum oxide slag at approximately 2760°C (5000°F). The liquid steel is sufficiently hot to melt and dissolve any metal with which it comes in contact and fuses with it to form a solid homogeneous mass when cooled. For this reason, this process is especially adapted to welding heavy steel and cast iron sections, such as those used in locomotive, marine, crankshaft and steel mill repairs, and is also used in pipe welding and rail welding. *See* THERMITE WELDING.

ALUMINUM

(Chemical symbol: Al). Aluminum is a silver-white, malleable, ductile, light, metallic element with good electrical and thermal conductivity, high reflectivity, and resistance to oxidation. Atomic weight, 26.97; melting point, 660°C (1220°F); specific gravity, 2.70 at 20°C (68°F).

Aluminum is one of the most abundant constituents of the earth's crust. It is found in most clays, soils and rocks, but the principal commercial source is the ore, bauxite, an impure hydrated oxide. The impurities are removed from bauxite by a chemical process leaving pure aluminum oxide, alumina. Pure metallic aluminum is obtained by electrolysis of the oxide.

Aluminum is third on the scale of malleability and fifth in ductility. It is only slightly magnetic and is strongly electro-positive, so that when in contact with most metals it corrodes rapidly. Aluminum will take a high polish, but it is likely to become "frosted" in appearance due to the formation of an oxide coating. Its electrical conductivity is about 60% that of copper.

Aluminum is used extensively as a deoxidizer in steel production, and as such it is an effective purifier. Aluminum lessens grain growth by forming dispersed oxides or nitrides.

ALUMINUM ALLOYS

Commercial aluminum alloys are grouped into two classifications: wrought alloys and cast alloys.

Wrought Alloys

Wrought alloys are those alloys which are designed for mill products for which final physical forms are obtained by mechanical working, such as rolling, forging, extruding and drawing. Wrought aluminum mill products include sheet, plate, wire, rod, bar, tube, pipe, forgings, angles, structural items, channels, and rolled and extruded shapes.

Cast Alloys

Cast alloys are those alloys which are shaped into final form by filling a mold with molten metal and allowing it to solidify in the mold.

Sand Casting. Sand casting utilizes a mold in sand made around a previously formed pattern to the exact shape desired in the final casting, but slightly larger in size to allow for shrinkage of the cast metal as it cools.

Permanent Mold Castings. Permanent mold castings are made by pouring molten metal into steel or iron molds.

Die Castings. Die castings are also made in steel molds, but the molten metal is forced under pressure into the die or mold cavities. Die casting yields a denser casting with a better surface finish, closer dimensional tolerances, and thinner sections when desired.

Clad Alloys

Clad alloys, which may be up to 5% of the total thickness on each side, yield a composite product which provides the high strength of the core alloy protected by the cladding.

Copper and zinc, when used as major alloying elements, reduce the overall resistance to corrosion of aluminum alloys. To gain the desired corrosion resistance in these alloys in sheet and plate form, they are clad with high purity aluminum, a low magnesium-silicon alloy, or an alloy of 1% zinc.

Wrought Alloy Designations

The Aluminum Association, an organization composed of manufacturers of aluminum and aluminum alloys, has devised a four-digit index system for designating wrought aluminum and wrought aluminum alloys. The first digit indicates the alloy group, i.e., the major alloying element, as shown in Table A-2. The second digit indicates a modification of the original alloy, or the impurity limit of unalloyed aluminum. The third and fourth digits identify the alloy or indicate the aluminum purity. *See* UNIFIED NUMBERING SYSTEM.

Table A-2
Aluminum Alloy Designations

Aluminum Alloy Group	Designation
Aluminum—99%	1xxx
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium & Silicon	6xxx
Zinc	7xxx
Other Element	8xxx

Wrought Alloy Temper Designations

In this index system, the letter following the alloy designation and separated from it by a hyphen indicates the basic temper designation. The addition of a subsequent digit, when applicable, refers to the specific treatment used to attain this temper condition.

Alloys which are hardenable only by cold working are assigned "H" designations; alloys hardenable by heat treatment or by a combination of heat treatment and cold work are assigned "T" designations. Table A-3 shows the basic temper designations and resulting condition of the alloy.

Casting Alloy Designations

A system of four-digit numerical designations is used to identify aluminum casting alloys, as shown in Table A-4. The first digit indicates the alloy group, the second two digits identify the aluminum alloy within the group, and the last digit (which is separated from the first three by a period) indicates the product form. A modification of the original alloy or impurity limits is indicated by a letter before the numerical designation. The temper designation system for castings is the same as that for wrought product shown in Table A-3.

ALUMINUM BRAZING

In brazing, specific fluxes and filler materials with melting points lower than that of the parent metal are used for making a joint without melting the pieces to be joined. Brazing can be used to advantage when sections are too thin for welding, and for those assemblies having many parts which must be joined in an intricate manner. Brazing is generally lower in cost than gas or arc welding and is adaptable to mass production. Brazed joints have a smoother appearance, with well-rounded fillets which often require no finishing.

Brazed joints should be carefully designed to provide for full penetration of filler metal, because its flow depends largely on capillary action and gravity. Joints should be self-jigging for easy assembly prior to brazing. Lock seams, lap fillet, and T-joints are preferred because they have greater strength than butt or scarf joints.

Three commonly used aluminum brazing methods are furnace, molten flux dip, and torch.

Furnace Brazing

Furnace brazing consists of applying a flux and filter material to the workpieces, arranging them, then heating in a furnace to a temperature that causes the filler material to melt and flow into the joint without melting the parent metal. Filler material in various forms is added to the joint. In many cases, filler material in the form of a flat shim or wire ring can be fitted into the joint. Filler material is also supplied by using clad brazing sheet, shaped to fit the joint.

Standard types of furnace heating systems include forced air circulation, direct combustion, electrical resistance, controlled atmosphere, and radiant tube. The selection of furnace type is determined by the application requirements, as furnace operation and results vary. For example, temperature is most easily controlled in electrical resistance furnaces. Although combustion furnaces are least expensive, some assemblies cannot be exposed to the gases which are always present in this type. Radiant heat furnaces are sometimes difficult to regulate, but the type of heat produced is excellent for most brazing requirements. Aluminum-coated steel or firebrick linings are preferred for all types of heating units.

Rate of production is another consideration when selecting a heating unit. In batch furnaces, brazing is accomplished by placing a tray of assemblies inside, heating for the required time, then removing the batch. Though simpler, this furnace is slower than the furnace with a continuous conveying system in which the work moves through on a belt. The continuous furnace is more conservative of heat, and the gradual heating reduces danger of warping.

Temperature for individual batches will necessarily depend on such factors as the design of the parts, size of fillets, and alloy to be brazed. However, furnaces should have operating temperature ranges from 540 to 650°C (1000 to 1200°F), with control capability within ±3°C (5°F). Since regulation of temperature is critical, automatic control is the rule in production

Table A-3
Basic Temper Designations Applicable to the Heat-Treatable Aluminum Alloys

Designation*	Description	Application
-0	Annealed	Applies to wrought products which are annealed to obtain the lowest strength temper, and to cast products which are annealed to improve ductility and dimensional stability. The 0 may be followed by a digit other than zero.
-F	As fabricated	Applies to products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.
-W	Solution heat treated	An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated; for example: W 1/2 hr.
-Tl		Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition. Applies to products which are not cold worked after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T2		Cooled from an elevated-temperature shaping process, cold worked, and naturally aged to a substantially stable condition. Applies to products which are cold worked to improve strength after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T3		Solution heat treated, cold worked, and naturally aged to a substantially stable condition. Applies to products which are cold worked to improve strength after solution heat treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T4		Solution heat treated and naturally aged to a substantially stable condition. Applies to products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T5		Cooled from an elevated-temperature shaping process and then artificially aged. Applies to products which are not cold worked after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T6		Solution heat treated and stabilized. Applies to products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T7		Solution heat treated and stabilized. Applies to products which are stabilized after solution heat treatment to carry them beyond the point of maximum strength to provide control of some special characteristic.
-T8		Solution heat treated, cold worked, and then artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T9		Solution heat treated, artificially aged, and then cold worked. Applies to products which are cold worked to improve strength.
-T10		Cooled from an elevated-temperature shaping process, cold worked, and then artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

*Additional digits, the first of which shall not be zero, may be added to designation Tl through T10 to indicate a variation in treatment which significantly alters the characteristic of the product.

Table A-4
Designations for Cast Aluminum Alloy Groups

Alloy Group	Designation
Aluminum—99.00% minimum purity	1xx.x
Copper	2xx.x
Aluminum-silicon-copper or aluminum-silicon magnesium	3xx.x
Aluminum-silicon	4xx.x
Aluminum-magnesium	5xx.x
Aluminum-zinc	7xx.x
Aluminum-tin	8xx.x
Other alloy systems	9xx.x

jobs. If uniform rise of temperature does not occur naturally, forced circulation is essential.

Assemblies are generally placed in the furnace immediately after fluxing. When large areas have been fluxed, most of the moisture must be removed because the brazing process may be hindered if it is not removed. Preheating the parts for about 20 minutes at approximately 200°C (400°F) is usually sufficient.

Brazing time depends on the thickness of the parts. For instance, material 0.15 mm (0.006 in.) thick reaches temperature in a few minutes, while 13 mm (0.5 in.) thick material may take up to 45 minutes. After the filler material begins to melt, it takes approximately five minutes for the material to fill the joints.

Dip Brazing

Parts are assembled and dipped into a molten flux in dip brazing. This method has been very successful for the manufacture of elaborate assemblies, such as heat exchanger units. The flux application does not require a separate operation and the bath transmits heat to the interior of thin walled parts without overheating outside surfaces. Contamination is also held to a minimum.

Dip brazing is versatile. It is used in the manufacture of delicate specialty parts where tolerances up to ±0.05 mm (0.002 in.) are maintained in production, or in making large parts approaching 450 kg (1000 lb).

A separate furnace is necessary to preheat the assembly to prevent undue cooling of the flux bath. A furnace used for furnace brazing operated at 280 to 300°C (540 to 565°F) is satisfactory for preheating. It should be located near the dip pot so heat loss will be held to a minimum.

Size of the dip pot will depend on the size of the assemblies to be brazed, but should be large enough to prevent the parts from cooling the flux more than 5°C (10°F) below operating temperature when they are added.

Dehydration of the flux bath is accomplished by dipping 1100 or 3003 alloy sheet into it. As the sheet is attacked, the hydrogen evolved is ignited on the surface. Residue that forms on the bottom of the pot must be removed on a regular basis.

A modification of dip brazing is the application of a flux mixture to the assembly prior to immersion in a salt bath furnace. A typical example consists of making a paste of a mixture of a dry, powdered aluminum-silicon (548°C [1018°F] flow point) brazing alloy and flux, and water, and applying as much as required to fill the joints and make fillets. Next, the assembly is placed in an oven and heated to about 540°C (1000°F) to remove the water. This leaves the brazing alloy powder firmly cemented to the aluminum surfaces, the flux serving as the cement.

When the assembly is placed in the molten brazing salt, the alloy is held firmly in place by the flux cement while it is being heated and melted. The flux cement has a higher melting point than either the brazing alloy or the brazing salt, but it is soluble in the salt bath, so the brazing alloy is held in place, even while melting, until the cement has been dissolved by the molten salt. As the flux cement is dissolved away from the molten filler metal, the alloy runs into the joint capillary spaces and also forms smooth fillets.

Torch Brazing

This method of brazing can be accomplished by using a standard torch as a heat source. Correct torch tip can best be determined through trial, and often depends on the thickness of the piece to be brazed. Filler alloys with suitable melting ranges and efficient fluxes are available for all brazeable aluminum alloys. Most work can be torch brazed with 3 mm (1/8 in.) diameter wire.

A reducing flame with an inner cone about 25 mm (1 in.) in length and a larger exterior blue flame is preferred. Oxyhydrogen, oxyacetylene, oxynatural gas, or gasoline blow torches can be used. Ample clearance space must be allowed where the filler will flow, and a path for flux to escape must be allowed.

After painting with flux paste, the entire area of the joint is heated until the filler melts when it is touched against the heated parent metal. Too hot a flame, or allowing the joint to cool repeatedly, will cause uneven results. Capillary flow tends to be toward the hottest spot, so it is important that the flow of the filler wire be controlled throughout. Heat should be applied just ahead of where flow is desired. Joints can be produced that have a final fillet that needs a minimum of finishing, if any.

All flux should be removed after brazing. If joints are accessible, a fiber brush with boiling water bath can be used. Scrubbing with hot water and rinsing with cold, then drying is often effective, as is blasting with a steam jet. When possible, a chemical treatment should be used to clean the joint.

Cleaning

Clean surfaces are essential if strong brazed joints are to result. All grease should be removed. Solvent or vapor cleaning will probably be sufficient for the non-heat-treatable alloys, but the for the heat-treatable alloys, the oxide film must be removed with a chemical or by abrasion with steel wool, or stainless steel brushes. All burrs should be removed, as flux will not flow around them.

In post-brazing cleaning, it is essential to remove all the flux. A solution of nitric acid (concentrated technical grade) in equal amounts of water is effective. When a large area is to be cleaned of residual flux, however, this method is not recommended because noxious fumes are generated. An exhaust system is advisable even for small production situations.

To achieve a uniform etch and remove flux in one operation, the work can be immersed in a nitric-hydrofluoric acid solution, using 2 L (0.5 gal) nitric acid, 1/8 L (1/4 pint) hydrofluoric acid, and 17 L (4.5 gal) of water. The major portion of flux should be removed first by immersing in boiling water, then immersing in the acid solution for 10 to 15 minutes, depending on the desired extent of etching. Parts are then drained and rinsed in cold running water, then in hot water. To avoid staining, the hot water bath should be limited to about 3 minutes.

Because of the reaction of a hydrofluoric acid solution with aluminum, in which hydrogen gas is generated, flux removal is efficiently accomplished by this method. The solution is compounded of 600 mL (1.25 pints) of acid, (technical concentrated grade) and 19 L (5 gal) of water. Though this solution is less contaminated by flux than those containing nitric acid, the hydrofluoric acid solution does dissolve aluminum. Therefore, immersion time should be limited to 10 minutes or less. Discoloration can be removed by a quick dip in nitric acid.

When maximum corrosion resistance is important, or when parts are thin, parts can be dipped in a solution of 2 L (2.25 qts.) of nitric acid (technical concentrated grade), 1.8 kg (4 lb.) of sodium dichromate, and 17 L (4.5 gal) of water. The usual procedure is to immerse the parts in hot water, then in the dip solution at 65°C (150°F) for 7 to 10 minutes, followed with rinsing in hot water.

ALUMINUM BRONZE (9% Aluminum Bronze)

A copper-aluminum alloy commonly used for the fabrication of corrosion resistant parts and marine hardware.

ALUMINUM CASTINGS, Welding

Both the gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) processes are used for welding aluminum castings. In general, welding aluminum alloy castings requires a technique similar to that used on aluminum sheet and other wrought products. However, many castings are susceptible to thermal strains and cracks because of intricate design and varying section thicknesses. In highly stressed structures, castings depend on heat treatment for strength. Welding tends to destroy the effect of the initial heat treatment. In these cases, welding is not recommended unless it is possible for the casting or assembly to be heat-treated again after welding, when the loss in strength can largely be restored.

Preparation for Welding

Before welding, castings should be cleaned carefully with a wire brush and an appropriate solvent to remove every trace of oil, grease and dirt. When welds are to be made in sections heavier than approximately 5 mm (3/16 in.), the edges should be beveled at an angle of about 45°. When preparing defective areas for welding, any unsoundness or dross must be completely melted or cut away before proceeding with the weld. When two or more pieces are to be assembled, or if a broken piece is to be welded, the parts should be held by a fixture and clamped in the correct position for preheating and welding. The clamps should be attached in a way that will permit free expansion of the casting during heating, otherwise stresses may develop which will result in excessive distortion or cracks.

Preheating

Prior to welding a casting that is large or intricate in design, it should be preheated slowly and uniformly in a furnace to avoid thermal stresses and facilitate development of the required temperature for welding. A temperature of 370 to 425°C (700 to 800°F) is generally sufficient for preheating. If the casting is small, or if the weld is near the edge and in a thin walled section, an experienced welder can often do the necessary preheating with an oxyfuel gas torch applied in the region of the weld. After welding, the casting should be cooled slowly and uniformly to room temperature to reduce the danger of excessive stresses and possible cracks.

Welding Precautions

Surface defects and small holes in aluminum castings can be repaired by welding after the part is correctly prepared and preheated. However, when working with assemblies or broken castings, there are several points to consider during welding. The individual parts should first be tack-welded into place, and actual welding should begin at the center and proceed toward the end. When any difference exists in the thickness of the sections being joined, the GTAW welder must carefully distribute the heat from the torch in order to avoid melting the lighter section while bringing the heavier section up to welding temperature. A similar precaution must be taken with sheet and casting assemblies, and welders may require a little experience to develop the proper technique.

Choice of Welding Rod

When welding castings of the non-heat-treatable aluminum alloys or assemblies involving such castings, consisting of welding rod Al-5%Si or Al-4%Cu, 3%Si is generally used. However, in the case of castings requiring subsequent heat treatment, a welding rod of the same alloy as the casting should be used. The size of the rod best suited for the job will, of course, depend to some extent on the thickness of the metal being welded, but in general, a rod 1.6 to 2.4 mm (1/16 in. to 3/32 in.) diameter will be satisfactory.

ALUMINUM, Oxyfuel Gas Welding

Satisfactory butt, lap, and fillet welds can be made with an oxyfuel gas torch on sections of aluminum ranging up to 25 mm (1 in.) in thickness. The oxyfuel gas welding process would only be used where a source of electric power is not available for arc welding. Oxyhydrogen or oxyacetylene flames produce the heat necessary to offset the high thermal conductivity of the aluminum. Generally, the other oxygen-gas combinations do not provide sufficient heat for welding, but may be used for preheating, which is often needed when joining thick sections.

Overlap joints are not recommended for gas welding because there is danger of flux entrapment in the overlap. When possible, the joint should be designed as a butt weld. If an overlap joint is made, it should be completely welded around the edges to seal the overlapped area.

Preheating is essential in gas welding to allow proper fusion. Sections thicker than 6 mm (1/4 in.) should be preheated to 310 to 370°C (600 to 700°F). Preheating above 425°C (800°F) is not recommended because there is danger of melting some of the alloying constituents. Heat should be applied uniformly to both parts being joined. *See* OXYFUEL GAS WELDING.

ALUMINUM, Gas-Shielded Arc Welding

One of several advantages of gas shielded arc welding of aluminum alloys over other methods of fusion welding is that the need for flux is eliminated, thus removing a potential source of corrosion. Other advantages are that welding can be accomplished in all positions; there is better visibility and greater speed. Sound, pressure-tight joints with high strength and low distortion can be produced. Because of these advantages, the inert-gas-shielded processes are the predominant methods of fusion welding aluminum alloys.

Relatively easy to perform, gas tungsten arc welding (GTAW) uses non-consumable tungsten electrodes, alternating current, and argon or helium shielding gas. When filler material is needed, it can be fed automatically or manually. Aluminum as thin as 0.6 mm (0.025 in.) can be welded, but production welding is more easily controlled when thickness is 1.0 mm (0.040 in.) or greater.

Gas metal arc welding (GMAW), employs aluminum wire as both electrode and filler metal, uses direct current, and a shielding gas of argon or helium, or a mixture of these. The filler wire is fed automatically into the welding zone at a speed compatible with the arc length and welding current, resulting in higher welding speeds than possible with the gas tungsten arc method. Because the heat zone on each side of the weld is narrower, GMAW produces welds of superior strength. A further advantage is that metal of considerable thickness can often be welded without preheating because of high current densities and the concentrated heat of the arc.

ALUMINUM, Pressure Welding

Pressure welding or solid phase bonding of aluminum is accomplished by applying high pressure on the surfaces to be joined, either with or without heat, in the complete absence of melting.

Pressure can be applied by aligning two punches or tapered rolls. Another method uses a shoulder punch on one side of the material and a flat plate or anvil on the other. A third method uses a single tapered roll and a flat surfaced roll. In some instances, punches with shoulders are employed to control the amount of punch penetration and flatten the deformation at the point of entry simultaneously.

Wire brushing is the most satisfactory method of surface preparation.

Pressure Gas Welding

Metal flow between clean interfaces is essential to a cold pressure weld. Simple pressure is not enough. Once started, metal flow must be vigorous and continuous, although speed seems to have little bearing on quality of weld. Pressure must be applied over a comparatively narrow strip, so that the metal can flow away from the weld at both sides. When continuous welds are to be used, the indentor should be of waved design, rather than straight, for maximum strength. Strip and sheet can also be butt welded, but as the width increases, the gripping problem for the dies also increases.

There are two basic methods of pressure gas welding: closed joint and open joint. Coalescence is produced simultaneously over the entire area of abutting surfaces by heating with oxyacetylene flames and then applying pressure. No filler metal is used.

In closed joint welding (also called solid phase and closed butt welding), weld faces are in contact during the complete welding cycle. Ends are carefully cleaned, butted, and heated to a high temperature, but not to the melting stage. Pressure is applied, thereby upsetting the weld zone in a plastic deformation. Various refinements are used in this method, particularly in pressure. Often a low initial pressure is applied, and the pressure is increased as the metal attains its plastic state. Maximum pressure can be applied throughout the welding process, or different pressures may be applied at regular or varying intervals.

In open joint welding, parts are spaced a short distance apart, and heated to the melting temperature. When melting temperature is reached, the parts are brought together rapidly, causing an upset, or partial fusion, weld. Most of the melted material is squeezed from the interface by the impact, and the resulting weld resembles a resistance flash weld.

ALUMINUM, Resistance Welding

Resistance welding is a process in which the welding heat is generated in the parts to be joined by resistance of the parts to the flow of an electric current. Spot welding, seam welding and flash welding are forms of resistance welding.

All the aluminum alloys can be resistance welded. Because the physical characteristics of aluminum are different from those of steel, somewhat different equipment may be required, although modified equipment is often adapted with excellent results. More electrical capacity is usually required for aluminum than for steel.

Advantages of resistance welding are low cost, high production speed, and automatic operation. The major disadvantage is the high initial cost of the equipment. Consequently, resistance welding is generally confined to mass production items where the low cost per weld will offset the high cost of the equipment.

Spot and Seam Welding

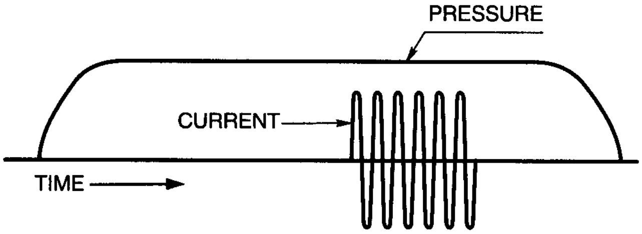
Three types of resistance welding equipment are used for spot and seam welding aluminum alloys. These are classified on the basis of the electrical system supplying welding current as follows: standard alternating current (ac), energy storage, electromagnetic, and energy storage, electrostatic. Electrostatic welding may be either magnetic or condenser energy storage. The comparative current and pressure cycles for these systems are shown in Figure A-4.

Alternating-Current Welding

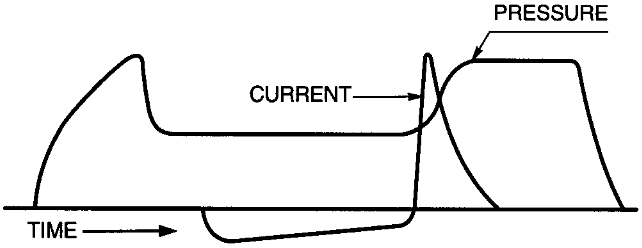
Since aluminum and its alloys have comparatively high thermal and electrical conductivities, high welding currents and relatively short welding times are required in spot welding.

In the widely used alternating-current method for spot welding, the high welding current required is obtained from the secondary coil of a welding transformer having a turns ratio from 20:1 to 100:1. The primary coil is usually connected to either 230 or 460-volt, 60 Hz power supply. An electronic control is used to time the application of welding current ranging from 1 to 30 cycles.

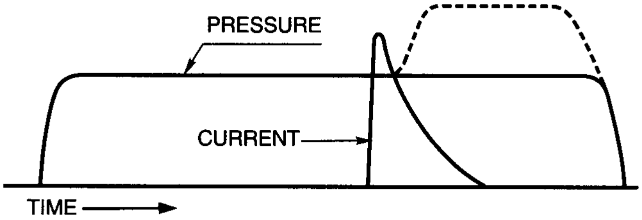
Current Regulation. The secondary current required varies with the thickness of the material to be welded, as shown in Table A-5. To obtain the correct current, an electronic control adjusts the current in steps of approximately 1000 amperes. Taps either on the primary of the welding transformer, or on a separate auto-transformer may be used. Where necessary, a series-parallel switch is provided on the welding transformer primary to permit adjustment of the current down to 25% of the maximum, which is usually sufficient to cover the normal range of material thickness.



STANDARD AC



ENERGY STORAGE—ELECTROMAGNETIC



ENERGY STORAGE—ELECTROSTATIC

Figure A-4—Comparative Pressure and Current Cycle for A-C and Energy-Storage Resistance Welding Systems

Pressure Regulation. The welding pressure is applied either by a cam and spring mechanism, a pneumatic cylinder or a hydraulic cylinder. Pneumatic operation is preferred, since most manufacturing plants have compressed-air systems and the welding pressure may be adjusted to the desired value. The pressure required on alternating-current welding machines is given in Table A-5.

Timing. The welding time is controlled by means of a switch in the supply line to the welding transformer primary. Both mechanically operated and magnetically operated welding contactors have been used for this purpose, but modern machines use solid state switches. Such devices should control the welding time to the values listed in Table A-5, with an accuracy of plus or minus one cycle. Improved welds result when the controls are adjusted to close the circuit at a uniform point in the voltage wave, and to open the circuit when the welding current passes through zero. However, some variation from this ideal condition is permissible for welding most of the aluminum alloys.

Table A-5
Machine Settings for A-C Spot Welding Aluminum Alloys

Thickness, in.	Time, cycles	Current, amperes	Tip pressure, lb. Min.	Tip pressure, lb. Max.
0.016	4	14 000	200	400
0.020	6	16 000	300	500
0.025	6	17 000	300	500
0.032	8	18 000	400	600
0.040	8	20 000	400	600
0.051	10	22 000	500	700
0.064	10	24 000	500	700
0.081	12	28 000	600	800
0.102	12	32 000	800	1000
0.128	15	35 000	800	1200

Electronic equipment for controlling the duration of welding current is widely used with alternating-current welding machines. When these machines are provided with means to start the flow of current in synchronism with the supply voltage, the consistency of weld strength and the appearance of the welds are improved over that obtained when less precise timing equipment is used. Electronic timing equipment for controlling the magnitude as well as the duration of welding current provides a smooth adjustment of the welding heat.

Current Demand. One of the chief objections to alternating-current spot-welding machines is that the high currents required for aluminum welding place a very high electrical demand on the system supplying the machines. This current demand is of intermittent nature, single-phase, and of very low power factor, and may cause disturbances in electric lights and other electric equipment. This condition can be alleviated to a large extent by installing static condensers in series with the primary of the welding transformer. The manufacturer of the welding equipment should be consulted to determine the size and number of condensers required.

Magnetic-Energy Storage Welding

The electrical current demand for spot welding aluminum can be reduced even further by using magnetic-energy storage equipment, which stores the welding energy in an inductor transformer by establishing a direct current of 100 to 400 amperes in the primary winding of this transformer. On interruption of the current by a contactor, a high value of current is established in the secondary circuit and through the work being welded. This current decays to a low value in 0.01 to 0.05 second.

Equipment for this process also has an electrode pressure system which permits the welding pressure to be varied during the welding operation. The combination of a short duration welding current impulse and a varying pressure results in welds of very sound structure and good appearance.

The maximum power demand for magnetic energy storage equipment is about one-tenth that required for alternating-current equipment, but this system can weld the same thickness of material because the energy is obtained by drawing a lower power for a longer time.

Condenser-Energy Storage Welding

The condenser-energy storage equipment utilizes static condensers to store the energy used for welding. Three-phase primary power is stepped up in voltage and rectified to charge the condensers to a voltage from 1000 to 3000 volts. When this bank of charged condensers is connected to the primary of the welding transformer, an impulse of welding current rises rapidly to its maximum value and decays to zero at a somewhat slower rate. When welding with this equipment, a constant high value of welding pressure is generally used. In some cases a higher pressure is used at the end of the weld to provide a forging action on the solidified weld metal.

Welds produced on this type equipment are excellent in appearance and the structure is very sound. Another advantage is that the maximum demand on the power system is about one-tenth of that required for a-c welding equipment to join the same thickness of material.

Electrodes

The correct selection of electrode shape and the maintenance of this shape in production is essential to achieving consistent spot welds on aluminum. Welding electrodes serve three functions: (1) They conduct the welding current into the parts being welded. (2) They exert sufficient pressure on the material to hold it in place. (3) They conduct the heat out of the parts welded to prevent the weld zone from reaching the outside surfaces of the material.

At least one of the electrodes must be shaped so that current will be highly concentrated in the weld. This electrode may be dome-shaped with a 25 to 50 mm (1 to 2 in.) radius, or it may be conical with a 158° to 166° included cone angle. Another tip shape often used with the energy-storage welding processes consists of a truncated cone with a 160° to 130° cone angle and a flat spot with a diameter equal to twice the thickness of the weld material, plus 3 mm (1/8 in.). The same shape electrode can be used on the other side of the work, or a flat electrode can be used on one side of the work to obtain a surface with the minimum of electrode marking. These flat electrodes may be from 16 to 30 mm (5/8 in. to 1-1/4 in.) in diameter. A further increase in diameter does not improve the appearance of the weld.

The electrodes must be of sufficient diameter to carry the required welding currents without undue heating. A 16 mm (5/8 in.) diameter electrode is suitable for currents up to 35 000 amp. and a welding time of 15 cycles, when the rate of welding is not more than 40 welds per minute. When higher welding currents or greater welding speeds are used, electrodes of 22 to 30 mm (7/8 to 1-1/4 in.) diameter should be used. For welding currents less than 20 000 amps and welding times less than 8 cycles, 12 mm (1/2 in.) diameter electrodes are satisfactory.

A coating of aluminum alloy gradually forms over the face of the electrode. This alloy "pickup" is of low electrical conductivity, and eventually causes the electrodes to stick to the work and to melt the surface of the base material. The pickup can be removed from the electrodes with No. 160 or No. 240 abrasive cloth, but in removing pickup from dome-shaped electrodes, it is important to maintain the original electrode shape.

On alternating-current welding machines using dome or cone shaped electrodes, pickup must be removed from the tips after 15 to 80 welds, depending on the material welded. On energy-storage equipment using the truncated cone electrodes, less pickup is formed, and from 60 to 300 welds may be made before the electrodes require cleaning. The tip cleaning operation requires from 2 to 3 seconds.

Seam Welding

Equipment for seam welding aluminum is similar to a-c spot-welding equipment except that the electrodes are replaced by roller electrodes from 10 to 16 mm (3/8 to 5/8 in.) thick and from 15 to 22 cm (6 to 9 in.) diameter. One or both of these wheels are trimmed to an included "V" angle of 158° to 166°, or a 25 to 50 mm (1 to 2 in.) radius to concentrate the current in the weld. The wheels and the work are cooled by a water flow of 8 to 12 L/min (2 to 3 gal/min), directed against the periphery of the wheel near the weld. Usually one of the wheels is driven at an adjustable constant speed from 30 to 150 cm/min (12 to 60 in./min). It is essential in seam welding that the electronic timing control initiate and close off the weld current in synchronism with the supply voltage.

Flash Welding

Aluminum alloys in the form of sheet, tubing, extrusions, and rolled bar can be butt- or miter-flash welded to form joints of equal or greater strength than those produced by fusion welding. In flash welding, the parts to be joined are securely clamped in dies on the welding machine, and an electric arc is established between the ends of the parts to be welded. This arc is maintained by placing the parts together as the aluminum material is consumed in the arc. When the ends of the parts are sufficiently heated by this arcing process, the weld is made by rapidly driving the heated ends together with sufficient pressure to hold the material in intimate contact until the weld metal has cooled.

Equipment. So that no arcing occurs when welding aluminum, the flash-welding machine must have sufficient transformer capacity to supply a current density of 15 500 amp/cm^2 (100 000 amp/in^2.) within the section welded, when the parts are in firm contact. The secondary voltage of the flash-welding transformer can be from 2 to 20 volts. The machine must be equipped with appropriate dies and die-clamping devices to securely hold the parts being welded to prevent slipping during the upsetting action which takes place when the weld is formed. One of the clamping dies must be driven toward the other with an accelerated motion to establish and maintain the flashing, and to obtain a very rapid upset motion at the end of the flashing period. The mechanism for driving the movable die must be sufficiently rigid and strong to upset the largest area of section to be welded.

Clamping Dies. Dies are made from hard-drawn copper or copper alloys. Water cooling is not required except on very high production machines. The clamping dies should securely contact at least 80% of the outside circumference of the part to be joined. The length of the dies is usually from 25 to 50 mm (1 to 2 in.) and is limited only by the possibility of crushing the material if too small a die length is used. In addition to holding the parts, the die blocks serve as a means of conducting electric current into the parts being welded and of conducting heat out of the parts during the welding process. A secure electrical connection between one of the dies contacting at least 40% of the circumference of the part must be made.

Flashing. The duration of the flashing motion must be sufficient to permit adequate coverage by the arc of the entire section welded. Considerable variation can be tolerated in both the amount of material flashed off and the time of flashing, providing a uniform, steady flash is maintained. Total material flashed off both pieces varies from 6 mm (1/4 in.) for small diameter wires to 18 mm (3/4 in.) for large diameter rod. Flashing times from one-half to one second are used, although the flashing time can be reduced to as low as 1/20 second, if sufficient current is available to maintain flashing.

Welding Current. Welding current is adjusted by varying the secondary voltage applied to the dies. It is usually done with taps on the primary of the welding transformer. An adjustment which provides an upset current of about 15 500 amp/cm^2 (100 000 amp. per in.^{2}) is used. The current obtained during flashing is from 1/5 to 1/3 of the current which flows after the parts have come into good contact during the upset.

Welding Time. The transformer is energized before the parts to be welded have come into contact and is de-energized by opening a contactor (or by other means) in the primary supply to the welding transformer. The time relation between the beginning of the upset motion and the cutoff of power from the welding transformer is the most critical adjustment in the flash welding of aluminum. The current is removed after 1 to 5 cycles following the initiation of the upset cycle. The time delay of mechanical current interruptions is critical. If the current is shut off too early, oxide inclusions occur in the welds; if it is shut off too late, overheating of the weld and low weld strength are the result.

Costs. The economics of constructing special dies to hold the parts, and the time and material necessary to adjust the machine for production are such that from 500 to 1000 joints are usually required to justify the cost of setting up the flash-welding process. Production rates from 60 to 200 welds per hour can be obtained, depending on methods used in clamping the parts. The actual welding operation lasts only one second.

Finishing the Welds. Chipping or grinding methods are used to remove the excess upset material to finish the weld. Welds finished and treated by the anodizing process exhibit only a narrow line of slight discoloration at the weld.

ALUMINUM SOLDERING

Soldering is an economical and practical means of joining aluminum on a production basis. With careful attention to such details as surface preparation, solder composition, temperature, and application of heat, a variety of joints can be soldered.

Although less heat is required to raise the temperature of a piece of aluminum sheet of a given thickness than is required for a sheet of copper or steel of the same thickness, aluminum must be heated from 55 to 110°C (100 to 200°F) higher than either of these metals when it is to be soldered. The higher temperature is specified to produce joints with good resistance to corrosion, and is one of the key factors in producing successful soldered joints in aluminum.

Preparing the Surface

As a first step, it is necessary to remove the oxide film on aluminum so that the filler metal can contact and bond with the parent metal. This is accomplished by one of the following methods:

(1) Mechanical abrasion
(2) Application of ultrasonic energy
(3) Electroplating
(4) Use of either chemical or reaction-type fluxes

Mechanical Abrasion

Scraping is the simplest way to remove oxide. Due to the rapid rate at which the film re-forms on aluminum, scraping is impractical unless it is accomplished in the presence of molten solder. The solder then wets and bonds with the parent metal and results in a precoated or "tinned" surface.

Although there are many variations of the process, one example is as follows: Two sheets of aluminum are heated to the melting temperature of the solder. A small amount of solder is then melted on the sheets and rubbed with an abrasion tool until the solder wets the surface. The two precoated sheets are then placed together and held in contact until the solder solidifies. A strong joint results.

A fibrous glass brush is one of the most satisfactory abrasion tools, since no corrosion hazard is created and the close-packed strands remove the oxide without damage to the parent metal.

Some solder rods, called "abrasion solders," have melting characteristics which permit them to perform the dual role of solder source and abrasion tool. However, only a precoated or "tinned" surface is produced, and a second operation is generally required to complete the joining.

Ultrasonic Cleaning and Soldering

Cleaning. Ultrasonic energy can be used to remove oxide film on aluminum. An electronic power oscillator is used to generate electrical impulses (currents) at frequencies from 15 to 50 kHz; these electrical impulses are converted to mechanical motion by a device known as a *magnetostrictive transducer.* Commercial transducers used in soldering tools consist of a nickel core and a coil around the core that is connected to the oscillator. When the nickel core (a laminated nickel core is generally used to reduce eddy currents) is subjected to an electromagnetic impulse resulting from electric current flowing through the coil, it constricts a maximum of 30/1 000 000 (30×10^{-6}) of its length. If the end of the vibrating core is brought into contact with molten solder, the vibrating core will produce numerous holes, or voids, within the liquid. When aluminum is immersed in the liquid solder, the collapse of the voids creates an abrasive effect known as *cavitation erosion* on the surface of the metal. This erosive action removes the oxide film.

Soldering. In ultrasonic aluminum soldering, the area to be precoated, or "tinned," is cleaned, heated to soldering temperature, about 190°C (375°F), and the solder, usually a 90-10 tin-zinc combination, is applied. A quantity of solder is melted on the surface to form a molten puddle, and the end of the transducer is swept over this surface. The ultrasonic energy removes the oxide from the aluminum, allowing a firm solder bond.

The ultrasonic method can also be applied in dip soldering, or, with modifications, in brazing and welding.

The primary advantages of the ultrasonic process are that no flux is required, and joint quality is equal to that of joints soldered by any other process using the same solder and parent metal. The disadvantages are high cost of equipment, small capacity of the units, and the limitation that direct soldering of lap or crimp joints is not practical.

Plated Surfaces for Soldering

It is possible to prepare the aluminum surface to be soldered by electrolytically plating it with a metal, such as copper. Before deposition of the copper, the aluminum surface is treated by immersing the aluminum in a solution of alkaline sodium zincate. The zincated surface is then electrolytically plated with copper to produce a surface that can be easily soldered with the conventional solders and fluxes used to solder copper.

Fluxes for Soldering Aluminum

Chemical and reaction fluxes are the types generally used for soldering aluminum. Chemical fluxes are usually recommended when the joint temperature is less than 275°C (525°F). However, in some applications, the maximum temperature limit can be successfully raised to 325°C (620°F). At temperatures exceeding 275°C (525°F), the chemical fluxes decompose; at temperatures above 325°C (620°F), this decomposition becomes so rapid that it is impractical to use this type of flux.

In general, chemical fluxes are used with the tin-lead-cadmium-zinc solders. For best results, the magnesium content of the aluminum alloy being soldered should not exceed 1%, and the silicon content should not exceed 5%.

All of the common commercial reaction fluxes deposit zinc or tin, or both, on the aluminum surfaces. These metals alloy with the aluminum, and a thin alloy layer is formed in the area near the original surface of the material.

Solders for Aluminum

There are four groups of commercial solders for aluminum: zinc base, zinc-cadmium base, tin-zinc base, and the tin-lead base. All these may contain appreciable quantities of other metals. Table A-6 shows the composition of typical solders for aluminum.

The zinc-base solders produce joints with shear strengths of 103 MPa (15 000 psi) and higher, with good corrosion resistance. These solders require soldering temperatures ranging from 370 to 435°C (700 to 820°F).

The zinc-cadmium base solders develop joints with shear strengths in excess of 70 MPa (10 000 psi), with intermediate corrosion resistance. They require soldering temperatures of 265 to 400°C (510 to 750°F).

The tin-zinc base solders develop joints with shear strengths in excess of 48 MPa (7000 psi), with intermediate corrosion resistance. They require soldering temperatures of 290°C (550°F) or higher.

The tin-lead solders containing cadmium or zinc produce joints with shear strength in excess of 34 MPa (5000 psi), with corrosion resistance adequate for interior applications only. These solders are applied at soldering temperatures of 230°C (450°F) or higher.

Solders high in zinc content are applied to aluminum for a soldered system that is very resistant to corrosive attack. Hot dip tinned surfaces are used in special applications to produce readily solderable surfaces, since tin quickly wets an aluminum surface from which the oxide has been removed. Thus, pretinned aluminum soldering materials and techniques cannot be used. However, molten tin penetrates aluminum-magnesium alloys along the grain boundaries, and alloys containing more than 0.5% magnesium can be seriously damaged by this penetration. Cadmium is only slightly soluble in solid aluminum and forms a very limited diffusion zone in aluminum soldered joints. Cadmium is not usually used as a solder by itself, but is used effectively to improve the properties of zinc- and tin-base solders. Lead is practically insoluble in solid aluminum and is not normally used as a solder by itself. In combination with tin, zinc and cadmium, lead forms an important class of solders for aluminum.

Joint Design

The joint designs used for soldering aluminum are similar to those used with other metals. The most common designs are lap, crimped, and T joints. Capillary spacing varies with method, alloy, solder, joint, and flux. Generally, joint spacings from 0.25 to 0.60 mm (0.010 to 0.025 in.) are maintained when a chemical flux is used, and from 0.05 to 0.25 mm (0.002 to 0.010 in.) with reaction fluxes.

Torch Soldering

Air-fuel gas or oxyfuel gas torches are used effectively to solder aluminum assemblies. The flame temperature (gas mixtures) and heat output (torch size) can be independently adjusted to provide optimum conditions for specific applications. The flux is usually painted on the joint, and the solder is either pre-placed or manually fed into the joint using solder wire. The best torch soldering technique involves heating the assembly initially on both sides of the joint area until solder flow can be initiated in the joint area. The flame can then be moved to a position directly over the joint and slightly behind the front of the solder flow. In this way the flame does not come into direct contact with

Table A-6
Composition of Typical Solders for Use with Aluminum

Solder Type	Sn	Zn	Al	Cd	Pb	Cu	Approximate Melting Range* °C	Approximate Melting Range* °F
Zn Base	—	94	4	—	—	2	382–393	720–740
Zn Base	—	95	5	—	—	—	380	710
Zn Base	—	79.6	10	0.4	3	5	216–400	420–750
Zn-Cd Base	—	90	—	10	—	—	265–404	509–760
Zn-Cd Base	—	17.5	—	82.5	—	—	265	509
Sn-Zn	20	15	0.8	64.2	—	—	110–120	230–250
Sn-Zn	30	70	—	—	—	—	200–380	390–710
Sn-Zn	60	39.4	—	—	0.1	0.5	200–340	390–645
Sn-Zn	69.3	28	0.7	—	2.0	—	195–335	385–635
Sn-Zn	80	20	—	—	—	—	200–275	390–530
Sn-Pb	36.9	—	—	3.8	58.3	—	145–230	290–450
Sn-Pb	31.6	9	—	8	51	0.4	140–250	282–485
Sn-Pb	40	15	0.8	—	44.2	—	170–360	335–675
Sn-Pb	20	15	0.8	64.2	—	—	110–275	230–530

*Solid-Liquid Range

the flux before it has performed its function, and the speed and ease of soldering is at a maximum.

Furnace Soldering

Furnace soldering is a highly productive, efficient method for fabricating aluminum assemblies. In this process, the entire assembly is raised to temperature, thus minimizing distortion. The solder is usually preplaced in the joint, using wires, shims, or washers of filler material. Flux is applied by spraying, painting, or immersing the part in the flux by flowing a liquid flux over the assembly. The assembly is then placed in a furnace and brought to temperature. The flux must be carefully protected against charring or volatilization before it has performed its function. Joint design and furnace characteristics should be such that all sections of the joint are brought to temperature at the same time in order to prevent excessive alloying and penetration by liquid solder.

Dip Soldering

Dip soldering is an efficient process for joining assemblies at a high production rate. It is a versatile process because the same techniques used for other metals can often be utilized for soldering aluminum by merely changing solder and flux. Any of the solders listed in Table A-6 can be used for dip soldering. Solder selection should be based on service and operating characteristics required, and cost of the solder.

In dip soldering, the flux tends to insulate the part to be soldered from the solder, thus a heavy coat of flux will reduce the rate at which the part is brought to soldering temperature. Since the rate of heating will be greatest if a small amount of flux is used, and because solder will prevent the surface from being reoxidized, a dilute liquid flux is recommended for dip soldering. Also, the flux should be selected to operate at the optimum temperature of the solder to minimize drossing, dissolution, and liquid metal penetration, and to provide the best operating characteristics possible.

Soldering Aluminum Alloys

While aluminum and all the aluminum alloys can be satisfactorily joined by soldering, the alloying elements influence the ease with which they are soldered. Alloys commonly used in commercial applications are 1100, 1145, 3003, 5005, and 6061.

Commercially pure aluminum (1100), aluminum of higher purity (1145), and aluminum-manganese (3003) alloys can be readily joined using all soldering techniques. Aside from ensuring that the surface is reasonably free of extraneous dirt or corrosive products, no special surface preparation is needed for soldering these alloys. They are also resistant to intergranular penetration by liquid solder.

Use of molten tin solders results in intergranular penetration in alloys containing 0.5% or more magnesium. Zinc solders will also cause intergranular penetration of aluminum-magnesium alloys, but the extent of penetration is usually not significant until the magnesium content of the parent alloy exceeds 0.7%.

Aluminum alloys containing more than 5% silicon are not usually soldered by procedures requiring the use of a flux.

The addition of zinc or copper to aluminum does not materially reduce the solderability. However, these metals are used in combination with other elements to form high-strength, heat-treatable alloys. Films formed on the surface during heat treatment reduce the solderability, so a chemical surface pre-treatment is usually recommended. In some instances, alloys such as 2024 and 7075 have been satisfactorily soldered using reaction fluxes without using chemical pretreatment. If chemical fluxes are used, a chemical pretreatment is usually required.

Additions of small amounts of magnesium and silicon to aluminum produce an alloy system commonly referred to as the aluminum-magnesium-silicate alloys. These alloys, 6061 and 6063, are easily soldered and are not as susceptible to intergranular penetration by liquid solder as the binary aluminum-magnesium alloys of a similar magnesium content.

Excellent Solderability. Binary aluminum-magnesium alloys, in sheet and other forms, provide excellent solderability, and include 1030, 1050, 1060, 1070, 1075, 1080, 1085, 1090, 1095, 1099, 1100, 1130, 1145, 1160, 1171, 1180, 1187, 1197, and 3003. Chemical or reaction fluxes may be used.

Good Solderability. Alloys considered "good" for soldering are 3004, 5005, 5357, 6053, 6061, 6062, 6063, 6151, 6253, 6951, 7072, and 8112. With the exception of the first two, reaction type flux is recommended.

Fair Solderability. Fair solderability is accorded alloys 2011, 2014, 2017, 2018, 2024, 2025, 2117, 2214, 2218, 2225, and 5050.

Poor Solderability. The alloys rated as poor for soldering are 5052, 5652, 7075, 7178, 7277, 4032, 4043, 4045, 4343, 5055, 5056, 5083, 5086, 5154, 5254, and 5356.

ALUMINUM, Ultrasonic Welding

Ultrasonic welding is a metal joining process in which high-intensity vibratory energy, usually at a frequency above audibility, or in excess of 15 kHz, is introduced into the area to be welded as the workpieces are held together under pressure. This process depends on the conversion of high-frequency alternating current to mechanical vibration. Ultrasonic welding involves complex relationships between the static clamping force, the oscillating shear forces, and a moderate temperature rise in the weld zone, creating conditions which result in atomic diffusion across the interface. The metal recrystallizes to a very fine grained structure having the properties of moderately cold-worked metal. The magnitude of the factors required to produce a weld are functions of the thickness, surface condition, and the mechanical properties of the workpieces. *See* ULTRASONIC WELDING.

Pieces to be joined are clamped at low pressure (4 to 160 kg [10 to 350 lb.]) between two welding members or sonotrodes, and the vibratory energy is introduced for a brief interval. The heart of the equipment is a magnetostrictive transducer, a rectangular stack built up of "A" nickel laminations wrapped with insulated wire. Nickel laminations are used for the transducer because of the transducer's substantial change in length when magnetized. The equipment develops power at supersonic frequency to drive the transducer stack which, in turn, converts electrical current to mechanical vibrations, then transmits them to the upper sonotrode. The high frequency vibratory energy produced by the transducer passes from the welding head through the two pieces to be welded, where it disrupts the oxide film at the interface and eliminates the need for any further preparation.

All combinations of aluminum alloys form a weldable pair. They may be joined in any available form: cast, extruded, rolled, forged, or heat-treated. Soft aluminum cladding on the surface of these alloys facilitates welding. Aluminum can be welded to most other metals, including germanium and silicon, the primary semiconductor materials.

Applications include electronic components, electrical connections, foil and sheet splicing, encapsulation and packaging, and structural welding.

ALUMINUM WROUGHT ALLOYS, Welding

Wrought aluminum alloys can be joined by most fusion and solid state processes, as well as by brazing and soldering (See ALUMINUM BRAZING *and* ALUMINUM SOLDERING).

The relative weldability of the wrought non-heat-treatable alloys is shown in Table A-7. Similar information for the wrought heat-treatable alloys is shown in Table A-8. In addition to the processes listed in the tables, wrought aluminum alloys are welded by electron beam and plasma arc welding, and such solid state processes as friction welding, diffusion welding, explosion welding, high frequency welding and cold welding. Submerged arc welding is one of the few processes not commercially used on wrought aluminum alloys.

The selection of a process for welding wrought aluminum alloys depends on many factors, such as the application and service environment, the physical dimensions of the parts being welded, the number of parts involved, the joint design required for the application, and the welding equipment available to do the job.

The selection of filler metals for welding wrought aluminum alloys depends on the particular alloy, but also may be influenced by the process selected and the service requirements of the product. Some additional considerations are joint design, dilution, cracking tendencies, strength and ductility requirements, corrosive environment, and appearance. Table A-9 shows a filler metal selection chart for welding aluminum alloys.

AMERICAN WIRE GAUGE

The gauge used to designate the sizes of solid copper wires used in the United States. Formerly called Brown and Sharpe gauge.

AMMETER

An instrument that measures and indicates in amperes the rate of flow of electricity through a circuit.

AMMETER SHUNT

A special low resistance conductor connected to the terminals of an ammeter to carry nearly all the current, allowing only a very small current to flow through the ammeter.

Table A-7
Weldability[1,2] of Nonheat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
1060	A	A	A	B	A	A	A
1100	A	A	A	A	A	A	A
1350	A	A	A	B	A	A	A
3003	A	A	A	A	A	A	A
3004	B	A	A	A	B	B	B
5005	A	A	A	A	A	B	B
5050	A	A	A	A	A	B	B
5052, 5652	A	A	A	A	B	C	C
5083	C	C	A	A	C	X	X
5086	C	C	A	A	B	X	X
5154, 5254	B	B	A	A	B	X	X
5454	B	B	A	A	B	X	X
5456	C	C	A	A	C	X	X

1. Weldability ratings are based on the most weldable temper:
   - A. Readily weldable.
   - B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures, performance, or both.
   - C. Limited weldability.
   - X. Particular joining method is not recommended.
2. All alloys can be adhesive bonded, ultrasonically welded, or mechanically fastened.

Table A-8
Weldability[1,2] of Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
2014	X	C	C	B	C	X	C
2017	X	C	C	B	C	X	C
2024	X	C	C	B	C	X	C
2036	X	C	B	B	C	X	C
2090	X	X	B	B	C	X	C
2218	X	C	C	B	C	X	C
2219	X	C	A	B	C	X	C
2519	X	C	B	B	C	X	C
2618	X	C	C	B	C	X	C
6005	A	A	A	A	B	A	B
6009	C	C	B	B	B	X	C
6010	C	C	B	B	B	X	C
6013	C	C	B	A	B	X	C
6061	A	A	A	A	B	A	B
6063	A	A	A	A	B	A	B
6070	C	C	B	B	B	X	C
6101	A	A	A	A	A	A	A
6262	C	C	B	A	B	B	B
6351	A	A	A	A	B	A	B
6951	A	A	A	A	A	A	A
7004	X	X	A	A	B	B	B
7005	X	X	A	A	B	B	B
7039	X	X	A	A	B	C	B
7075	X	X	C	B	C	X	C
7079	X	X	C	B	C	X	C
7178	X	X	C	B	C	X	C

1. Weldability ratings are based on the most weldable temper:
   - A. Readily weldable.
   - B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures, performance, or both.
   - C. Limited weldability.
   - X. Particular joining method is not recommended.
2. All alloys can be adhesive bonded, ultrasonically welded, or mechanically fastened.

Table A-9
Guide to the Selection of Filler Metal for Aluminum Welding[a,b,c]

Base Metal	201.0 206.0 224.0	319.0, 333.0, 354.0, 355.0, C355.0	356.0, A356.0, 357.0, A357.0, 413.0, 443.0, A444.0	511.0, 512.0, 513.0, 514.0, 535.0	7004, 7005, 7039, 701.0, 712.0	6009 6010 6070	6005, 6061, 6063, 6101, 6151, 6201, 6351, 6951	5456	5454
1016, 1070, 1080, 1350	ER4145	ER4145	ER4043[d,e]	ER5356[e,f,g]	ER5356[e,f,g]	ER4045[d,e]	ER4043[e]	ER5356[g]	ER4043[e,g]
1100, 3003, Alc. 3003	ER4145	ER4145	ER4043[d,e]	ER5356[e,f,g]	ER5356[e,f,g]	ER4043[d,e]	ER4043[e]	ER5356[g]	ER4043[e,g]
2014, 2036	ER4145[h]	ER4145[h]	ER4145	—	—	ER4145	ER4145	—	—
2219	ER2319[d]	ER4145[h]	ER4145[e,f]	ER4043[e]	ER4043[e]	ER4043[d,e]	ER4043[d,e]	—	ER4043[e]
3004, Alc. 3004	—	ER4043[e]	ER4043[e]	ER5356[i]	ER5356[i]	ER4043[e]	ER4043[e,i]	ER5356[g]	ER5356[i]
5005, 5050	—	ER4043[e]	ER4043[e]	ER5356[i]	ER5356[i]	ER4043[e]	ER4043[e,i]	ER5356[g]	ER5356[i]
5052, 5652[l]	—	ER4043[e]	ER4043[e,i]	ER5356[i]	ER5356[i]	ER4043[e]	ER5356[f,i]	ER5356[i]	ER5356[i]
5083	—	—	ER5356[e,f,g]	ER5356[g]	ER5183[g]	—	ER5356[g]	ER5183[g]	ER5356[g]
5086	—	—	ER5356[e,f,g]	ER5356[g]	ER5356[g]	—	ER5356[g]	ER5356[g]	ER5356[g]
5154, 5254[l]	—	—	ER4043[e,i]	ER5356[i]	ER5356[i]	—	ER5356[i]	ER5356[i]	ER5356[i]
5454	—	ER4043[e]	ER4043[e,i]	ER5356[i]	ER5356[i]	ER4043[e]	ER5356[f,i]	ER5356[i]	ER5554[h,i]
5456	—	—	ER5356[e,f,g]	ER5356[g]	ER5356[g]	—	ER5356[g]	ER5556[g]	—
6005, 6061, 6063, 6101, 6151, 6201, 6351, 6951	ER4145	ER4145[e,f]	ER4043[e,i,j]	ER5356[i]	ER5356[e,f,i]	ER4043[d,e,j]	ER4043[e,i,j]	—	—
6009, 6010, 6070	ER4145	ER4145[e,f]	ER4043[d,e,j]	ER4043[e]	ER4043[e]	ER4043[e,i,j]	—	—	—
7004, 7005, 7039 710.0, 712.0	—	ER4043[e]	ER4043[e,i]	ER5356[i]	ER5356[g]	—	—	—	—
511.0, 512.0, 513.0, 514.0, 535.0	—	—	ER4043[e,i]	ER5356[i]	—	—	—	—	—
356.0, A356.0, 357.0, A357.0, 413.0 443.0, A444.0	ER4145	ER4145[e,f]	ER4043[e,k]	—	—	—	—	—	—
319.0, 333.0, 354.0, 355.0, C355.0	ER4145[h]	ER4145[e,f,k]	—	—	—	—	—	—	—
201.0, 206.0, 224.0	ER2319[d,k]	—	—	—	—	—	—	—	—

a. Service conditions such as immersion in fresh or salt water, exposure to specific chemicals, or a sustained high temperature [over 66°C (150°F)] may limit the choice of filler metals. Filler metals ER5183, ER5356, ER5556, and ER5654 are not recommended for sustained elevated-temperature service.

b. Recommendations in this table apply to gas shielded arc welding processes. For oxyfuel gas welding, only ER1188, ER1100, ER4043, ER4047, and ER4145 filler metals are ordinarily used.

c. Where no filler metal is listed, the base metal combination is not recommended for welding.

d. ER4145 may be used for some applications.

e. ER4047 may be used for some applications.

f. ER4043 may be used for some applications

g. ER5183, ER5356, or ER5556 may be used.

h.–m. See table footnotes on next page.

Table A-9 (Continued)
Guide to the Selection of Filler Metal for Aluminum Welding

Base Metal	5154 5254[l]	5086	5083	5052 5652[i]	5005 5050	3004 Alc. 3004	2219	2014 2036	1100 3003 Alc. 3003	1060, 1070 1080 1350
1060, 1070, 1080, 1350	ER5356[e,f,g]	ER5356[g]	ER5356[g]	ER4043[e,g]	ER1100[e,f]	ER4043[e,g]	ER4145[e,f]	ER4145	ER1100[e,f]	ER1188[e,f,k,m]
1100, 3003, Alc. 3003	ER5356[e,f,g]	ER5356[g]	ER5356[g]	ER4043[e,g]	ER1100[e,f]	ER4043[e,g]	ER4145[e,f]	ER4145	ER1100[e,f]	—
2014, 2036	—	—	—	—	ER4145	ER4145	ER4145[h]	ER4145[h]	—	—
2219	ER4043[e]	—	—	ER4043[e,g]	ER4043[d,e]	ER4043[d,e]	ER2319[d]	—	—	—
3004, Alc. 3004	ER5356[i]	ER5356[g]	ER5356[g]	ER5356[e,f,i]	ER5356[f,i]	ER5356[f,i]	—	—	—	—
5005, 5050	ER5356[i]	ER5356[g]	ER5356[g]	ER5356[e,f,g]	ER5356[f,i]	—	—	—	—	—
5052, 5652[l]	ER5356[i]	ER5356[g]	ER5356[g]	ER5654[f,i,l]	—	—	—	—	—	—
5083	ER5356[g]	ER5356[g]	ER5183[g]	—	—	—	—	—	—	—
5086	ER5356[g]	ER5356[g]	—	—	—	—	—	—	—	—
5154, 5254[l]	ER5654[i,l]	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—

a–g. See table footnotes on preceding page.

h. ER2319 may be used for some applications. It can supply high strength when the weldment is postweld solution heat-treated and aged.

i. ER5183, ER5356, ER5554, ER5556, and ER5654 may be used. In some cases, they provide: (1) improved color match after anodizing treatment, (2) highest weld ductility, and (3) higher weld strength. ER5554 is suitable for sustained elevated-temperature service.

j ER4643 will provide high strength in 12.7 mm (1/2 in.) and thicker groove welds in 6XXX alloys when postweld solution heat treated and aged.

k Filler metal with the same analysis as the base metal is sometimes used. Filler alloys (ER4009 or R4009, ER4010 or R4010, and R4011 meet the chemical composition limits of R-C355.0, R-A356.0 and R-A357.0 alloys, respectively.

l. Base metal alloys 5254 and 5652 are useful for hydrogen peroxide service. ER5654 filler metal is used for welding both alloys for low-temperature service [66°C (150°F) and below].

m. ER1100 may be used for some applications.

AMORPHOUS STRUCTURE

A non-crystalline structure.

AMPERE

A unit of electrical current used to state the rate of flow of electricity through a circuit. One ampere is equivalent to the steady current produced by one volt applied across a resistance of one ohm. *See* ELECTRICAL UNITS.

ANGLE

The figure formed between two intersecting lines or projecting surfaces. Angles are measured in degrees; one degree (1°) is 1/360 of a complete circle. For specific angles used in beveling workpieces to be welded and methods of forming angles, *see* BEVELING.

ANGLE OF BEVEL

See STANDARD WELDING TERMS. *See also* BEVEL ANGLE.

ANNEALING

A treatment process in which a material in the solid state is heated, then cooled at a slow rate. *See* HEAT TREATMENT.

The annealing temperature and the rate of cooling depend on the material and the purpose of the treatment. Annealing is used to effect any of the following changes in metal:

(a) Relieve stresses

(b) Induce softness

(c) Alter ductility, toughness, electrical, magnetic, or other physical properties

(d) Refine the crystalline structure

(e) Remove gases

(f) Produce a definite microstructure

Annealing is a comprehensive term. Some specific annealing heat treatments are:

Full Annealing. Heating iron-base alloys above the critical temperature range, holding above that range for a specified period of time, followed with slow cooling to below that range.

The annealing temperature is generally about 55°C (100°F) above the upper limit of the critical temperature range, and the holding time is usually not less than one hour for each inch of section of the workpiece being treated. The workpiece is then allowed to cool slowly in the furnace. In some applications, the workpiece is removed from the furnace and placed in a medium which will cool the material at a slower rate than unrestricted cooling at room temperature.

Process Annealing. Heating iron-base alloys to a temperature below or close to the lower limit of the critical temperature, followed with cooling as specified.

Spheroidizing. Any process of heating and cooling steel that induces a rounded or globular form of carbide. The spheroidizing methods generally used are:

(1) Prolonged heating at a temperature just below the lower critical temperature, usually followed by relatively slow cooling.

(2) For small parts made of high carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range.

(3) Tool steel is generally spheroidized by heating to a temperature in the range of 750 to 800°C (1380 to 1480°F) for carbon steels (higher for many alloy tool steels), holding at heat from 1 to 4 hours, and cooling slowly in the furnace.

Malleablizing. An annealing operation performed on white cast iron partially or wholly to transform the combined carbon to temper carbon, and in some cases wholly to remove the carbon from the iron by decarbonization. Temper carbon is free graphite carbon in the form of rounded nodules composed of an aggregate of minute crystals.

Graphitizing. Graphitizing is a type of annealing for gray cast iron in which some or all of the combined carbon is transferred to free graphitic carbon.

ANNEALING, ELECTRIC

Annealing of small parts can be accomplished by placing them between the terminals of an electric resistance welding machine, and turning on the current in the usual manner. Sufficient heat will quickly be generated to soften the metal.

Annealing with electric heating apparatus, correctly termed *stress relieving*, has been applied very successfully to welded carbon-molybdenum steel piping systems. These steels harden during the welding process and residual stresses are likely to be set up in the joint. Stress relieving after welding will adjust these stresses. *See* ANNEALING, FURNACES, HEAT TREATMENT, METALLURGY, *and* INDUCTION HEATING.

ANODE

An electrode with a positive charge; the electron-collecting electrode of an electron tube in an electric circuit. The anode is the terminal on which oxygen gas collects in an electrolytic oxygen-hydrogen generator.

It is the terminal of a primary cell, or of a storage battery when it is delivering current.

ANODE DROP

See VOLTAGE DROP.

ANODIZING

Coating a metal with a protective film by electrolytic action.

Anodizing refers to the surface treatment of aluminum to prevent oxidation. It is a "deplating" process, since the work itself becomes the anode in the plating bath and metal is thrown off rather than put on. Nascent oxygen is released at the anode. This immediately attacks the metal surface and forms an extremely hard oxide film. The anodizing treatment is widely used in the aircraft industry, and to treat aluminum automobile pistons.

APPARENT EFFICIENCY

In alternating current apparatus, apparent efficiency is the ratio of net power output to the volt-ampere input.

ARC

See STANDARD WELDING TERMS. *See also* WELDING ARC.

An electric arc is formed when two conductors of an electric circuit are brought together forming electrical contact, then separated, with sufficient voltage available to maintain the current of electricity through the intervening gaseous medium.

In a continuous current arc, the conductor from which the current flows is called the *positive electrode*, or *anode*. The conductor to which the current flows is called the *negative electrode,* or *cathode*. The heated gases are sometimes called the arc flame, or the arc plasma.

ARC BLOW

The deflection of an arc from its normal path because of magnetic forces. See STANDARD WELDING TERMS.

Arc blow, when it occurs, is encountered principally with direct-current welding of magnetic materials (iron and nickel). It can be encountered with alternating current under some conditions, but these cases are rare, and the intensity of the arc blow is always much less severe. Direct current flowing through the electrode and base metal sets up magnetic fields around the electrode which tend to deflect the arc to the side at times, but usually the arc is deflected either forward or backward along the joint.

Back blow is encountered when welding toward the workpiece connection near the end of the joint or into a corner. Forward blow is encountered when welding away from the lead at the start of the joint. In general, arc blow is the result of two basic conditions:

(1) The change of direction of the current flow as it enters the work and is conducted toward the work lead.

(2) The asymmetric arrangement of magnetic material around the arc, a condition that normally exists when welding is done near the end of ferromagnetic materials.

Although arc blow cannot always be eliminated, it can be controlled or reduced to an acceptable level through a knowledge of the above two conditions.

Except in cases where arc blow is unusually severe, certain corrective steps may be taken to eliminate it or at least to reduce its severity. Some or all of the following steps may be necessary:

(1) Place the workpiece lead connections as far as possible from the joints to be welded.

(2) If back blow is the problem, place the workpiece connection at the start of welding, and weld toward a heavy tack weld.

(3) If forward blow causes the trouble, place the workpiece connection at the end of the joint to be welded.

(4) Position the electrode so that the arc force counteracts the arc blow.

(5) Use the shortest possible arc consistent with good welding practice. This helps the arc force to counteract the arc blow.

(6) Reduce the welding current.

(7) Weld toward a heavy tack or runoff tab.

(8) Use the backstep sequence of welding.

(9) Change to ac, which may require a change in the electrode classification.

(10) Wrap the workpiece lead around the workpiece in the direction that sets up a magnetic field which will counteract the magnetic field causing the arc blow.

ARC BRAZING

An electric brazing process in which the heat is obtained from an electric arc formed between the base metal and an electrode, or between two electrodes. See STANDARD WELDING TERMS.

ARC CHAMBER

A nonstandard term for PLENUM CHAMBER.

ARC CONTROL

Arc control in d-c welding machines is accomplished primarily by a rheostat in the welding circuit. On a-c machines, controlling the output current is of prime importance and can be accomplished by using one of the following: movable shunt control, movable coil control, tapped reactor coil control and electronic control. The method is usually dictated by process requirements, economics of manufacturing, and the necessity for remote control capabilities.

ARC CUTTER

See STANDARD WELDING TERMS. *See also* THERMAL CUTTER.

ARC CUTTING (AC)

A group of thermal cutting processes that severs or removes metal by melting with the heat of an arc between the electrode and workpiece. See STANDARD WELDING TERMS.

This definition covers a number of processes that are or have been used for cutting or gouging metals, including the following:

(1) Plasma Arc Cutting (PAC)
(2) Air Carbon Arc Cutting (CAC-A)
(3) Shielded Metal Arc Cutting (SMAC)
(4) Gas Metal Arc Cutting (GMAC)
(5) Oxygen Arc Cutting (AOC)
(6) Gas Tungsten Arc Cutting (GTAC)
(7) Carbon Arc Cutting (CAC)

Thermal gouging is a thermal cutting process variation that removes metal by melting or burning the entire removed portion, to form a bevel or groove.

ARC CUTTING GUN

A device used to transfer current to a continuously fed cutting electrode, guide the electrode, and direct the shielding gas. See STANDARD WELDING TERMS.

ARC CUTTING OPERATOR

See THERMAL CUTTING OPERATOR.

ARC CUTTING ELECTRODE, OXYGENLESS

All metals can be cut using the shielded metal arc welding (SMAW) process and oxygenless arc cutting electrodes. The electrode coating is formulated to react exothermically, concentrating the heat and force of the arc at the point of cut. They are designed to have a slow burn-off rate, so that maximum length of cut can be achieved with each electrode. They are capable of withstanding a higher range of cutting amperages. Oxygenless arc cutting is not limited to ferrous metals, since it does not depend on the heat generated by the oxidation of the iron to propagate the process.

Application technique is a factor to be considered when specifying electric arc cutting. Welding personnel proficient in the use of conventional electrodes are also able to use the specially designed oxygenless arc cutting electrodes.

ARC CUTTING TORCH

See STANDARD WELDING TERMS. *See also* AIR CARBON ARC CUTTING TORCH, GAS TUNGSTEN ARC CUTTING TORCH, *and* PLASMA ARC CUTTING TORCH.

ARC FORCE

The axial force developed by an arc plasma. See STANDARD WELDING TERMS.

ARC FURNACE

An electric furnace in which the heat is produced by an arc between two electrodes. *See* FURNACE.

ARC GAP

A nonstandard term when used for ARC LENGTH.

ARC GAS

A nonstandard term when used for ORIFICE GAS.

ARC GOUGING

Thermal gouging that uses an arc cutting process variation to form a bevel or groove. See STANDARD WELDING TERMS. *See also* ARC CUTTING.

When the compressed-air carbon arc process is used, the metal to be gouged or cut is melted with an electric arc and blown away with a high-velocity jet of compressed air parallel to the electrode. A special torch directs a stream of air along the electrode and external to it. The torch is connected to an arc welding machine and any compressed-air line which delivers approximately 690 kPa (100 psi) of compressed air. Since this pressure is not critical, a regulator may not be necessary.

The electrode is a special composition of carbon and graphite and is usually copper clad to increase its operating life.

ARC LENGTH

The distance from the tip of the welding electrode to the adjacent surface of the weld pool. See STANDARD WELDING TERMS.

Arc length is the distance through the center of the arc from the end of the electrode to the point where the arc makes contact with the surface of the work.

The length of the arc for a coated electrode (SMAW) is usually greater than that of the bare electrode (GMAW) because with the latter, the greater heat intensity of the arc assures penetration and fusion, while the gas shield protects the molten metal from atmospheric contamination.

The arc length of the coated electrode is usually longer than the portion that may be apparent to the eye, because the end of the electrode core wire burns away more rapidly than the coating and allows the coating to come closer to the molten pool than the actual end of the core of the electrode.

ARC OXYGEN CUTTING

A nonstandard term for OXYGEN ARC CUTTING.

ARC PLASMA

A gas that has been heated by an arc to at least a partly ionized condition, enabling it to conduct an electric current. See STANDARD WELDING TERMS.

ARC SEAM WELD

A seam weld made by an arc welding process. See STANDARD WELDING TERMS. *See* Figure A-5. *See also* ARC WELDING.

ARC SEAM WELD SIZE

See STANDARD WELDING TERMS. *See also* SEAM WELD SIZE.

ARC SPOT WELD

A spot weld made by an arc welding process. See STANDARD WELDING TERMS. *See* Figure A-6. *See also* ARC WELDING.

ARC SPOT WELD SIZE

See STANDARD WELDING TERMS. *See also* SPOT WELD SIZE.

ARC SPRAYER

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYER.

ARC SPRAYING (ASP)

A thermal spraying process using an arc between two consumable electrodes of surfacing materials as a heat source and a compressed gas to atomize and propel the surfacing material to the substrate. See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING.

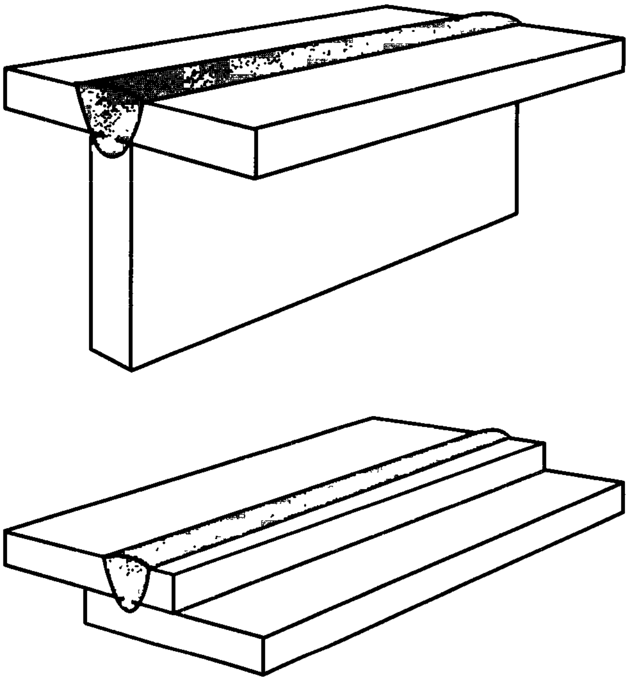


Figure A-5—Arc Seam Welds

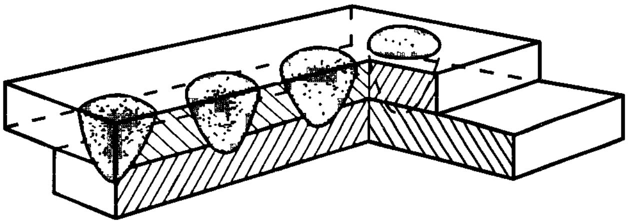


Figure A-6—Arc Spot Welds

The arc spray process is used to apply coatings of various materials which enhance, protect, or seal the workpiece. The process uses an arc between two wires (feedstock), and is sometimes referred to as *wire arc spraying*. The wires are kept insulated from each other and automatically advance to meet at a point within an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires initiates an arc as they converge, melting the tips of both wires. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets which form the atomized spray, and ejecting them from the arc at the rate of several thousand particles per second. The velocity of the gas through the atomizing nozzle can be regulated to control deposit characteristics.

In comparison with wire flame spraying, the quantity of metal oxides is better controlled and spray rates are higher in wire arc spraying, so this process is often more economical.

Equipment. The wire arc spray system can be operated from a control console or from the gun. The control console will have the switches and regulators necessary for controlling and monitoring the operating circuits that power the gun and control the spray procedure, as follows:

(1) A solid-state direct current power source, usually the constant voltage type

(2) A dual wire feeding system

(3) A compressed gas supply with regulators and flowmeter built into the control assembly

(4) Arc spray gun and appropriate console switching

The wire control unit consists of two reel (or coil) holders, which are insulated from each other, and connected to the spray gun with flexible insulated wire guide tubes. Wire sizes range from 1.6 to 3.2 mm (1/16 to 1/8 in.). The wire arc spray process can deposit as little as 0.45 kg/hr (1 lb/hr). Factors controlling the rate of application are the current rating of the power source and the permissible wire feed rate to carry the available power.

Direct current constant potential power sources providing a voltage of 18 to 40 volts are normally used in this process. This permits operation over a wide range of metals and alloys. The arc gap and spray particle size increase with a rise in voltage. The voltage should be kept at the lowest possible level, consistent with good arc stability, to provide the smoothest coatings and maximum coating density.

Advantages and Limitations. Compared to flame spraying, energy and labor costs are lower for arc spraying because of its higher deposition rate, lower maintenance, low gas costs, and higher deposition efficiencies.

One adverse effect of the high energy state of the atomized particles is their tendency to change composition through oxidation or vaporization, or both. These effects can be minimized by judicious wire selection.

The arc spray method is less versatile than flame or plasma methods, because powders and nonconductive materials cannot be used.

A technique called *bond coat mode* can be used in this process to achieve higher strength bonds with some materials; when the conditions of this mode are carried out, the following are ensured: (1) fine spray particle size, (2) minimum loss of alloy constituents, (3) concentrated spray pattern, and (4) high melting rate.

Arc Spraying Applications

Arc spray deposits can provide protection against many types of corrosive attack on iron and steel. Zinc, aluminum, and stainless steels can be used as surfacing materials. A thick layer of zinc or aluminum can protect steel against oxidation and provide a strong bond for an organic coating.

Safety

Local, state, and federal safety regulations should be investigated, and procedures must comply with them. The potential hazards involved in arc spraying operations are electrical shock, fire, gases, dust and fumes, arc radiation and noise. These potentials are not unique to thermal spraying; the general requirements for the protection of thermal spray operators are the same as for welders, set forth in ANSI Z49.1, *Safety in Welding, Cutting and Allied Processes;* ANSI Z87.1, *Practices for Occupational and Educational Eye and Face Protection*; ANSI Z88.2, *Practices for Respiratory Protection;* ANSI Z89.1, *Safety Requirements for Industrial Head Protection.* Also, CGA P-1, *Safe Handling of Compressed Gases.*

ARC SPRAYING OPERATOR

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING OPERATOR.

ARC STRIKE

A discontinuity resulting from an arc, consisting of any localized remelted metal, heat-affected metal, or change in the surface profile of any metal object. See STANDARD WELDING TERMS.

ARC STUD WELDING (SW)

An arc welding process that uses an arc between a metal stud, or similar part, and the other workpiece. The process is used without filler metal, with or without shielding gas or flux, with or without partial shielding from a ceramic or graphite ferrule surrounding the stud, and with the application of pressure after the faying surfaces are sufficiently heated. See STANDARD WELDING TERMS.

In arc stud welding, the base end of the stud is joined to the other work part by heating the stud and the work with an arc drawn between the two. When the surfaces to be joined are properly heated, they are brought together under low pressure. Stud welding guns are used to hold the studs and move them in proper sequence during welding. There are two basic power supplies used to create the arc for welding studs. One type uses d-c power sources similar to those used for shielded metal arc welding (SMAW). The other type uses a capacitor storage bank to supply the arc power. The stud arc welding processes using these two types of power sources are known as *arc stud welding* and *capacitor discharge stud welding*, respectively.

Arc stud welding, the more widely used of the two major stud welding processes, is similar in many respects to manual SMAW. The heat necessary for welding of studs is developed by a d-c arc between the stud (electrode) and the plate (work) to which the stud is to be welded. Welding time and the plunging of the stud into the molten weld pool to complete the weld are controlled automatically. The stud, which is held in a stud welding gun, is positioned by the operator, who then actuates the unit by pressing a switch. The weld is completed quickly, usually in less than a second. This process generally uses a ceramic arc shield, called a *ferrule*. It surrounds the stud to contain the molten metal and shield the arc.

Capacitor discharge stud welding derives its heat from an arc produced by the rapid discharge of electrical energy stored in a bank of capacitors. During or immediately following the electrical discharge, pressure is applied to the stud, plunging its base into the molten pool of the workpiece. The arc may be established either by rapid resistance heating, and vaporization of a projection on the stud weld base (arc time: 3–6 milliseconds), or by drawing an arc as the stud is lifted away from the workpiece (arc time: 6–15 milliseconds). The capacitor discharge process does not require a shielding ceramic ferrule because of the short arc duration and small amount of molten metal expelled from the joint. It is suited for applications requiring small to medium studs.

For either process, a wide range of stud styles is available. They include such types as threaded fasteners, plain or slotted pins, and internally threaded fasteners. Most stud styles can be rapidly applied with portable equipment.

Capabilities. Because arc stud welding time cycles are very short, heat input to the base metal is very small compared to conventional arc welding. Consequently, the weld metal and heat-affected zones are very narrow. Distortion of the base metal at stud locations is minimal.

Studs can be welded at the appropriate time during construction or fabrication without access to the back side of the base member. Drilling, tapping, or riveting for installation is not required.

Small studs can be welded to thin sections by the capacitor discharge method. Studs have been welded to sheet as thin as 0.75 mm (0.03 in.) without melt-through. They have been joined to certain materials (stainless steel, for example) in thicknesses down to 0.25 mm (0.01 in.). Because the depth of melting is very shallow, capacitor discharge welds can be made without damage to a refinished opposite side. No subsequent cleaning or finishing is required.

Limitations. Only one end of a stud can be welded to the workpiece. If a stud is required on both sides of a member, a second stud must be welded to the other side. Stud shape and size are limited because the stud design must permit chucking of the stud for welding. The stud base size is limited for thin base metal thicknesses.

Studs applied by arc stud welding usually require a disposable ceramic ferrule around the base. It is also necessary to provide flux in the stud base or a protective gas shield to obtain a sound weld.

The arc stud welding process involves the same basic principles as any of the other arc welding processes. Application of the process consists of two steps:

(1) Welding heat is developed with an arc between the stud and the plate (work).

(2) The two pieces are brought into intimate contact when the proper temperature is reached.

Applications

Arc stud welding has been widely accepted by all the metalworking industries. Specifically, stud welding is used extensively in the following fields: automotive, boiler and building and bridge construction, farm and industrial equipment manufacture, railroads, and shipbuilding. Defense industry applications include missile containers, armored vehicles, and tanks.

Some typical applications are attaching wood floors to steel decks or framework; fastening linings or insulation in tanks, boxcars, and other containers, securing inspection covers, mounting machine accessories; securing tubing and wire harnesses; and welding shear connectors and concrete anchors to structures.

Equipment

The most basic equipment arrangement consists of the stud gun, a control unit (timing device), studs and ferrules, and an available source of d-c welding current. In terms of portability and ease of operation, the equipment involved in stud welding compares with that of manual SMAW.

Guns. There are two types of stud welding guns, portable hand-held and fixed production types. Automatic stud feeding systems are available for both.

Power Sources. A direct-current power source is used for arc stud welding. Alternating current is not suitable. The three basic types of d-c power sources that can be used are: transformer-rectifier; motor-generator, (motor or engine driven), and battery. The following are general characteristics desired in a stud welding power source:

(1) High open-circuit voltage, in the range of 70 to 100 V.

(2) A drooping output volt-ampere characteristic

(3) A rapid output current rise to the set value

(4) High current output for a relatively short time. The current requirements are higher, and the duty cycle is much lower for stud welding than for other types of arc welding.

Duty Cycle. The basis for rating special stud welding power sources is different from that of conventional arc welding machines. Because stud welding requires a high current for a relatively short time, the current output requirements of a stud welding power source are higher, but the duty cycle is much lower than those for other types of arc welding.

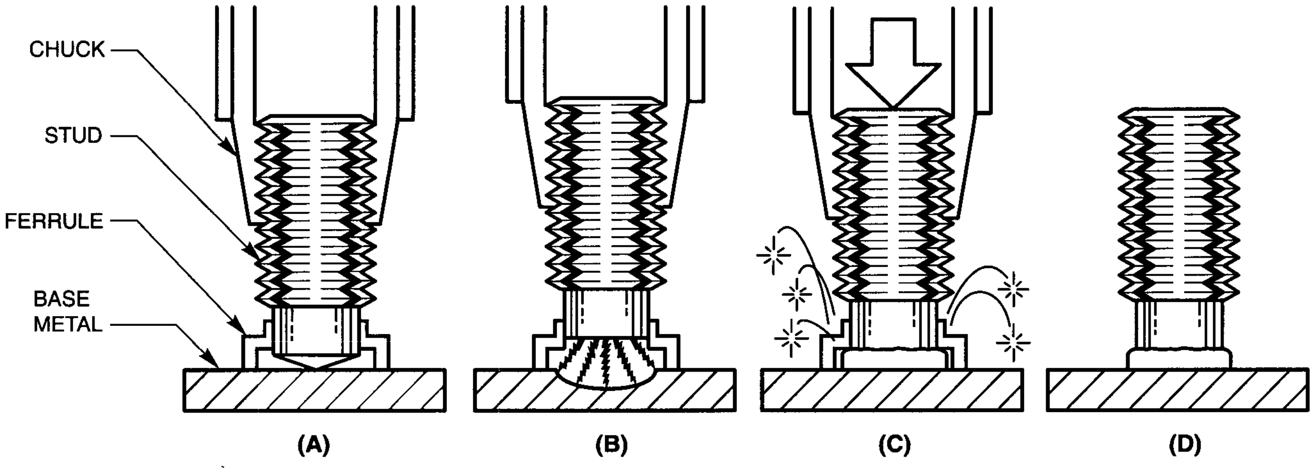
The duty cycle for stud arc welding machines is based on the formula:

Percent duty cycle = 1.7 × number of one-second loads per minute, where the one-second load is the rated output.

Thus, if a machine can be operated six times per minute at rated load without causing its components to exceed their maximum allowable temperatures, then the machine would have a 10% duty cycle rating.

Power Control Units. The control unit consists fundamentally of a contactor suitable for conducting and interrupting the welding current, and a weld timing device with associated electrical controls. Once set, the control unit maintains the proper time interval for the size of stud being welded.

Procedure. The mechanics of the process are illustrated in Figure A-7. The stud is loaded into the chuck,



(A) Gun is Properly Positioned, (B) Trigger is Depressed and Stud is Lifted, Creating an Arc, (C) Arcing Period is Completed and Stud is Plunged Into Molten Pool of Metal on Base Metal, (D) Gun is Withdrawn From the Welded Stud and Ferrule is Removed.

Figure A-7—Steps in Arc Stud Welding

the ferrule (*arc shield*) is placed in position over the end of the stud, and the gun is properly positioned for welding. The trigger is then depressed, starting the automatic welding cycle. A solenoid coil within the body of the gun is energized. This lifts the stud off the work, and at the same time, creates an arc. The end of the stud and the workpiece are melted by the arc. When the preset arc period is completed, the welding current is automatically shut off and the solenoid is de-energized by the control unit. The mainspring of the gun plunges the stud into the molten pool on the work to complete the weld. The gun is then lifted from the stud, and the ferrule is broken off. The time required to complete a weld varies with the cross-sectional area of the stud. An average rate is approximately 6 studs per minute, although a rate of 15 studs per minute can be achieved for some applications.

Inspection. The latest edition of ANSI/AWS D1.1, *Structural Welding Code-Steel*, contains provisions for the installation and inspection of steel studs welded to steel components. Quality control and inspection requirements for stud welding are also included. ANSI/AWS C5.4, *Recommended Practices for Stud Welding*, latest edition, briefly covers inspection and testing of both steel and aluminum stud welds.

Capacitor Discharge Stud Welding

Capacitor discharge stud welding is a stud arc welding process in which d-c arc power is produced by a rapid discharge of stored electrical energy with pressure applied during or immediately following the electrical discharge. The process uses an electrostatic storage system as a power source in which the weld energy is stored in capacitors of high capacitance. No ferrule or fluxing is required.

There are three different types of capacitor discharge stud welding: initial contact, initial gap, and drawn arc. They differ primarily in the manner of arc initiation. Initial contact and initial gap capacitor discharge stud welding studs have a small, specially designed projection (tip) on the weld end of the stud. Drawn arc stud welding creates a pilot arc as the stud is lifted off the workpiece by the stud gun. That version is similar to arc stud welding.

Initial Contact Method. In initial contact stud welding, the stud is placed against the work. The stored energy is then discharged through the projection on the base of the stud. The small projection presents a high resistance to the stored energy, and it rapidly disintegrates from the high current density. This creates an arc that melts the surfaces to be joined. During arcing, the pieces to be joined are being brought together by action of a spring, weight, or an air cylinder. When the two surfaces come in contact, fusion takes place, and the weld is completed.

Initial Gap Method. To begin, the stud is positioned off the work, leaving a gap between it and the work. The stud is released and continuously moves toward the work under gravity or spring loading. At the same time, open-circuit voltage is applied between the stud and the work. When the stud contacts the work, high current flashes off the tip and initiates an arc. The arc melts the surfaces of the stud and work as the stud continues to move forward. Finally, the stud plunges into the work, and the weld is completed.

Drawn Arc Method. Arc initiation is accomplished in a manner similar to that of arc stud welding. The stud does not require a tip on the weld face. An electronic control is used to sequence the operation. Weld time is controlled by an electronic circuit in the unit. The welding gun is similar to that used for arc stud welding.

The stud is positioned against the work; the trigger switch on the stud welding gun is actuated, energizing the welding circuit and a solenoid coil in the gun body. The coil motion lifts the stud from the work, drawing a low amperage pilot arc between them. When the lifting coil is de-energized, the stud starts to return to the work. The welding capacitors are then discharged across the arc. The high amperage from the capacitors melts the end of the stud and the adjacent work surface. The spring action of the welding gun plunges the stud into the molten metal to complete the weld.

Applications

Some industrial applications of capacitor discharge stud welding are aircraft and aerospace, appliances, building construction, maritime construction, metal furniture, stainless steel equipment, and transportation.

It is possible to weld studs to dissimilar metals with capacitor discharge stud welding because the penetration into the work from the arc is so shallow that there is very little mixing of the stud metal and work metal. A few of the combinations that may be welded are steel to stainless steel, brass to steel, copper to steel, brass to copper, and aluminum to die cast zinc.

The process can be used on parts that have had the face surface painted, plated, polished, or coated with ceramic or plastic, because postweld cleaning or finishing operations on the side of the base metal opposite to the stud attachment are eliminated.

Safety Precautions

Personnel operating stud welding equipment should be provided with face and skin protection to guard against burns from spatter produced during welds. Eye protection in the form of goggles or a face shield with a No. 3 filter lens should be worn to protect against arc radiation. Before repairs to equipment are attempted, electrical power should be turned off and electric switch boxes locked out. Capacitors used in capacitor discharge equipment should be completely drained of electrical charge before attempting repairs.

Reference: American Welding Society, *Welding Handbook*, 8th Edition, Vol. 2. Miami, Florida: American Welding Society, 1991.

ARC TIME

The time during which an arc is maintained in making an arc weld. See STANDARD WELDING TERMS.

ARC VOLTAGE

The voltage across the welding arc. See STANDARD WELDING TERMS.

Arc voltage is the total voltage between the electrode holder and the base metal immediately adjacent to the arc terminals. It is the summation of the cathode voltage drop, the anode voltage drop and the arc stream voltage drop.

Arc voltage may vary with a number of conditions, such as length of the arc, temperature, and gaseous content of the arc. Usually, as long as the welding current remains constant, arc voltage increases as the arc is lengthened and decreases as the arc is shortened. This change in voltage, however, is not in direct proportion to the length of the arc. The voltage across a given arc length may also vary with current changes, because of the peculiar characteristics of the arc in which resistance decreases as current passing through it is increased.

When the arc torch uses two electrodes, the welding arc voltage is the total voltage between the two electrode holders.

ARC WELDER

Arc welder is another term for *arc welding machine* applied to a source of electric energy which produces welding currents within reasonable limits for use in arc welding. *See* ARC WELDING.

ARC WELDING (AW)

A group of welding processes that produces coalescence of workpieces by heating them with an arc. The processes are used with or without the application of pressure and with or without filler metal. See STANDARD WELDING TERMS. *See also* Appendix 12.

Arc welding is a nonpressure (fusion) welding process in which the welding heat is obtained from an arc either between the base metal or weld metal and an electrode, or between two electrodes.

Historical Background

1881–1887. Arc welding had its practical beginning shortly after the introduction of arc lights in 1881. Early experiments in arc welding provided the basic theories for the development of two systems of arc welding five or six years later.

In some respects, arc welding might be considered an outgrowth of the electric furnace. In the electric furnaces of Henry Moissan, a French chemist, and others, the metal to be melted was placed between two carbon electrodes in the path of electric current. While this was considered at that time to be an internal resistance process to melt metal by an electric current, it is now realized that these furnaces represented the earliest examples of metal melting with the electric arc.

Arc welding experiments were first undertaken by DeMeritens in 1881. In his experiments the various parts of a battery plate were joined by lead welding using a carbon arc as the heat source. Guided by these early experiments, N. Von Benardos, a Russian, perfected and patented a carbon arc welding process. The patents were filed on this process in Petrograd on December 3, 1885 and issued May 17, 1887.

In the light of present day welding practice, the Benardos system of arc welding seems difficult and hazardous. It was a direct-current welding process operating on voltages ranging from 100 to 300 volts with a welding current of 600 to 1000 amp. The equipment was operated on straight polarity, which is still the preferred method in carbon arc welding, using carbon electrodes varying in size from 6 to 38 mm (0.25 to 1.5 in.) in diameter. It was common practice to weld with an arc from 50 to 100 mm (2 to 4 in.) long. The equipment was cumbersome and awkward to handle; the electrode holder alone was nearly 50 cm (20 in.) long and very heavy.

1889–1908. A short time later the Slavinoff system of arc welding, in which the carbon electrode of the Benardos system was replaced by a bare metal electrode, came into use. American patents on the metal arc process were issued to Coffin in 1889. In 1908 Kjellberg applied a coating to the bare electrode and began the development of coated metal arc welding. It is estimated that more than 90% of present day manual arc welding is accomplished using the principles developed by Kjellberg.

As has been the case with many inventions, the industrial world was slow to recognize the inherent possibilities of the process. Many years elapsed before electrical equipment, welding wire, and process control had been sufficiently well developed so that the processes could be economically and safely applied for general manufacturing purposes. Then, too, the engineering community had to be sold on the merits of the welding processes.

1916–1926. Welding was used in a very limited way for manufacturing purposes prior to the World War I period (1914–1918). The war emergency resulted in the use of welding for many applications previously considered inadvisable. During this period, the need for better and less expensive ships allowed persons familiar with ship design and those familiar with the merits of welding to carry out a great deal of design work involving all-welded steel construction. A few small all-welded vessels were produced. If the war had not been terminated by the Armistice (Nov. 11, 1918), all-welded ships would have been produced in quantities within the following few years.

During the war the U. S. Government authorized formation of the U. S. Shipping Board-Emergency Fleet Corporation, which in turn (March 13, 1918) established a sub-committee on welding. At the close of the war this committee had accomplished so much in laying the foundation for welded ship construction that it was considered an economic necessity to continue the work, and to extend the applications in all metal working industries. As a result, the membership of the subcommittee on welding was reorganized in the spring of 1919 under the name "American Welding Society." The reorganization expanded the scope of activities and offered membership to all interested individuals and industries.

From 1919 to 1925, much fundamental research work was carried out by various manufacturers, but the general application of welding in the construction of buildings and bridges did not occur until the latter part of 1925 and early in 1926. This was the beginning of the implementation of welding on a large scale, not only of plain steel but also alloy steels and nonferrous alloys.

1926–1950. A desire to improve the quality of welds produced by arc welding led to the development of several welding processes which combine gas and arc welding. The first of these is the atomic hydrogen process on which basic patents were obtained in 1924 by Dr. Irving Langmuir. This process employs a pair of tungsten electrodes to maintain an arc which is shielded by a stream of hydrogen. It may be used for either manual or automatic welding.

During this period various carbon steel welding electrodes were manufactured which have produced improved welds in terms of reduced slag inclusions and greater resistance to corrosion. Welds were made with ultimate tensile strengths in the range of 480 MPa (70 000 psi), and ductility such as 28% elongation in 50 mm (2 in.) and 60% reduction of area. Similarly, electrodes were developed for welding various alloy steels such as 12% manganese steel, and stainless steel of the low carbon 18% chromium,8% nickel class. Also, electrodes for welding nonferrous metals, i.e., copper and aluminum, were developed, making it possible to weld practically all commercial metals and alloys in all positions.

During this period, the submerged arc welding (SAW) process was developed for welding carbon steel.

World War II put additional demands on the metal fabricating industry. The search for a method to weld magnesium resulted in the gas tungsten arc welding (GTAW) process. It was originally called Heliarc™ welding because it used helium to shield the arc.

1951–Present. This period saw commercialization of a number of welding processes: gas metal arc, electron beam, laser beam, friction, inertia, electroslag, electrogas, explosion, plasma arc, and hot wire.

ARC WELDING, Automatic

Automatic arc welding equipment involves mechanical or electronic means of controlling welding conditions such as welding current, arc length, filler wire or electrode feed, and travel speeds. Movement and guidance of the electrode, torch or welding head along the line of weld can be similarly controlled.

The advantages of such equipment are numerous. A less experienced operator can handle the welding machine and produce satisfactory results. A smaller percentage of welding electrode is lost in stub ends. A much shorter arc is uniformly maintained by the automatic machine than is possible by a manual operator. A much higher current can be used with a given size of welding wire to produce better fusion. A much higher welding speed can be obtained. Welding is continuous from the beginning to the end of the seam, thereby eliminating intermediate craters unavoidable in manual work. The elimination of craters makes for a stronger, more homogenous, better weld for retaining liquids under pressure. Welding wire in coils for the automatic machine, though more expensive, provides for nearly continuous welding with either a-c or d-c automatic equipment.

ARC WELDING, Carbon

See CARBON ARC WELDING.

ARC WELDING DEPOSITION EFFICIENCY

The ratio of the weight of filler metal deposited in the weld metal to the weight of filler metal melted, expressed in percent. See STANDARD WELDING TERMS.

ARC WELDING ELECTRODE

A component of the welding circuit through which current is conducted and that terminates at the arc. See STANDARD WELDING TERMS.

ARC WELDING GUN

A device used to transfer current to a continuously fed consumable electrode, guide the electrode, and direct the shielding gas. See STANDARD WELDING TERMS. *See also* Appendix 10, Figure D.

ARC WELDING TORCH

A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas. See STANDARD WELDING TERMS. *See also* Appendix 10, Figures A and B.

ARGON

(Chemical symbol: Ar) A colorless, tasteless, odorless, nonflammable gaseous element; atomic number: 18; atomic weight: 39.94; specific gravity (air = 1) 1.378; critical temperature: –122.5°C (–188.5°F); critical pressure: 4865 kPa (705.6 psia).

Argon was discovered in 1895 by Lord Rayleigh and Sir William Ramsey. About 0.8% of the earth's atmosphere is made up of argon, and it is also found in volcanic gases. Argon is an inert gas; inert gases do not react with other elements. It is used as a shielding gas in certain forms of arc welding.

Argon is commercially available in purity exceeding 99.996% in the gaseous and liquid form. One gallon of liquid argon will produce 113.2 cu ft at 70°F. The boiling point of argon is –185.9°C (–302.6°F).

ARM, Resistance Welding

A projecting beam extending from the frame of a resistance welding machine that transmits the electrode force and may conduct the welding current. See STANDARD WELDING TERMS. *See also* HORN.

ARMATURE

The part of a dynamo that rotates, consisting of coils wound around an iron core. Also, the moving part of an electromagnetic device that supplies a motor or generator with direct current. As a part of a generator, an armature delivers or receives electrical energy. Also, a piece of iron or steel that connects the poles of an electromagnet.

ARMOR WELDING

The technique of welding armor varies only slightly from the techniques used in welding other alloy steels.

Armor plate is essentially a high carbon-chrome-nickel-molybdenum alloy. Specifications for electrodes which produce successful welds on this high-carbon alloy include ballistic requirements, high weld strength, and good toughness, yet with sufficient ductility so that there is some flexibility under impact. The welds must also be relatively free of porosity and should have all these physical characteristics without preweld or postweld heat treatment.

Historical Background

During World War II, welding armor plate for the armed services became a critical issue for the United States, and the welding industry responded with the development of electrodes that would perform this job.

The carbon content of early armor plate ranged between 0.45 and 0.50%. Because of this high carbon content and the combination of alloys, a very difficult welding problem was presented. The solution seemed to be to weld with a 25% chrome, 20% nickel stainless steel electrode. This type of welding material was satisfactory; however, it became necessary to change because of a critical shortage of nickel and chrome.

The next electrode developed for welding armor plate was an 18/8 stainless steel, modified with 1.5% molybdenum, which was used until a shortage of molybdenum developed. A third electrode used to weld armor plate was a 3.5% manganese-modified 18/8 stainless. Some difficulties were experienced with the manganese-modified electrode, because root cracks would frequently develop when weld metal was deposited without preheating. This condition was not wholly caused by the electrode, since the high carbon content of the armor plate as well as poor fit-up in the root of the weld were contributing factors.

When the supply situation improved, the arsenals returned to a molybdenum modified 18/8 stainless and used that for most of the armor plate welding.

A ferritic type of electrode was developed for the welding of cast armor. This electrode was essentially a manganese-molybdenum-silicon alloy used primarily for the repair of cast armor while the castings were still hot in the mold. Since welding had to be done on castings other than in the mold, it was necessary to preheat them to a temperature of 200 to 315°C (400 to 600°F) prior to welding.

ASBESTOS

A mineral found in serpentine and occurring in veinlets 12 to 150 mm (1/2 to 6 in.) wide. It readily separates into long flexible fibers which were used to make non-combustible, nonconductive, and chemically resistant materials until it was found to be a possible carcinogen.

Asbestos has the property of withstanding high temperatures, has a low thermal conductivity and is highly resistant to the action of acids. It was formerly used as a heat insulator, and to some extent, as an electric insulator.

AS-BRAZED *(adj.)*

Pertaining to the condition of brazements after brazing, prior to any subsequent thermal, mechanical, or chemical treatments. See STANDARD WELDING TERMS.

ASSIST GAS

A gas used to blow molten metal away to form the kerf in laser beam inert gas cutting, or to blow vaporized metal away from the beam path in laser beam evaporative cutting. See STANDARD WELDING TERMS.

AS-WELDED *(adj.)*

Pertaining to the condition of weld metal, welded joints, and weldments after welding, but prior to any subsequent thermal, mechanical, or chemical treatments. See STANDARD WELDING TERMS.

ASME BOILER CONSTRUCTION CODE

See BOILER WELDING.

ATMOSPHERE

Unit used in measuring the pressure of gases. One atmosphere is a pressure of 103 kPa (14.7 psi).

ATOM

The smallest unit of matter that can exist either alone or in combination. An atom has a dense central nucleus of protons, positively charged, around which a system of electrons revolve, characteristically remaining undivided in chemical reactions except for limited removal, transfer, or exchange of certain electrons. Knowledge of the atomic structure of metals is useful in the study of welding processes and the fabrication and utilization of metals.

ATOMIC HYDROGEN WELDING (AHW)

An arc welding process that uses an arc between two metal electrodes in a shielding atmosphere of hydrogen and without the application of pressure. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

Historical Background

Atomic hydrogen welding was the forerunner of the gas shielded arc welding processes. In the 1930s, it was the best process for welding metals other than carbon and low-alloy steels. With the development and ready availability of inert gases, the gas shielded arc welding processes have largely replaced atomic hydrogen welding.

The Atomic Hydrogen Process

In the atomic hydrogen process, an arc is maintained between two tungsten electrodes in a shielding atmosphere of hydrogen. Filler metal may or may not be added. The work is part of the electrical circuity only to the extent that a portion of the arc comes in contact with the work, at which time a voltage exists between the work and each electrode.

Both manual and automatic atomic hydrogen welding methods can be used. The simplest equipment is that used for manual welding. It consists of a power control unit, electrode holder, start-stop controls, a source of hydrogen, and the necessary cable and hose for conducting current and hydrogen.

The power control unit is a high reactance, moveable-coil transformer with an open-circuit voltage that permits easy starting and arc maintenance. The arc voltage in this process is higher than in metal arc welding, running as high as 90 or 100 volts. Unlike other methods of arc welding, in atomic hydrogen arc welding the arc does not generate heat in the work. Heat generated in the arc is transferred to the work by the hydrogen. As hydrogen passes through the arc from the jets or orifices around the tungsten electrodes, the molecules of hydrogen separate into their component parts (atoms). As the gas in the atomic state is being displaced with molecular hydrogen under a slight pressure, it is urged out of the intense heat of the arc and recombines with atomic gases in the outer edge of the arc stream, giving up heat produced by dissociation. This heat produces the welding temperature.

The Arc Fan

The arc stream, or "fan" as it is commonly known, follows a horseshoe-shaped path from the electrodes, expanding and contracting as the arc is lengthened and shortened. Ordinarily, a 10 to 20 mm (3/8 in. to 3/4 in.) fan or a 50 to 90 volt arc, (which produces a singing noise), is used. A short arc, ranging from 20 to 40 volts (often termed a "silent arc") is occasionally used to obtain a point source of heat. A long, narrow heat source can be produced by adjusting the arc length. To make a very narrow weld, the fan is carried vertically and approximately parallel to the line of weld; heat is applied over an elongated area, with length approximately four times the width.

ATOMIC WEIGHT

The weight of one atom of an element, as compared to the weight of one atom of hydrogen.

AUSTEMPERING

A method of controlled quenching of steel which eliminates the formation of martensite, with its attendant generation of high internal stresses. Austempering also eliminates the necessity for subsequent heat treatment to give quenched steel good mechanical properties. The treatment is based on the rate of transformation between austenite and pearlite at temperatures below 700°C (1300°F).

AUSTENITE

Solid solutions in which gamma iron is the solvent. Gamma iron dissolves carbon to a great extent. The maximum solubility is at 1130°C (2066°F), at which point it will dissolve 1.7% carbon. This decreases with temperature to .80% at 720°C (1333°F). *See* METALLURGY.

AUSTENITIC ALLOY STEELS

Steels that remain austenitic in structure (gamma iron) on slow cooling from the temperature of solidification. These steels exhibit no critical temperature on cooling. They cannot be hardened by heat treatment, although they may be cold work-hardened and annealed. Austenitic steels exhibit great shock strength, low elastic strength, and are very ductile. They work harden very rapidly and develop great resistance to wear and abrasion. Outstanding examples are the manganese steels. The stainless austenitic steels are very resistant to corrosion.

AUSTENITIC STAINLESS STEEL

A term applied to the "300" series of stainless steels. A stainless steel of this grade may be formed while cold; however, it is susceptible to work hardening effects. Most stainless steels in this classification are readily weldable. *See* STEEL, STAINLESS.

AUTO BODY REPAIR

The GMAW and resistance spot welding processes are the most widely used methods of joining automobile body panels and structures in auto body repair shops.

Low-Current Gas Metal Arc Welding (GMAW)

Low-current GMAW is a logical choice for auto body repair work. Using the short-circuiting arc, the whole range of metal gauges commonly worked on in auto body repair can be handled by one small-diameter wire size. Low heat input results in minimal distortion, and welding often can be performed in close proximity to glass, trim and upholstery. The equipment produces consistent high-quality results, and can be used in many ways to reduce time for a job.

For example, the time savings which result from eliminating the need to remove trim, upholstery, floor coverings and other items are enormous. The low heat input also enables large areas of thin metals to be welded without distortion, thus eliminating the need for costly panel beating, bending and stretching. Parts which would normally have to be removed for resistance spot welding can be welded in place because gas metal arc welding machines are capable of welding in any position, and from one side only for either spot or seam welding. Another advantage is that GMAW machines can be changed from seam welding to spot welding at the flick of a switch.

Gas metal arc spot welding is particularly suited to body shop work because access is needed only to one side of the work, and there is no need to clean the back side of the metal. A further advantage over resistance welding is that fit-up is not nearly as critical, because gas metal arc spot and seam welding can be used to bridge fairly large gaps. These features offer considerable savings in many applications. *See* GAS METAL ARC WELDING *and* RESISTANCE SPOT WELDING.

AUTOGENOUS WELD

A fusion weld made without filler metal. See STANDARD WELDING TERMS.

AUTOMATIC, (*adj.*)

Pertaining to the control of a process with equipment that requires only occasional or no observation of the welding, and no manual adjustment of the equipment controls. See STANDARD WELDING TERMS.

AUTOMATIC ARC WELDING CURRENT

The current in the welding circuit during the making of a weld, but excluding upslope, downslope, and crater fill current. See STANDARD WELDING TERMS.

AUTOMATIC ARC WELDING DOWNSLOPE TIME

The time during which the current is changed continuously from final taper current or welding current to final current. See STANDARD WELDING TERMS.

AUTOMATIC ARC WELDING UPSLOPE TIME

The time during which the current changes continuously from the initial current to the welding current. See STANDARD WELDING TERMS.

AUTOMATIC ARC WELDING WELD TIME

The time interval from the end of start time or end of upslope to beginning of crater fill time or beginning of downslope. See STANDARD WELDING TERMS.

AUTOMATIC BRAZING

See STANDARD WELDING TERMS. *See also* AUTOMATIC WELDING.

AUTOMATIC GAS CUTTING

A nonstandard term for AUTOMATIC OXYGEN CUTTING.

AUTOMATIC SOLDERING

See STANDARD WELDING TERMS. *See also* AUTOMATIC WELDING.

AUTOMATIC SPOT WELD

See RESISTANCE WELDING.

AUTOMATIC THERMAL CUTTING

See STANDARD WELDING TERMS. *See also* AUTOMATIC WELDING.

AUTOMATIC THERMAL SPRAYING

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING *and* AUTOMATIC WELDING.

AUTOMATIC WELDING

Welding with equipment that requires only occasional or no observation of the welding, and no manual adjustment of the equipment controls. Variations of this term are THERMAL CUTTING, *and* AUTOMATIC THERMAL SPRAYING. *See* STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING, MANUAL WELDING, MECHANIZED WELDING, ROBOTIC WELDING, *and* SEMIAUTOMATIC WELDING.

AUTO TRANSFORMER

A single winding transformer in which the primary voltage is applied to the winding. The secondary voltage is taken from taps on the winding.

AUXILIARY CIRCUIT

A supplementary circuit in addition to the main circuit, often a control circuit.

AUXILIARY ENLARGER

A nonstandard term for AUXILIARY MAGNIFIER.

AUXILIARY LIFT

A device to permit manual or power operation of the top electrode holder or arm beyond and independent of its normal welding stroke.

AUXILIARY MAGNIFIER

An additional lens used to magnify the field of vision. See STANDARD WELDING TERMS.

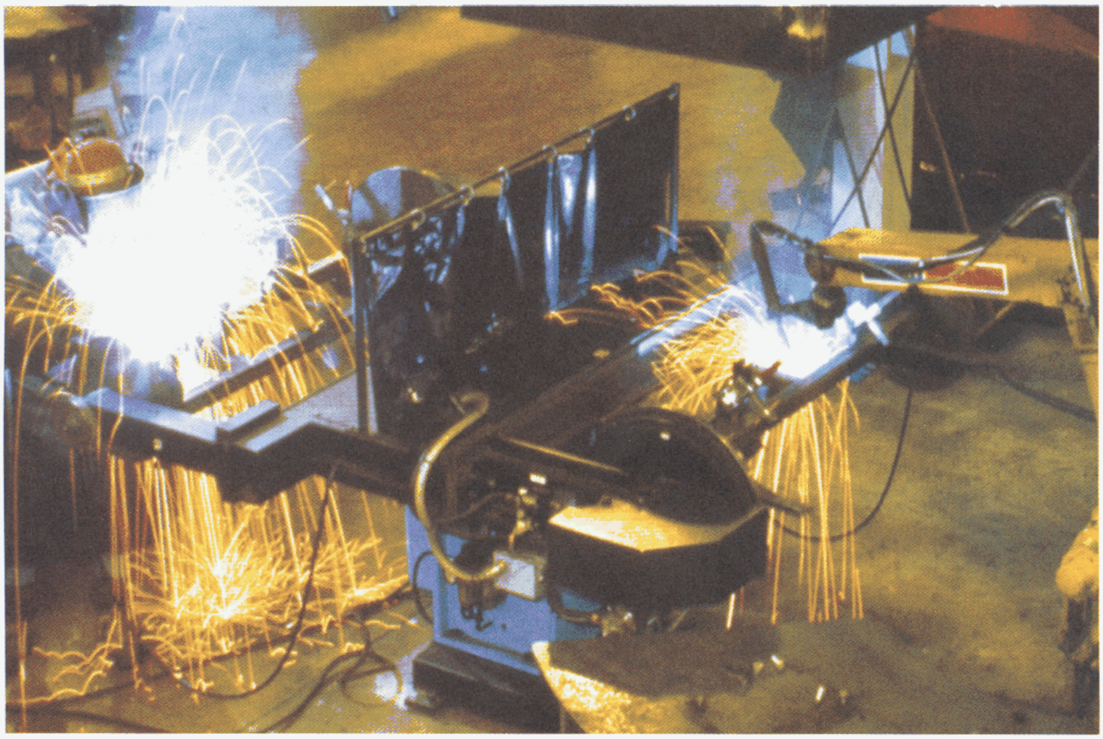
AWS CERTIFICATION PROGRAM

A program developed by the American Welding Society (AWS) to certify personnel involved in welding. The AWS currently has programs to certify welders, welding inspectors, and welding educators. Contact the American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126.

AXIS OF WELD

See STANDARD WELDING TERMS. *See also* WELD AXIS.

Several welding processes are used in the manufacture of this Boeing 777 jet aircraft



Robotic cell in operation using the gas metal arc welding process

B

B.H.N.

Abbreviation for Brinell hardness number.

B.T.U.

See BRITISH THERMAL UNIT.

BABBITT

Babbitt is a term applied to a series of tin-base alloys used for bearings. These relatively soft, low friction alloys are composed essentially of tin, with additions of antimony and copper to increase hardness, strength and fatigue resistance. The amount of lead in these alloys is usually limited to 0.35% to 0.50% to prevent formation of a lead-tin eutectic which reduces strength.

The basic composition range of these tin-base babbitts is 75% to 95% tin, 2% to 10% copper, and 2% to 10% antimony. Lead-base babbitts containing up to 10% tin and 12% to 18% antimony are used for bearings, but do not have the strength of the tin-base babbitts.

Babbitt is frequently melted with an air-fuel gas or oxyfuel gas flame prior to pouring. A similar flame is often used to melt babbitt from bearings and bearing caps for re-babbitting.

BACK BEAD

A weld bead resulting from a back weld pass. See STANDARD WELDING TERMS.

BACK BEND

See GUIDED BEND TEST.

BACK CAP

A device used to exert pressure on the collet to hold the electrode in a gas tungsten arc welding torch and create a seal to prevent air from entering the back of the torch. See STANDARD WELDING TERMS.

BACKFIRE

The momentary recession of the flame into the welding tip or cutting tip followed by immediate reappearance or complete extinction of the flame, accompanied by a loud report. See STANDARD WELDING TERMS.

BACKGOUGING

The removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and complete joint penetration on subsequent welding from that side. See STANDARD WELDING TERMS.

BACKHAND WELDING

A welding technique in which the welding torch or gun is directed opposite to the progress of welding. See STANDARD WELDING TERMS. *See also* TRAVEL ANGLE, WORK ANGLE, *and* DRAG ANGLE.

Backhand welding is sometimes referred to as the "pull gun" technique in gas metal arc (GMAW) and flux core arc welding (FCAW).

BACKING

A *material or device placed against the back side of the joint, or at both sides of a weld in electroslag and electrogas welding, to support and retain molten weld metal. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal. See* STANDARD WELDING TERMS. *See also* Figure B-1.

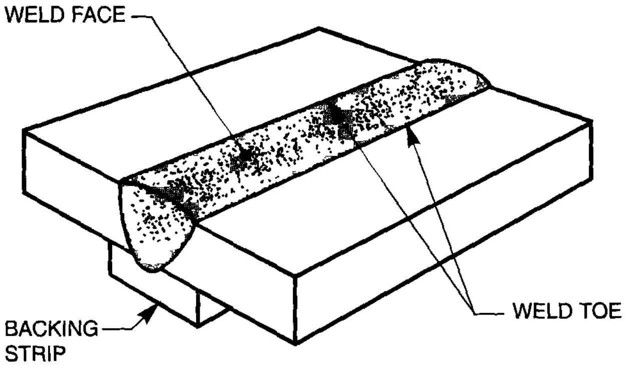


Figure B-1—Single-V-Groove Weld with Backing

BACKING BEAD

A weld bead resulting from a backing pass. See STANDARD WELDING TERMS.

BACKING FILLER METAL

A nonstandard term for CONSUMABLE INSERT.

BACKING PASS

A weld pass made for a backing weld. See STANDARD WELDING TERMS.

BACKING RING

Backing in the form of a ring, generally used in the welding of pipe. See STANDARD WELDING TERMS.

A backing ring helps maintain correct alignment of the pipe or tube ends during welding, and assures complete fusion to the root of the joint without the formation of slag, icicles, or spatter within the bore. The backing ring can be made from a strip of metal which is formed into a ring and fitted to the inside surface of a pipe or tube prior to welding. The ring should be substantially the same chemical composition as the pipe or tube to be welded.

BACKING SHOE

A nonconsumable backing device used in electroslag and electrogas welding that remains unfused during welding. See STANDARD WELDING TERMS. *See* Appendix 10, Figure 3.

BACKING, Split-Pipe

Backing in the form of a pipe segment used for welding round bars.

BACKING STRAP

See BACKING STRIP.

BACKING STRIP

Backing in the form of a strip of metal, carbon, or ceramic to retain molten metal at the root of a weld.

BACKING WELD

Backing in the form of a weld. See STANDARD WELDING TERMS. *See also* Figure B-2.

BACKING PASS

A weld pass made for a backing weld. See STANDARD WELDING TERMS.

BACKSTEP SEQUENCE

A longitudinal sequence in which weld passes are made in the direction opposite to the progress of welding. See STANDARD WELDING TERMS. *See also* Figure B-3.

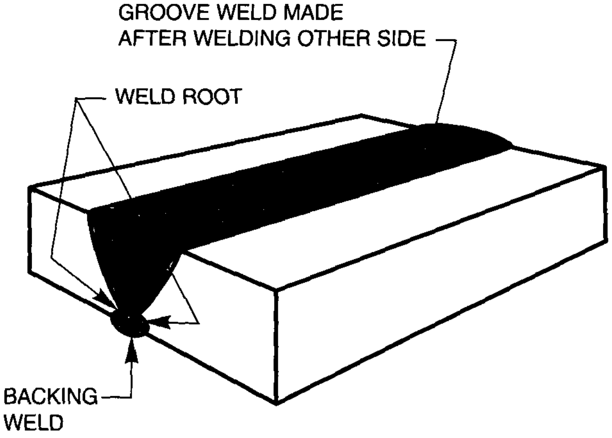


Figure B-2—Backing Weld

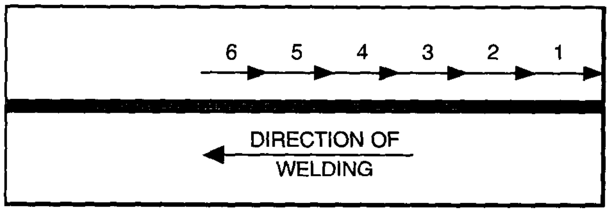


Figure B-3—Backstep Sequence

The backstep sequence is a welding technique used to prevent accumulation of stresses and distortion by distributing deposited weld metal. This method consists of dividing the weld into short increments, and depends on depositing the weld metal in a direction opposite to the direction of progression. The welds may be made in the sequence shown in Figure B-3, or this sequence may be changed. For example, the welds may be made in the order of 1, 2, 3, 4, 5, 6, etc., or 1, 3, 5, 2, 4, 6, etc. The latter is an illustration of the skip backstep method, which is a combination of skip and back-step welding. In skip backstep welding the welds may be made in any convenient order. *See* BLOCK SEQUENCE, CASCADE SEQUENCE, CONTINUOUS SEQUENCE, CROSS SECTIONAL SEQUENCE, *and* LONGITUDINAL SEQUENCE.

BACKSTEP WELDING

See BACKSTEP SEQUENCE.

BACKUP, Flash and Upset Welding

A locator used to transmit all or a portion of the upset force to the workpieces or to aid in preventing *the workpieces from slipping during upsetting. See* STANDARD WELDING TERMS.

BACKUP BARS AND PLATES

Backing material used to retain molten metal or to assure complete fusion. Successful welding of various materials often depends on the type of backup bar or plate that is used. The high heat conductivity of a copper backup bar or plate, for example, will prevent it from sticking to the weld metal, while its chill-mold effect will assure a clean, smooth weld metal surface. Electrolytic copper has proven to be the most satisfactory material for backing up a weld.

Copper backup bars are usually made by cutting pieces from copper plate or sheet. Electrolytic copper in cold rolled bars and plates is available in a variety of sizes for these applications. While these copper pieces give more satisfactory results than other backing materials, they must be made carefully to provide accurate dimensions and good surfaces.

Figure B-4 illustrates the use of a copper backup bar to obtain a full penetration weld in heavy plate.

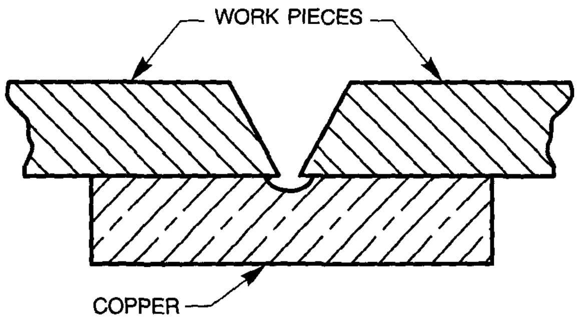


Figure B-4—Positioning of Copper Backup Bar Used to Obtain Full Penetration Weld

BACK WELD

A weld made at the back of a single groove weld. See STANDARD WELDING TERMS. *See also* Figure B-5.

BACKWARD WELDING

A British term for BACKHAND WELDING.

BALANCED PRESSURE TORCH

An oxyacetylene torch that operates under equal, or balanced, pressures for oxygen and acetylene, from 7 to 100 kPa (1 to 15 psig), with the capability of supplying oxygen in pressures up to 170 kPa (25 psig). The ports at the entrance to the mixing chamber are equal in area, and deliver equal volumes of gases at equal pressures to the mixing chamber.

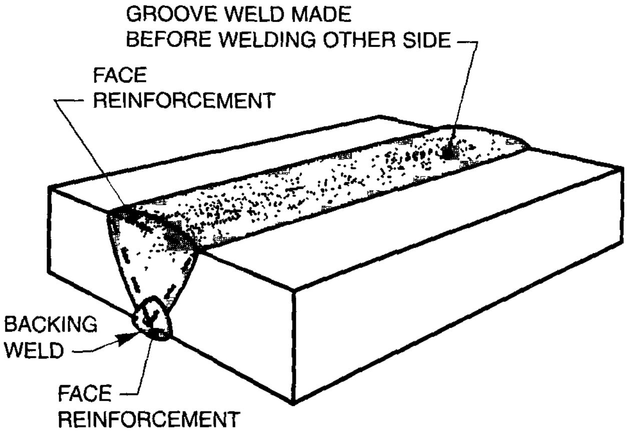


Figure B-5—Example of a Back Weld

BALLING UP

The formation of globules of molten brazing filler metal or flux due to lack of wetting of the base metal. See STANDARD WELDING TERMS.

BAND SAW BLADE REPAIRS

Silver solder is used to braze band saw blades. The ends to be brazed should be scarfed to a good, sharp edge. The length of the scarf depends on the width of the saw blade. Ribbon silver solder should be applied between the surfaces to be brazed or soldered, using a prepared flux, or damp, powdered borax. Apply the heat of the torch carefully, and as the solder melts, clamp the beveled edges together. Let the joint cool gradually and finish by grinding or filing as needed.

Another method is to scarf the edges of the saw blade, coat the edges with a thin paste of brazing flux mixed with water, and insert a small piece of thin, ribbon silver solder between the edges. The joint is held securely in a jig. A heavy pair of tongs, with thick jaws made for this purpose, is placed in the forge, or heated with a torch until red hot. The joint is then gripped with the hot tongs and held until the silver solder is melted and cooled. The surfaces and silver solder are not oxidized in this method, and the joint is a strong one if carefully made.

Many band saw machines are fitted with resistance butt welders for butt welding the saw blades. When used according to instructions, butt welding is simpler and faster than the brazing method, and produces equally strong joints.

BARE ELECTRODE

A filler metal electrode that has been produced as a wire, strip, or bar with no coating or covering other than that incidental to its manufacture or preservation. See STANDARD WELDING TERMS.

Used in arc welding, bare electrodes have no coating of flux, slag or other material except chemically formed rust or lime, or lubricant from drawing.

BARE METAL ARC WELDING (BMAW)

An arc welding process which produces coalescence of metals by heating them with an electric arc between a bare or lightly coated metal electrode and the weld pool. The process is used without shielding, without the application of pressure, and filler metal is obtained from the electrode. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

BARIUM

(Chemical symbol: Ba). A malleable, toxic, metallic element, soft and silvery-white. Barium is used in various alloys. It belongs to the alkaline earth group, chemically resembling calcium. It occurs only in combination with other elements. Atomic number, 56; atomic weight, 137.37; melting point, 850°C (1562°F); specific gravity, 3.80 at 0°C (32°F). Salts of barium produce a green color when put in a flame.

BAR MAGNET

A straight permanent magnet.

BAR STOCK

Ferrous and non-ferrous materials in bar or rod form.

BASE MATERIAL

The material to be welded, brazed, soldered, or cut. See STANDARD WELDING TERMS. *See also* BASE METAL *and* SUBSTRATE.

BASE METAL

The metal that is welded, brazed, soldered, or cut. See STANDARD WELDING TERMS. *See also* BASE MATERIAL, SUBSTRATE *and* PARENT METAL.

BASE METAL TEST SPECIMEN

A test specimen composed wholly of base metal. See STANDARD WELDING TERMS.

BASE PLATE

A nonstandard term when used for base metal plate.

BATTERY CAPACITY

The maximum amount of energy that can be obtained from a storage battery. Battery capacity is usually expressed in *ampere-hours*.

BEAD

See STANDARD WELDING TERMS. *See also* WELD BEAD.

BEAD FORMING

Depositing metal as the result of a pass. Bead forming is basic to the metal arc process, and is usually the first exercise for the beginning welder. The object of bead forming is to make all of the electrode material flow into the crater or weld pool produced by the arc. To do this successfully, it is necessary to keep the arc just ahead of the metal which has been deposited, i.e, on the advancing edge of the crater. An examination of the beads will show whether the operator is using the correct current and arc length. An excess of heat will cause the arc to produce a larger crater than the deposit will fill, leaving a small crevice along the edge of the bead. Holding too long an arc will cause the deposit to overlap excessively on the parent metal without achieving proper penetration.

BEADING WELD

A weld made so that the metal is deposited by advancing in a single direction. *See* STRINGER BEAD WELDING.

BEAD WELD

A nonstandard term for SURFACING WELD.

BEAM DIVERGENCE

The expansion of a beam's cross section as the beam emanates from its source. See STANDARD WELDING TERMS.

BEARING

The support or wear surface for a revolving shaft.

BELLS, Repair Welding

Bells are usually cast from bell metal, which ranges in composition from three to four parts copper to one part tin. Copper-tin alloys tend to be hot-short and to crack during fusion welding. While being welded, tin oxidizes preferentially before copper and can reduce weld strength because of oxide entrapment. For these reasons, it is important that heavy bells be preheated to minimize stresses, and that the weld area be shielded to prevent oxidation of the tin.

Cracked bells have been successfully repaired by welding, without changing the tone of the bell. One case involved repair of a fifty-year-old, 750 kg (1650 lb) bronze bell. The bell was 1.5 m (5 ft) from lip to lip, with the sides about four inches thick. It was a copper-tin alloy, which chipped like hard brass and welded like cast iron.

Since it was not economically feasible to remove the bell from its mounting, a charcoal-fueled brick oven was built in the belfry to preheat the bell. The crack was located on the side adjacent to the supporting frame, so it was necessary to loosen the bell, turn and tip it until the crack was horizontal. The entire crack was ground out to form a V-groove. A piece of steel plate was clamped inside the bell under the crack to prevent the molten metal from dropping through. Charcoal was placed in and around the bell in the oven. The charcoal was ignited with an oxyacetylene torch and blown with a molder's hand bellows. The bell was heated to the point at which solder would melt when applied to the surface.

Three hours were required for welding. Two cylinders of acetylene, three cylinders of oxygen and 17 kg (37 lb) of bronze filler rod were consumed in this repair operation. After the weld was complete, it was polished with a small portable grinder.

Other welding rods which are used for welding bells include bell metal, containing about 80% copper and 20% tin; phosphor-bronze, phos-copper; and other phosphor-bronzes which are high in tin content.

BELT GRINDER

A grinder fitted with a belt coated with abrasive particles used extensively in welding operations for grinding and polishing. The belt runs on two rollers, one of which is driven. *See also* SWING GRINDER.

BENARDOS PROCESS

A carbon-arc welding process named for one of its inventors, Nikolas de Benardos, of Russia.

The process was based on the principle that if an electric circuit in which the current is flowing is interrupted, the current will continue to flow across the gap in the circuit until the distance across the gap exceeds the force (voltage) driving the current. The gases in the gap offer such great resistance to the flow of current that they are heated to incandescence. This heat melts the base metal to make the weld. As cumbersome as Benardos' equipment might have been, it paved the way for future developments in arc welding.

Benardos and his associate, Stanislav Olszewski, were granted a British patent in 1885 for a welding process employing carbon electrodes. Benardos patented the process in Russia in 1887, and is credited with the first patent on arc welding.

In the Benardos process, the work was connected to the positive pole of a d-c power source, and the carbon rod was connected to the negative pole. The rod was fitted with an insulated handle so it could be manipulated by hand.

To start the weld, the carbon electrode was touched to the work to complete the electrical circuit, then the tip of the electrode was withdrawn a slight distance to establish the arc. The gap was usually between 3 and 12 mm (1/8 and 1/2 in.). Usually there was insufficient material in the workpiece to fill a joint, so a rod of similar composition was melted by the arc to supply the material necessary to fill the joint.

BEND TEST

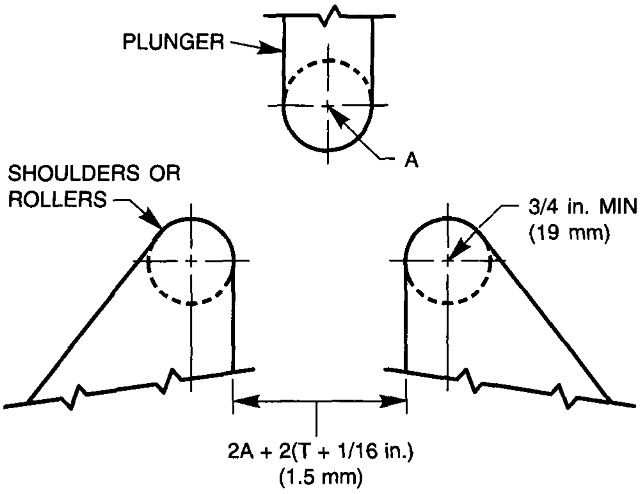
A test in which a specimen is bent to a specified bend radius. See STANDARD WELDING TERMS.

Various types of bend tests are used to evaluate the ductility and soundness of welded joints. Guided bend specimens may be longitudinal or transverse to the weld axis, and may be bent in tensile test machines or in wrap-around bend test jigs. Typical guided bend testing fixtures are illustrated in Figure B-6.

Face bend tests are made with the weld face in tension; root bend tests are made with the weld root in tension. When bend testing thick plates, transverse slices or side bend test specimens are usually cut from the welded joint and bent with the weld cross section in tension. The relative orientations of these specimens are illustrated in Figure B-7. The guided bend test is most commonly used in welding procedure and welder performance qualification. *See* FACE BEND, FREE BEND, GUIDED BEND, ROOT BEND *and* U-BEND.

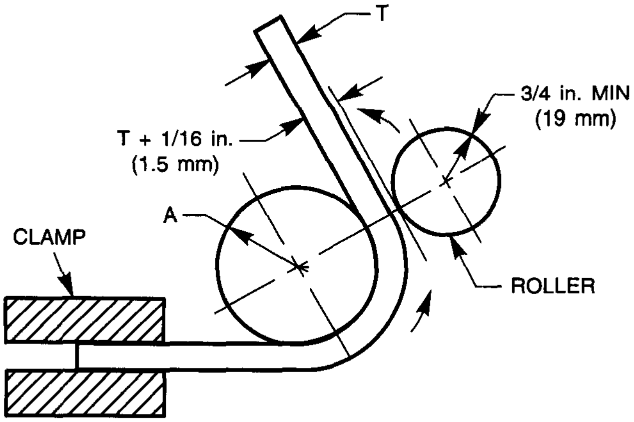
BERYLLIUM

(Chemical symbol, Be). A rare, lightweight, strong, brittle, toxic, bivalent metallic element which occurs in beryl and other silicates. It is alloyed with copper as an age-hardening agent and is used in aerospace structural material. Beryllium resembles magnesium in appearance and chemical properties. It is separated from its chloride by displacement with sodium. Atomic number, 4; atomic weight, 9.02; melting point, 1280°C (2336°F); specific gravity, 1.85.



T = SPECIMEN THICKNESS

(A) GUIDED BEND TEST JIG



T = SPECIMEN THICKNESS

(B) WRAP-AROUND BEND TEST JIG

Figure B-6—Guided Bend Test Jigs

BERYLLIUM COPPER

An age-hardenable copper-beryllium alloy containing 1.5% to 2.75% beryllium. It is used for springs and non-sparking tools. In the annealed condition, it has a tensile strength of 483 MPa (70 000 psi).

BETA BRASS

A copper-zinc alloy with approximately 54% copper and about 40% zinc. Its microstructure is all beta phase, which can exist at room temperature for compositions from 51% to 55% copper. Quenching from higher temperatures considerably broadens this range. With additions of between 64% and 55% copper, the copper-zinc alloys are two-phase alpha and beta. With the addition of copper as high as 70%, mixed alpha and beta phases may occur when rapidly cooled from temperatures near the melting point.

BEVEL

An angular edge shape. See STANDARD WELDING TERMS. *See also* Appendix 6.

BEVEL ANGLE

The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member. See STANDARD WELDING TERMS. *See also* Appendix 6.

BEVEL CUTTING

See OXYGEN CUTTING *and* THERMAL CUTTING.

BEVEL EDGE SHAPE

A type of edge shape in which the prepared surface or surfaces lies at some angle other than perpendicular to the material surface. See STANDARD WELDING TERMS. *See* Appendix 6.

BEVEL-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See also* Appendix 6.

BEVELING

The process of preparing an angular edge on material prior to welding. It may consist of a single bevel or double bevel, generally with bevel angles up to 45°. Two plates butted together, each with 45° bevels, form a 90° groove. *See* JOINT GEOMETRY, JOINT DESIGN, *and* EDGE PREPARATION.

BEVEL RADIUS

The radius used to form a J-edge shape. See STANDARD WELDING TERMS. *See* Appendix 6.

BEVEL WELD

See GROOVE WELD.

BILLET NICKING

Billet nicking is used to make a controlled break of a billet up to 14 cm (5-1/2 in.) thick. The billet is nicked to a depth of 12 to 18 mm (1/2 to 3/4 in.) by

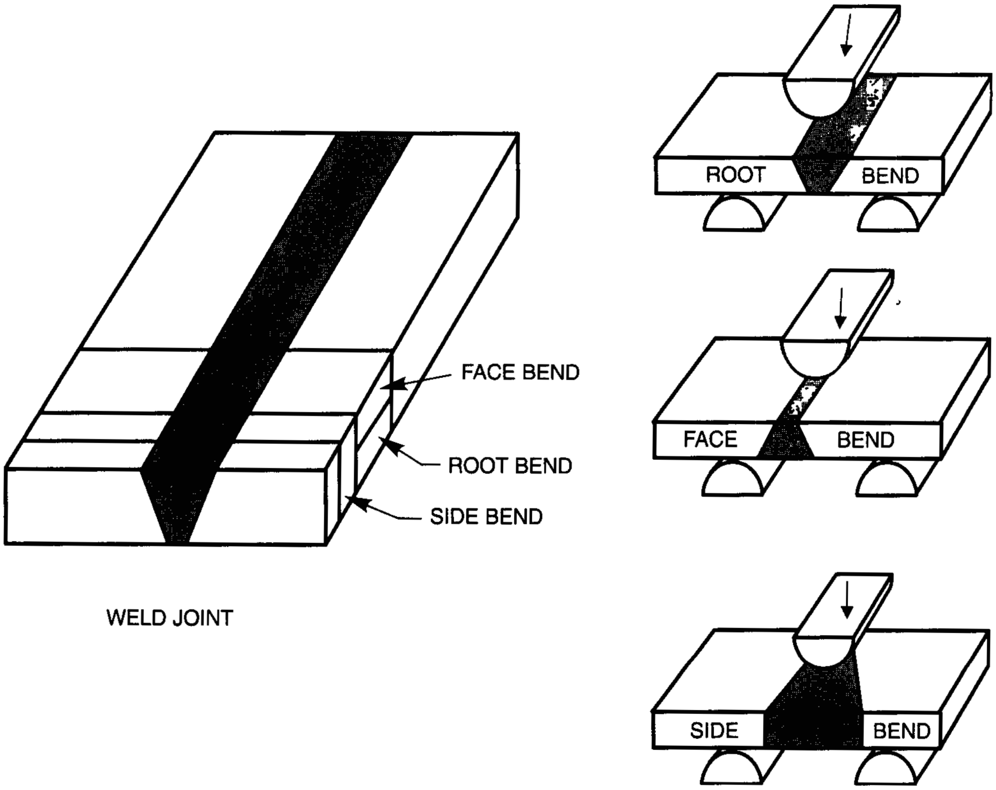


Figure B-7—Orientation of Bend Test Specimens

means of flame cutting or carbon arc cutting. Cold water is then poured into the nick in the hot metal, causing a crack, and the break is completed with force from a drop hammer, hydraulic press, or bulldozer.

BIRMINGHAM WIRE GAUGE (B.W.G.)

A standard system and gauge for measuring iron and steel telephone and telegraph wires. Also known as the Stubbs Gauge.

BIT, Soldering

The point of the soldering iron, usually made of copper, which actually transfers heat (and sometimes solder) to the joint.

BLACKSMITH WELDING

A nonstandard term for FORGE WELDING.

BLASTING

See ABRASIVE BLASTING.

A cleaning or surface-roughening technique using a forcibly projected stream of sharp angular abrasive particles.

BLIND JOINT

A joint, no portion of which is visible. See STANDARD WELDING TERMS.

BLAU-GAS

Blau-Gas was the trade name for a combustible gas produced by the destructive distillation of a liquid hydrocarbon, such as mineral oil. Blau-Gas is no longer used, however it was used for brazing and welding aluminum, and was also used with oxygen as a fuel gas for cutting iron and steel with a cutting torch. Blau-gas derived its name from the German chemist, Herman Blau, who invented this gas.

BLOCK BRAZING (BB)

A brazing process that uses heat from heated blocks applied to the joint. This is an obsolete or seldom-used process. See STANDARD WELDING TERMS.

In block brazing, coalescence is produced by the heat obtained from heated blocks applied to the part to be joined, and by using non-ferrous filler metal with a melting point above 425°C (800°F) but below that of the base metal. The filler metal is distributed in the joint by capillary attraction.

BLOCK SEQUENCE

A combined longitudinal and cross-sectional sequence for a continuous multiple pass weld in which separated increments are completely or partially welded before intervening increments are welded. See STANDARD WELDING TERMS. *See also* PROGRESSIVE BLOCK SEQUENCE *and* SELECTIVE BLOCK SEQUENCE.

BLOCK SEQUENCE WELDING

A welding sequence developed in the shipyards for welding ship hull plates which is adaptable to many welding situations which involve the closing of butt joints. This sequence was developed to establish the order of deposition of weld metal in butt joints to minimize cracking in the root pass caused by thermal stresses, slag inclusions and oxidized craters at points of withdrawal of the electrode from the molten puddle.

In the application illustrated, a variation of the block sequence was developed for welding vertical butt joints for which E-6010 electrodes were specified.

As shown in Figure B-8, the first increment of the root pass was started about 25 cm (10 in.) from the top

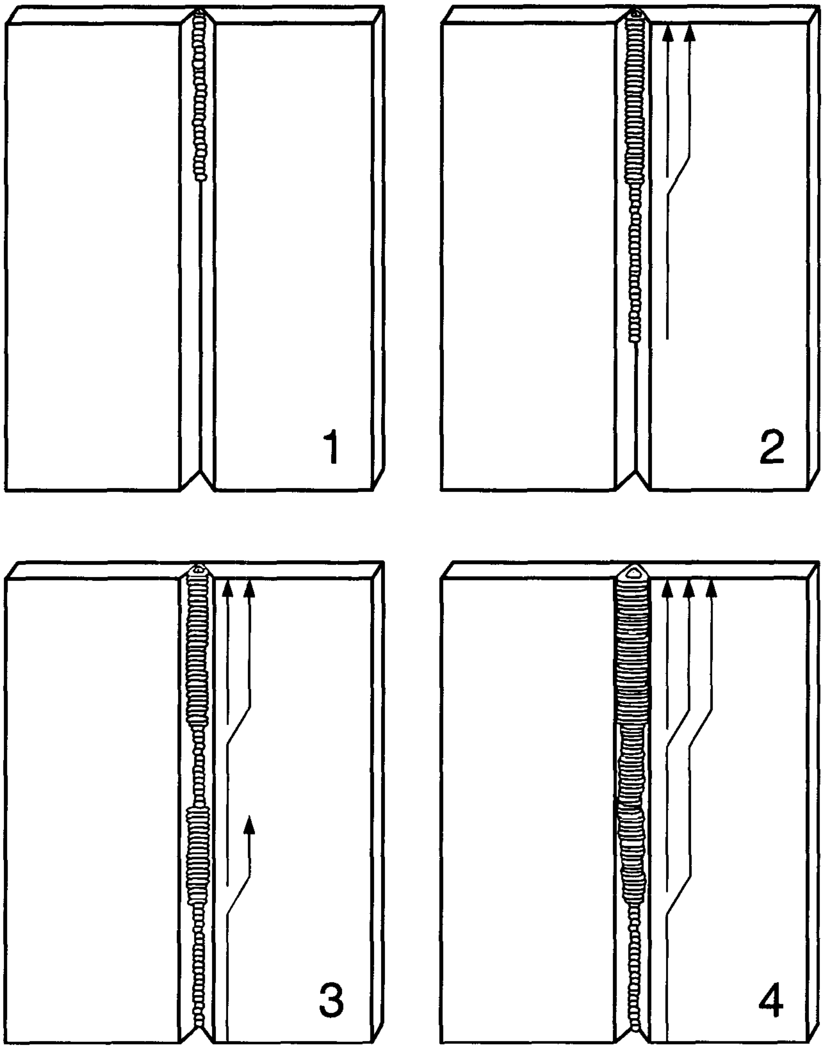


Figure B-8—Block Sequence Welding

and welded up to the top. The second root increment was started 50 cm (20 in.) from the top, welded up to the first increment, and up over it to the top without breaking the arc. The third increment was started 75 cm (30 in.) from the top, welded up to and over the second increment, and up over the first increment.

This technique of lapping passes avoids defects caused by stopping a weld pass and leaving a crater at the point of poor fusion where another pass is started.

Residual stresses in vertical butt welds were minimized by block welding with skips between, by preheating in cold weather and by chipping out tack increments as the welding progressed. Peening each pass immediately after deposition was found to be sufficient to minimize residual stresses.

BLOWHOLE

A nonstandard term when used for POROSITY.

A blowhole is a cavity formed in a weld deposit by trapped gas, dirt, grease or other foreign substances. *See* POROSITY.

BLOWOFF VALVE

A safety valve on a boiler, pressure vessel, or acetylene generator, designed to prevent pressure build-up or explosion by releasing the pressure when it exceeds a specific amount. Sometimes called a *pop valve.*

BLOWPIPE

See STANDARD WELDING TERMS. *See also* BRAZING BLOWPIPE *and* SOLDERING BLOWPIPE.

BLUE ANNEALING

The formation of a bluish-black oxide on the surface of a sheet of steel resulting from being annealed in an open furnace at a temperature within the transformation range.

BLUE BRITTLENESS

An embrittlement which occurs during tempering in which a blue color appears on the surface of clean steel. Blue brittleness is caused by precipitation hardening that develops in iron and some steels over the temperature range of about 200 to 450°C (400 to 800°F). The severity of the embrittlement depends on the strain present in the metal prior to heating, and on the time spent in the blue brittleness temperature range.

BOILER CODE COMMITTEE

A committee of the American Society of Mechanical Engineers (ASME) organized to formulate rules for the construction of steam boilers and other pressure vessels. This committee has one subcommittee for welding. The ASME maintains a Boiler and Pressure Vessel Code and a Code for Pressure Piping. The first ASME Boiler Code Committee was appointed on September 15, 1911.

BOILER CONSTRUCTION CODE

Construction and repair of boilers and pressure piping systems is done under strict regulations set forth in the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code and ASME B31 Code for Pressure Piping.

ASME Boiler and Pressure Vessel Code

The ASME maintains a *Boiler and Pressure Vessel Code* (B&PV Code) and a *Code for Pressure Piping*, both of which are recognized by the American National Standards Institute (ANSI). The ASME codes govern design, construction, maintenance, inspection and care of power boilers, heating boilers, nuclear power plant components, pressure piping systems, and pressure vessels operating at 103 kPa (15 lb/in.^{2}) and higher. Specifications for these codes are prepared and updated by volunteer committees rendering consensus of technical expertise. These codes are recognized and highly respected for the solid technical base they present.

The ASME *Boiler and Pressure Vessel Code* is referenced in the safety regulations of most states and major cities. It is also included by various federal agencies as part of their regulations, and is often used by authorities of other countries. An important aspect of the ASME code is that it requires third party inspection independent of the fabricator and user; inspection is commissioned by the National Board of Boiler and Pressure Vessel Inspectors (NBBPVI).

The ASME code is published in 11 sections, as outlined in Table B-1. A new edition of the code is issued by the ASME every three years. Users may submit inquiries to the ASME at any time for clarification of requirements, or to pose other questions. Inquiries dealing with significant topics are given a case number, and both the question and ASME's response are regularly published in *ASME Mechanical Engineering,* and in separate booklet form as a supplement to the code. Subsequently, these case interpretations are carefully reviewed to determine revisions to the next editions of the code. As a result, it is important to work with the current issue of the code and to review any case interpretations that may have been published.

ASME B-31 Code for Pressure Piping

The ASME Code for Pressure Piping, B 31, is published in six sections, as outlined in Table B-2. Each

Table B-1
ASME Boiler and Pressure Vessel Code

Organization of Sections and Their Contents

Section No.	Title	Coverage
I	Power Boilers	Construction of power, electric and miniature boilers, and high-temperature boilers used in stationary service. Also, power boilers used in locomotive, portable, and traction service.
II	Material Specifications	Code-adopted standards and specifications for ferrous and non-materials, welding rods, electrodes, and filler metals.
III	Nuclear Power Plant Components	Seven subsections covering (1) general requirements, (2) Class 1 components, (3) Class 2 components, (4) Class 3 components, (5) Class MC components, (6) component supports, and (7) core support structures.
IV	Heating Boilers	A construction code covering design, fabrication, installation and inspection of steam heating and hot water supply boilers directly fired by oil, gas, electricity, or coal.
V	Nondestructive Examination	NDT methods accepted for use under the Code.
VI	Recommended Rules for Care and Operation of Heating Boilers	Guide to owners of steel and cast iron heating boilers regarding maintenance and repair.
VII	Recommended Rules for Care of Power Boilers	A guide similar to that in Section VI covering stationary, portable, and traction-type power boilers.
VIII	Pressure Vessels, Division 1	Basic rules for construction, design, fabrication, inspection, and certification of pressure vessels. Rules formulated on basis of design principles and construction practices applicable to vessels for pressures up to 20.7 MPa (3000 psi).
VIII	Pressure Vessels, Division 2	Division 2 provides an alternative to the minimum construction requirements of Division 1. Division 2 rules are more restrictive in the choice of materials, but they permit higher design stress intensity values in the range of temperatures over which the design stress intensity value is controlled by the ultimate or yield strength. Division 2 rules cover vessels installed at stationary locations.
IX	Welding and Brazing Qualifications	Relates to the qualification of welders and welding operators and the procedures to be followed to comply with the Code.
X	Fiberglass-Reinforced Plastic Pressure Vessels	A recent construction Code established general specifications for the glass and resin used in fabrication, and qualification procedures. Limits are given for permissible service conditions.
XI	Rules for Inservice Inspection of Nuclear Power Plant Components	Requirements for maintaining a nuclear power plant in a safe and expeditious manner, and for returning a plant to service following an outage.

Table B-2
ASME B31 Code for Pressure Piping

Organization of Sections and Their Contents

Section	Title	Coverage
B31.1	Power Piping	Power and auxiliary service systems for electric generation stations; industrial and institutional plants: central and district heating plants; and district heating systems.
B31.2	Fuel Gas Piping	Systems for fuel gases such as natural gas, manufactured gas, liquefied petroleum gas (LPG)—air mixtures above the upper combustible limits.
B31.3	Chemical Plant and Petroleum Refinery Piping	All piping within the property limits of facilities engaged in processing or handling of chemical, petroleum, or related products. Also applies to piping systems that handle all fluids, including fluidized solids, and all types of service including raw, intermediate, and finished chemicals: oil and other petroleum products: gas: steam: air: water: and refrigerants, except as specifically excluded.
B31.4	Liquid Petroleum Transportation Piping Systems	Piping for transporting liquid petroleum between producers' lease facilities, tank farms, natural gas processing plants, refineries, stations, terminals and other delivery and receiving points.
B31.5	Refrigeration Piping	Piping systems for refrigerant and brine at temperatures as low as –196°C (–320°F), whether erected on the premises or factory assembled. Does not include (1) self-contained or unit refrigeration systems subject to requirements of Underwriters' Laboratories or any other nationally recognized testing laboratory, (2) water piping, or (3) piping designed for external or internal pressure not exceeding 103 kPa (15 psig) regardless of size.
B31.8	Gas Transmission and Distribution Piping Systems	Gas compressor stations, gas metering and regulation stations, gas mains, and service lines up to the outlet of the customer's meter set assembly. Gas storage lines and gas storage equipment of the close-pipe type that is either fabricated or forged from pipe, or fabricated from pipe and fittings.

section prescribes requirements for design, materials, fabrication, erection, testing, and inspection of a designated piping system. Third-party inspection is not required under the Code for Pressure Piping. However, pressure piping external to a boiler is covered by the ASME Boiler and Pressure Vessel Code, and therefore, third-party inspection is required. Some sections of the Code for Pressure Piping require qualifications to be performed in accordance with other documents. Examples of documents that add to the total requirement are Section IX of the *ASME Boiler and Pressure Vessel Code*, and American Petroleum Institute (API) *Standard 1104*.

Reference: Linnert, George E; *Welding Metallurgy: Fundamentals* Vol. 1, 4th Edition, Miami, Florida: American Welding Society, 1995.

BOILER WELDING

See BOILER CONSTRUCTION CODE.

BOND

See COVALENT BOND, IONIC BOND, MECHANICAL BOND, *and* METALLIC BOND.

BOND BAR

A nonstandard term for BOND SPECIMEN.

BOND CAP

A nonstandard term for BOND SPECIMEN.

BOND COAT, Thermal Spraying

A preliminary (or prime) coat of material which improves adherence of the subsequent thermal spray deposit. See STANDARD WELDING TERMS.

BONDED FLUX, Submerged Arc Welding

A type of granular flux produced by powdering and dry mixing the ingredients with bonding agents. This wet mixture is then pelletized and baked at a temperature below its melting point, followed by processing to produce the desired particle size. See STANDARD WELDING TERMS.

BONDING

A nonstandard term when used for welding, brazing, or soldering.

BONDING FORCE

The force that holds two atoms together; it results from a decrease in energy as two atoms are brought closer to one another. See STANDARD WELDING TERMS.

BOND LINE, Thermal Spraying

The cross section of the interface between a thermal spray deposit and the substrate. See STANDARD WELDING TERMS. *See also* Figure B-9.

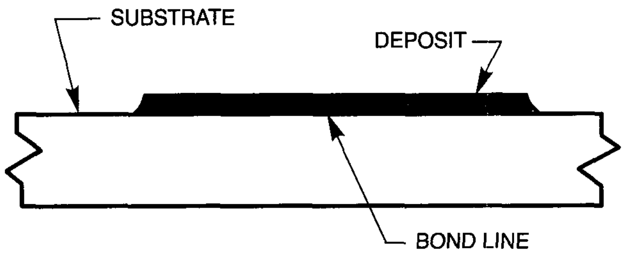


Figure B-9—Thermal Spray Deposit

In a weldment, the junction between weld metal and base material, between thermal spray deposits and substrate, or between base metal (material) parts when filler metal is not used.

In an adhesive bonded joint, the cross section of the interface between adhesive and adherent.

BOND SPECIMEN, Thermal Spraying

The test specimen on which a thermal spray deposit has been applied to determine bond strength and thermal spray deposit strength. See STANDARD WELDING TERMS.

BOND STRENGTH, Thermal Spraying

The unit of force required to separate a thermal spray deposit from the substrate. See STANDARD WELDING TERMS.

BOOM

A movable arm on which wire feeders, welding cable and other welding components are mounted to provide flexibility of movement and increased operating range in gas metal arc welding operations. Since the wire feeder is mounted at the tip of the boom, the usual 3 to 5 m (10 to 15 ft) service range is considerably extended.

BOOTH, Protective

See EYE PROTECTION *and* PROTECTION FOR WELDERS.

BORAX

($Na_2B_4O_{10}H_2O$) A hydrated sodium borate, crystalline and slightly alkaline, used as a flux for brazing and welding. Borax, or mixtures of borax and boric acid, as well as calcine borax and borax glass are among the most successful fluxes. They are used to restrict the formation of metallic oxides and exert a solvent action on these oxides as they are formed.

Borax is fluid at 760°C (1400°F), but begins to thicken below this point. The addition of boric acid tends to produce a more viscous flux, but it is not as active as borax in dissolving oxides of metal. When heated, boric acid does not bubble like common borax, but spreads over the surface of the joint, thus protecting it from oxidation. The bubbling of heated borax results from driving off the water of crystallization, but this can be avoided by using fused borax. Alcohol is added to fused borax; water must not be added, as it will rapidly cake.

Dry borax flux can be sprinkled along the joint, but if a torch is used for heating, it is better to warm the joint so that the flux will adhere and not blow away. A thin paste is a satisfactory form of borax, because an even coating of the paste can be brushed over the surface. Bare spots must be carefully avoided. *See* FLUX.

BORING, Oxyacetylene

See OXYGEN LANCE.

BORON

(Chemical symbol: B). A soft brown, crystalline, trivalent non-metallic element used in hard alloys and abrasives. It is found in nature only in combination with other elements and is obtained by heating boron trioxide with magnesium powder. Atomic number, 5; atomic weight: 10.82; melting point: 2300°C (4172°F); specific gravity of crystals, 2.45.

The addition of boron to steel in the range of .0025% to .0030% gives steel a greater depth of hardenability. The addition of more than .003% adds very little additional hardenability, and if over .006% boron is added, the steel rapidly loses ductility and breaks up much like steel with high sulphur content. If .01% boron is added, the steel will break up during rolling.

BORON CARBIDE

(Chemical symbol: B_4C). A very hard compound produced by heating boric acid (B_2O_3) and coke together at about 2500°C (5430°F), used on an abrasive cutting tool when extreme hardness is required. At ordinary temperatures, boron carbide is highly resistant to chemical reagents

BOTTLE

A nonstandard term when used for GAS CYLINDER.

BOURDON TUBE PRESSURE Gauge

See PRESSURE GAUGE.

BOXING

The continuation of a fillet weld around a corner of a member as an extension of the principal weld. See STANDARD WELDING TERMS. *See also* Figure B-10.

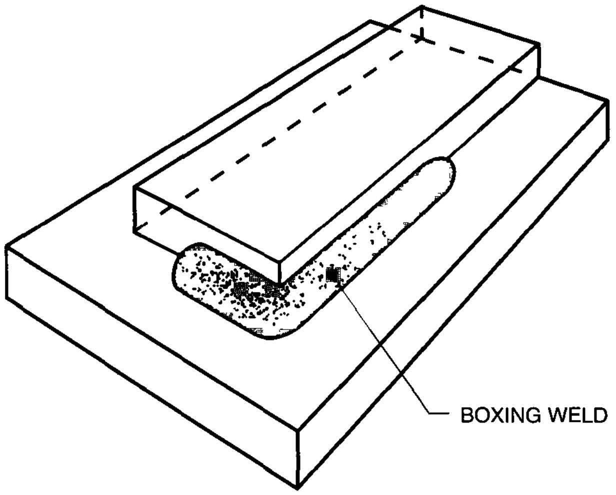


Figure B-10—An Example of Boxing

BOYLE'S LAW

The principle of Boyle's law is that the volume of gas confined at constant temperature is inversely proportional to the increase of pressure on it; or $p_1V_1 = p_2V_2$, where

p_1 = initial absolute pressure, Pa (lb/in.^{2})
V_1 = initial volume, m^3 (ft^3)
p_2 = final absolute pressure, Pa (lb/in.^{2})
V_2 = final volume, m^3 (ft^3).

For example, this law expresses the fact that if the pressure of a certain volume of gas is doubled, the volume will be reduced to one-half the original volume, provided the temperature remains constant.

BRAKE HORSEPOWER

The actual power of a machine or engine as measured by a dynamometer or brake.

BRASS

The generic name for alloys consisting essentially of copper and zinc.

The solid solubility of zinc in copper is over 38% at 450°C (850°F) and drops to about 30% at room temperature; therefore most brasses are single-phase solid solution at normal processing and service temperatures.

BRAZE

A weld produced by heating an assembly to the brazing temperature using a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action. See STANDARD WELDING TERMS.

BRAZEABILITY

The capacity of a metal to be brazed under the imposed fabricating conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service. See STANDARD WELDING TERMS.

BRAZE INTERFACE

The interface between filler metal and base metal in a brazed joint. See STANDARD WELDING TERMS.

BRAZEMENT

An assembly whose component parts are joined by brazing. See STANDARD WELDING TERMS.

BRAZE METAL

That portion of a braze that has been melted during brazing. See STANDARD WELDING TERMS.

BRAZER

One who performs manual (or semi-automatic) brazing. See STANDARD WELDING TERMS.

BRAZE WELDING (BW)

A welding process that uses a filler metal with a liquidus above 450°C (840°F) and below the solidus of the base metal. The base metal is not melted. Unlike brazing, in braze welding the filler metal is not distributed in the joint by capillary action. See STANDARD WELDING TERMS. *See also* FLOW WELDING.

The term *braze welding* is sometimes used to describe the joining of bronzes with a filler rod of bronze. In this instance, there is complete fusion of base metal with filler metal since both have approximately the same melting point. This provides complete metallurgical bonding, as in fusion welding of steel.

BRAZING (B)

A group of welding processes that produce coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action. See STANDARD WELDING TERMS.

Brazing must meet each of three criteria:

(1) The parts must be joined without melting the base metals.

(2) The filler metal must have a liquidus temperature above 450°C (840°F).

(3) The filler metal must wet the base metal surfaces and be drawn into or held in the joint by capillary action.

To achieve a good joint using any of the various brazing processes described in this chapter, the parts must be properly cleaned and must be protected by either flux or atmosphere during the heating process to prevent excessive oxidation. The parts must be designed to afford a capillary for the filler metal when properly aligned, and a heating process must be selected that will provide the proper brazing temperature and heat distribution.

Brazing differs from soldering, in that soldering filler metals have a liquidus below 450°C (840°F). Braze welding is also different from brazing, since the filler metal is not distributed by capillary action.

Brazing with silver alloy filler metals is sometimes called silver soldering, a nonpreferred term. Silver brazing filler metals are not solders; they have liquidus temperatures above 450°C (840°F).

Applications

The brazing process is used to join together various materials for numerous reasons. By using the proper joint design, the resulting braze can function better than the base metals being joined. In many instances it is desirable to join different materials to obtain the maximum benefit of both materials and have the most cost- or weight-effective joint. Applications of brazing cover the entire manufacturing arena from inexpensive toys to highest quality aircraft engines and aerospace vehicles. Brazing is used because it can produce results which are not always available with other joining processes. Brazing provides the following advantages:

(1) It is economical for complex assemblies.

(2) It is a simple way to join large joint areas.

(3) It provides excellent stress and heat distribution.

(4) Coatings and claddings can be maintained during brazing.

(5) Dissimilar materials can be joined.

(6) Nonmetals can be joined to metals.

(7) Widely different thicknesses can be joined.

(8) Complex arrangements of precision parts can be joined.

(9) Joints require little or no finishing.

(10) Many parts can be joined at one time (batch processing).

Process Advantages and Disadvantages

Among the advantages of brazing is that it is generally very economical when done in large batches, with costs varying with the heating method employed. A major benefit of brazing is that brazed joints can be taken apart at a later time. Dissimilar metals can be joined by brazing without melting the base metals as required by other joining methods. In many instances, several hundred parts with multiple joints can be brazed at one time. When protective atmosphere brazing is used, parts are kept clean and a heat treatment cycle may be employed as part of the brazing cycle.

There are some disadvantageous factors of brazing that should be considered. In the brazing process, a molten metal flows between the materials to be joined; consequently there is the possibility of liquid metal interactions which are unfavorable. Depending on the material combinations involved and the thickness of the base sheets, base metal erosion may occur. In many cases, the erosion may be of little consequence, but when brazing heavily loaded or thin materials, the erosion can weaken the joint and make it unsatisfactory for its intended application. Also, the formation of brittle intermetallics or other phases can make the resulting joint too brittle to be acceptable.

A disadvantage of some of the manual brazing processes is that highly skilled technicians are required to perform the operation. This is especially true for gas torch brazing when using a brazing filler metal with a high melting point. Nevertheless, with the proper joint design, brazing filler metal, and process selection, a satisfactory brazing technique can be developed for most joining applications. Brazing is often selected when it is not feasible, because of strength or economic considerations, to join the materials with a fusion welding process.

Principles of Operation

Capillary flow is the dominant physical principle that assures good brazements when both faying surfaces to be joined are wet by the molten filler metal. The joint must be spaced to permit efficient capillary action that results in coalescence. Specifically, capillary action is a result of surface tension between base metal(s) and filler metal, protected by a flux or atmosphere, and promoted by the contact angle between base metal and filler metal. In actual practice, brazing filler metal flow is influenced by dynamic considerations involving fluidity, viscosity, vapor pressure, gravity, and especially the effects of metallurgical reactions between filler metal and base metal.

Brazing Procedure. The typical brazed joint has a relatively large area and very small gap. In the simplest brazing application, the surfaces to be joined are cleaned to remove contaminants and oxides. Next, they are coated with flux. A flux is a material which is capable of dissolving solid metal oxides and also preventing new oxidation. The joint area is then heated until the flux melts and cleans the base metals, which are protected against further oxidation by the layer of liquid flux.

Brazing filler metal is then melted at some point on the surface of the joint area. Capillary attraction between the base metal and the filler metal is much higher than that between the base metal and the flux. Accordingly, the flux is displaced by the filler metal. The joint, on cooling to room temperature, will be filled with solid filler metal, and the solid flux will be found on the joint periphery.

Joints to be brazed are usually made with clearances of 0.025 to 0.25 mm (0.001 to 0.010 in.). The fluidity of the filler metal, therefore, is an important factor. High fluidity is a desirable characteristic of brazing filler metal since capillary action may be insufficient to draw a viscous filler metal into closely fitted joints.

Brazing is sometimes done under an active gas, such as hydrogen, or in an inert gas or vacuum. Atmosphere brazing eliminates the necessity for postbraze cleaning and ensures the absence of corrosive mineral flux residue. Carbon steels, stainless steels, and superalloy components are widely processed in atmospheres of reacted gases, dry hydrogen, dissociated ammonia, argon, or vacuum. Large vacuum furnaces are used to braze zirconium, titanium, stainless steels, and the refractory metals. With good processing procedures, aluminum alloys can also be vacuum-furnace brazed with excellent results.

Brazing is economically attractive for the production of high strength metallurgical bonds while preserving desired base metal properties.

Brazing Processes

Brazing processes are customarily designated according to the sources or methods of heating. Industrial methods currently significant are the following:

(1) Torch brazing
(2) Furnace brazing
(3) Induction brazing
(4) Resistance brazing
(5) Dip brazing
(6) Infrared brazing

Whatever the process used, the filler metal has a melting point above 450°C (840°F), but below that of the base metal, and it spreads within the joint by capillary action.

Torch Brazing

Torch brazing is accomplished by heating with one or more gas torches. Depending on the temperature and the amount of heat required, the fuel gas i.e., acetylene, propane, or natural gas, may be burned with air, compressed air, or oxygen. Flame temperature increases as the oxygen content of the gas is increased.

For manual torch brazing, the torch may be equipped with a single tip, either single- or multiple-flame. Manual torch brazing is particularly useful on assemblies involving sections of unequal mass. Machine operations can be set up, where the rate of production warrants, using one or more torches equipped with single or multiple-flame tips. The machine may be designed to move either the work or the torches, or both.

Torch heating for brazing can be used with filler metals supplied with flux or self-fluxing. The list includes aluminum-silicon, silver, copper-phosphorus, copper-zinc, and nickel. With the exception of the copper-phosphorus filler metals, they all require fluxes. For certain applications even the self-fluxing copper-phosphorus filler metals require added flux.

The filler metal can be placed on the joint and fluxed before heating, or it may be face-fed. Heat is applied to the joint, first melting the flux, then continuing until the brazing filler metal melts and flows into the joint. Overheating of the base metal and brazing filler metal should be avoided because rapid diffusion and "drop through" of the metal may result. Natural gas is well suited for torch brazing because its relatively low flame temperature reduces the danger of overheating.

Brazing filler metal may be preplaced at the joint in the forms of rings, washers, strips, slugs, or powder, or it may be fed from hand-held filler metal, usually in the form of wire or rod. In any case, proper cleaning and fluxing are essential.

Torch brazing techniques differ from those used for oxyfuel gas welding. Operators experienced only in welding techniques may require instruction in brazing techniques. It is good practice, for example, to prevent the inner cone of the flame from coming in contact with the joint except during preheating, since melting of the base metal and dilution with the filler metal may increase its liquidus temperature and make the flow more sluggish. In addition, the flux may be overheated and thus lose its ability to promote capillary flow, and low melting constituents of the filler metal may evaporate.

Furnace Brazing

Furnace brazing, as illustrated in Figure B-11, is used extensively. This process is selected in applications where multiple brazed joints are to be formed simultaneously on a completed assembly, and when many similar assemblies are to be joined. It is successful when the following conditions can be met: (1) the parts to be brazed can be preassembled or jigged to hold them in the correct position, (2) the brazing filler metal can be placed in contact with the joint, and (3) the complex parts can be heated uniformly to prevent the distortion that would result from local heating of the joint area.

Electric, gas, or oil heated furnaces with automatic temperature control capable of holding the temperature within ±6°C (±10°F) should be used for furnace brazing. Fluxes or specially controlled atmospheres that perform fluxing functions must be provided.

Parts to be brazed should be assembled with the filler metal and flux, if used, located in or around the joints. The preplaced filler metal may be in the form of wire, foil, filings, slugs, powder, paste, or tape. The assembly is heated in the furnace until the parts reach brazing temperature and brazing takes place. The assembly is then removed. These steps are shown in Figure B-11.

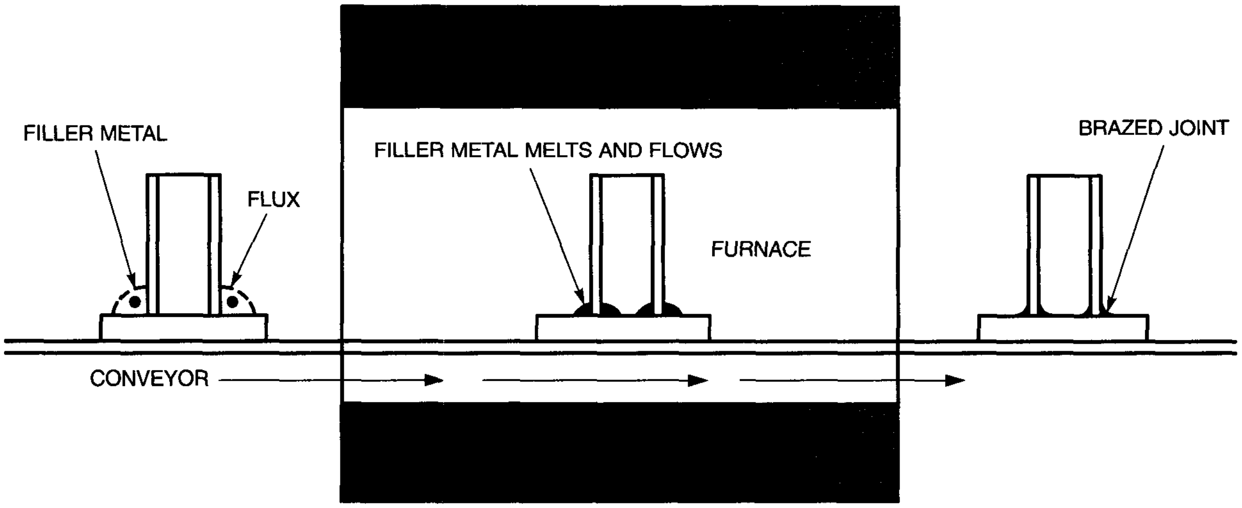


Figure B-11—Illustration of Furnace Brazing Operation

Many commercial fluxes are available for both general and specific brazing operations. Satisfactory results are obtained if dry powdered flux is sprinkled along the joint. Flux paste is satisfactory in most cases, but in some cases it retards the flow of brazing alloy. Flux pastes containing water can be dried by heating the assembly at 175 to 200°C (350 to 400°F) for 5 to 15 minutes in drying ovens or circulating air furnaces.

To avoid excessive interaction between the filler metal and base metal, brazing time should be restricted to the time necessary for the filler metal to flow through the joint. Normally, one or two minutes at the brazing temperature is sufficient to make the braze. A longer time at the brazing temperature will be beneficial where the remelt temperature of the filler metal is to be increased and where diffusion will improve joint ductility and strength. Times of 30 to 60 minutes at the brazing temperature are often used to increase the braze remelt temperature.

Furnaces. Furnaces used for brazing are classified as (1) batch type with either air or controlled atmosphere, (2) continuous type with either air or controlled atmosphere, (3) retort type with controlled atmosphere, or (4) vacuum. Figure B-12 shows a high-temperature, high-vacuum brazing furnace with control panel and charging carriage.

Most brazing furnaces have a temperature control of the potentiometer type connected to thermocouples

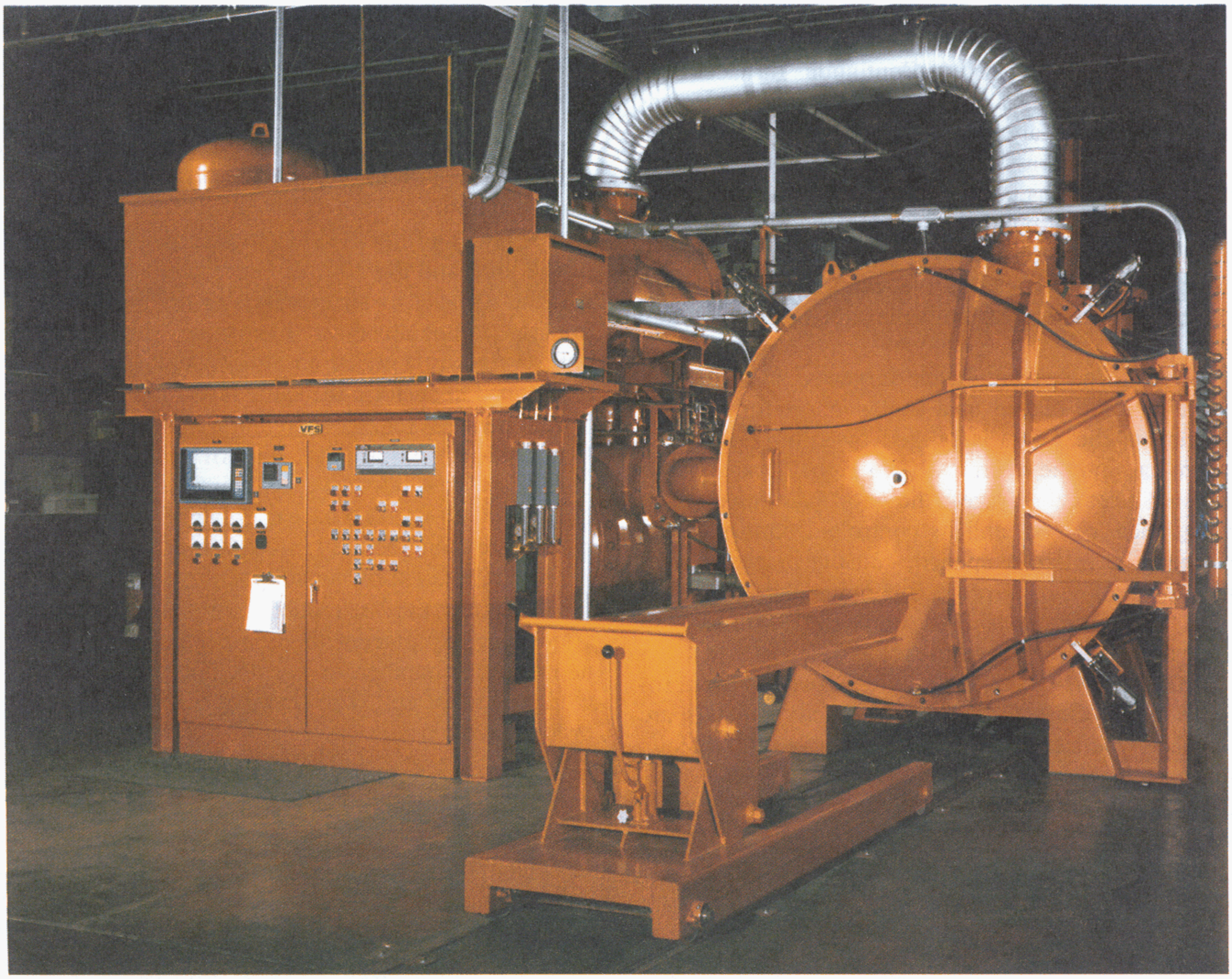


Figure B-12—A High Temperature, High Vacuum Brazing Furnace with Control Panel and Charging Dolly

and gas control valves or contactors. Most furnaces are heated by electrical resistance using silicon-carbide, nickel-chromium, or refractory metal (Mo, Ta, W) heating elements. When a gas or oil flame is used for heating, the flame must not impinge directly on the parts.

With controlled atmosphere furnaces, a continuous flow of the atmosphere gas is maintained in the work zone to avoid contamination from outgassing of the metal parts and dissociation of oxides. If the controlled atmosphere is flammable or toxic, adequate venting of the work area and protection against explosion are necessary.

Batch type furnaces heat each workload separately. When a furnace is lowered over the work, it is called a bell furnace.

Continuous furnaces are equipped with conveyors so that the furnace receives a steady flow of incoming assemblies. The parts move through the furnace either singly or in trays or baskets. Continuous furnaces usually contain a preheat or purging area which the parts enter first. In this area, the parts are slowly brought to a temperature below the brazing temperature. If brazing atmosphere gas is used in the brazing zone, it also flows over and around the parts in the preheat zone, under positive pressure. The gas flow removes any entrapped air and starts the reduction of surface oxides. Atmosphere gas trails the parts into the cooling zone.

Retort furnaces are batch furnaces in which the assemblies are placed in a sealed retort for brazing. The air in the retort is purged by controlled atmosphere gas and the retort is placed in the furnace. After the parts have been brazed, the retort is removed from the furnace, cooled, and its controlled atmosphere is purged. The retort is opened, and the brazed assemblies are removed. A protective atmosphere is sometimes used within a high-temperature furnace to reduce external scaling of the retort.

Vacuum furnace brazing is widely used in the aerospace and nuclear fields, where reactive metals are joined or where entrapped fluxes would be intolerable. Stainless steels, superalloys, aluminum alloys, titanium alloys, and metals containing refractory or reactive elements are brazed with vacuum brazing equipment. Base metals that can generally be brazed only in vacuum are those containing more than a few percent of aluminum, titanium, zirconium, or other elements with particularly stable oxides.Vacuum is a relatively economical "atmosphere" which prevents oxidation by removing air from around the assembly. Surface cleanliness is nevertheless required for good wetting and flow.

Induction Brazing

Induction brazing is used when very rapid heating is required. Time for processing is usually in the range of seconds when large numbers of parts are handled automatically. Induction brazing has been used extensively to produce consumer and industrial products; structural assemblies; electrical and electronic products; mining, machine, and hand tools; military and ordnance equipment; and aerospace assemblies.

The heat for brazing with this process is obtained from an electric current induced in the parts to be brazed, hence the name induction brazing. For induction brazing, the parts are placed in or near a water-cooled coil carrying alternating current. They do not form a part of the electrical circuit. Parts to be heated act as the short circuited secondary of a transformer where the work coil, which is connected to the power source, is the primary. On both magnetic and nonmagnetic parts, heating is obtained from the resistance of the parts to currents induced in them by the transformer action.

The brazing filler metal is preplaced. Careful design of the joint and the coil setup are necessary to assure that the surfaces of all members of the joint reach the brazing temperature at the same time. Flux is employed except when an atmosphere is specifically introduced to perform the same function.

Frequencies for induction brazing generally vary from 10 kHz to 450 kHz. The lower frequencies are obtained with solid-state generators and the higher frequencies with vacuum tube oscillators. Induction generators are manufactured in sizes from one kilowatt to several hundred kilowatts output.

Assemblies may be induction brazed in a controlled atmosphere by placing the components and coil in a nonmetallic chamber, or by placing the chamber and work inside the coil. The chamber can be quartz Vycor or tempered glass.

Resistance Brazing

The heat necessary for resistance brazing is obtained from the flow of an electric current through the electrodes and the joint to be brazed. The parts comprising the joint become part of the electric circuit. The brazing filler metal, in some convenient form, is preplaced or face-fed. Fluxing is done with due attention to the conductivity of the fluxes. (Most fluxes are insulators when dry.) Flux is employed except when an atmosphere is specifically introduced to perform the same function. The parts to be brazed are held between two electrodes, and proper pressure and current are applied. The pressure should be maintained until the joint has solidified.

For copper and copper alloys, the copper-phosphorus filler metals are most satisfactory since they are self-fluxing. Silver base filler metals may be used, but a flux or atmosphere is necessary. A wet flux is usually applied as a very thin mixture just before the assembly is placed in the brazing fixture. Dry fluxes are not used because they are insulators and will not permit sufficient current to flow.

Electrodes for resistance brazing are made of high-resistance electrical conductors, such as carbon or graphite blocks, tungsten or molybdenum rods, or even steel in some instances. The heat for brazing is mainly generated in the electrodes and flows into the work by conduction. It is generally unsatisfactory to attempt to use the resistance of the workpieces alone as a source of heat.

The pressure applied by a spot welding machine, clamps, pliers, or other means must be sufficient to maintain good electrical contact and to hold the pieces firmly together as the filler metal melts. The pressure must be maintained during the time of current flow and after the current is shut off until the joint solidifies. The time of current flow will vary from about one second for small, delicate work to several minutes for larger work. This time is usually controlled manually by the operator, who determines when brazing has occurred by the temperature and the extent of filler metal flow.

Dip Brazing

Two methods of dip brazing are molten metal bath dip brazing and molten chemical (flux) bath dip brazing.

Molten Metal Bath. This method is usually limited to the brazing of small assemblies, such as wire connections or metal strips. A crucible, usually made of graphite, is heated externally to the required temperature to maintain the brazing filler metal in fluid form. A cover of flux is maintained over the molten filler metal. The size of the molten bath (crucible) and the heating method must be such that the immersion of parts in the bath will not lower the bath temperature below brazing temperature. Parts should be clean and protected with flux prior to their introduction into the bath. The ends of the wires or parts must be held firmly together when they are removed from the bath until the brazing filler metal has fully solidified.

Molten Chemical (Flux) Bath. This brazing method requires either a metal or ceramic container for the flux and a method of heating the flux to the brazing temperature. Heat may be applied externally with a torch or internally with an electrical resistance heating unit. Suitable controls are provided to maintain the flux within the brazing temperature range. The size of the bath must be such that immersion of parts for brazing will not cool the flux below the brazing temperature. See Figure B-13.

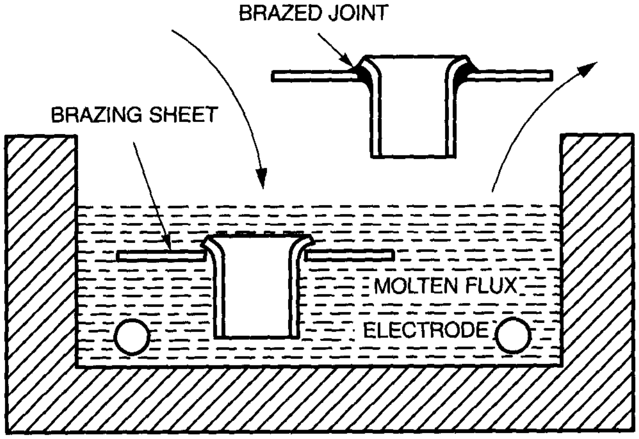


Figure B-13—Illustration of Chemical Bath Dip Brazing

Parts should be cleaned, assembled, and preferably held in jigs prior to immersion into the bath. Brazing filler metal is preplaced as rings, washers, slugs, paste, or as a cladding on the base metal. Preheat may be necessary to assure dryness of parts and to prevent the freezing of flux on parts which may cause selective melting of flux and brazing filler metal. Preheat temperatures are usually close to the melting temperature of the flux. A certain amount of flux adheres to the assembly after brazing. Molten flux must be drained off while the parts are hot. Flux remaining on cold parts must be removed by water or by chemical means.

Infrared Brazing

Infrared brazing may be considered a form of furnace brazing, with heat supplied by long-wave light radiation. Heating is by invisible radiation from high intensity quartz lamps capable of delivering up to

5000 watts of radiant energy. Heat input varies inversely as the square of the distance from the source, but the lamps are not usually shaped to follow the contour of the part to be heated. Concentrating reflectors focus the radiation on the parts.

For vacuum brazing or inert-gas protection, the assembly and the lamps are placed in a bell jar or retort that can be evacuated or filled with inert gas. The assembly is then heated to a controlled temperature, as indicated by thermocouples.

Brazing Filler Metals

Brazing filler metals must have the following properties:

(1) Ability to form brazed joints with mechanical and physical properties suitable for the intended service application

(2) Melting point or melting range compatible with the base metals being joined, and sufficient fluidity at brazing temperature to flow and distribute themselves into properly prepared joints by capillary action

(3) Composition of sufficient homogeneity and stability to minimize separation of constituents (liquation) during brazing

(4) Ability to wet surfaces of base metals and form a strong, sound bond

(5) Depending on requirements, ability to produce or avoid filler-metal interactions with base metals.

To simplify filler metal selection, ANSI/AWS A5.8, *Specification for Brazing Filler Metal,* divides filler metals into seven categories and various classifications within each category. The specification lists products which are commonly used, commercially available filler metals. Other brazing filler metals not currently covered by the specification are available for special applications.

Two sources of further information on brazing are:

American Welding Society, Brazing Handbook, American Welding Society, Miami, Florida. 1991

American Welding Society, The Welding Handbook, Vol.2, 8th Edition. American Welding Society, Miami, Florida. 1991.

BRAZING ALLOY

A nonstandard term for BRAZING FILLER METAL.

BRAZING BLOWPIPE

A device used to obtain a small, accurately directed flame for fine work. A portion of any flame is blown to the desired location by the blowpipe, which is usually mouth operated. See STANDARD WELDING TERMS.

The brazing blowpipe is used for intricate work, such as in dental and jewelry applications. A flame produced by any means may be used. A portion of the flame is blown to the desired location for the required time by the blowpipe.

BRAZING, Carbide Tools

Carbide tool tips used for turning metals on a lathe can be brazed with silver base copper-zinc alloys and copper. Silver alloys containing nickel (B Ag-3 and B Ag-4) are preferred because of their improved wettability. The 85% Ag-15% Mn and 85% Cu-15% Mn alloys are suitable for torch brazing. Carbide tip manufacturers' recommendations for brazing tips should be consulted. Reference: American Welding Society, *Brazing Handbook,* Chapter 30, Carbide Tools, Miami, Florida: American Welding Society, 1994.

Brazing Procedures

In general, brazing procedures are as follows:

(1) Make sure that all joint surfaces on the tip and shank recess are clean. These surfaces can be cleaned by rubbing on silicon carbide abrasive cloth or the flat face of a silicon carbide wheel, then wiping with an organic solvent.

(2) Cut a thin sheet of brazing filler metal to fit into the recess as shown in Figure B-14 (A). An alternate method is to pre-coat all joint surfaces with the braze alloy.

(3) Apply brazing flux (silver or copper) to the shank recess, carbide tip and brazing alloy sheet. Fit the fluxed braze sheet and carbide tip into position on the tool shank.

(4) Apply torch heat to the underside of the shank, as shown in Figure B-14 (B), so the heat will be conducted up to the carbide tip. Use a holding rod to keep the tip in position. Keep the flame in constant motion to avoid hot spots and do not apply it to the tip at any time.

(5) Watch for the flux to become clear and liquid, indicating that the flow temperature of the braze is being approached. Just as soon as the tip can be moved on the molten alloy, withdraw the flame and apply a light pressure with a slight circular motion of the holding rod, to ensure a strong bond and squeeze out excess flux and gas bubbles.

(6) As soon as the braze alloy has solidified, cool the tool slowly in a powdered insulating material, such as mica or lime, to prevent cracking the tip by rapid cooling.

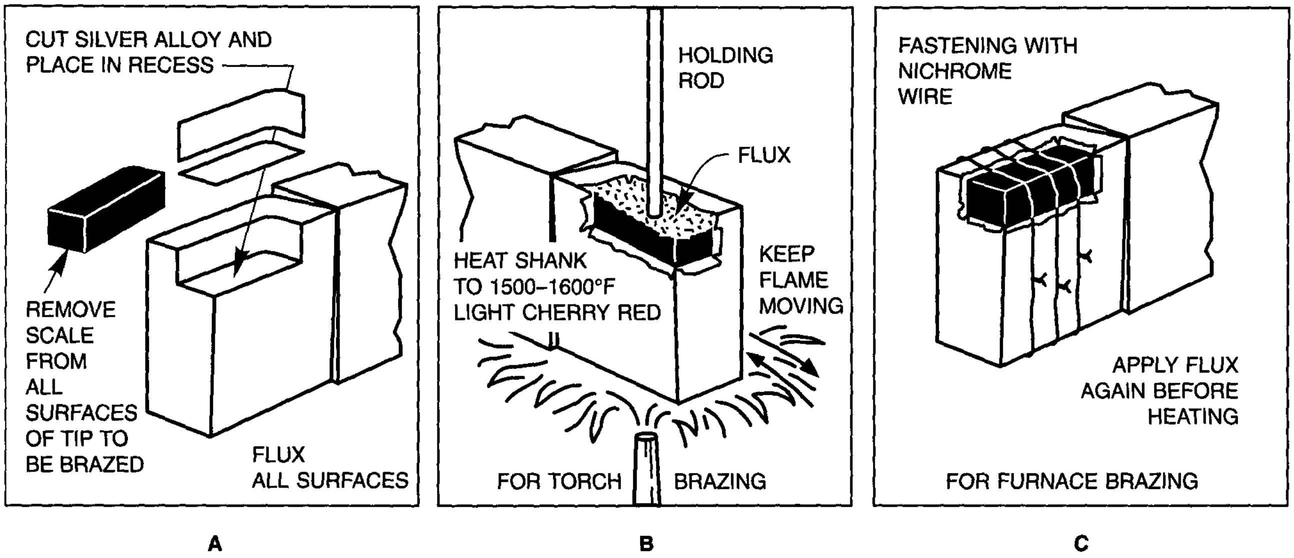


Figure B-14—Steps in the Brazing of Carbide Tipped Tools

An alternate to torch heating is the use of a controlled atmosphere furnace or a closed muffle furnace. For furnace brazing, the assembly should be wrapped tightly with several strands of Nichrome wire as shown in Figure B-14 (C). In a controlled atmosphere, a flux may not be necessary or may be used sparingly.

Sandwich Brazing

The above procedure applies to carbide tips under 18 mm (3/4 in.) width; for tips over this width and irregularly shaped tips, the sandwich procedure is recommended to minimize shrinkage strains. The "sandwich" is made by using a thin sheet of copper or Constantan (40% Ni, 60%Cu alloy) between two layers of the braze alloy. The same procedure described above can be used, except that the torch flame should be applied to the sides of the shank as well as the bottom, and can be applied to the tip itself after the brazing filler metal has melted. *See* SILVER ALLOY BRAZING *and* TOOL BRAZING.

BRAZING, Diffusion Bonding

See DIFFUSION BRAZING *and* DIFFUSION WELDING.

BRAZING FILLER METAL

The metal or alloy used as a filler metal (which fills the capillary joint clearance), which has a liquidus above 450°C (840°F) but below the solidus of the base metal. See STANDARD WELDING TERMS.

BRAZING OPERATOR

One who operates automatic or mechanized brazing equipment. See STANDARD WELDING TERMS.

BRAZING PROCEDURE

The detailed methods and practices involved in the production of a brazement. See STANDARD WELDING TERMS. *See also* BRAZING PROCEDURE SPECIFICATION.

BRAZING PROCEDURE QUALIFICATION RECORD (BPQR)

A record of brazing variables used to produce an acceptable test brazement and the results of tests conducted on the brazement to qualify a brazing procedure specification. See STANDARD WELDING TERMS.

BRAZING PROCEDURE SPECIFICATION (BPS)

A document specifying the required brazing variables for a specific application. See STANDARD WELDING TERMS.

BRAZING PROCESSES

Several brazing processes are classed according to the source of heat. *See* TORCH BRAZING, FURNACE BRAZING, INDUCTION BRAZING, DIP BRAZING, RESISTANCE BRAZING, BLOCK BRAZING, DIFFUSION BRAZING, ELECTRON BEAM BRAZE WELDING, EXOTHERMIC

BRAZING, FLOW BRAZING, INFRARED BRAZING, LASER BEAM BRAZE WELDING, *and* STEP BRAZING.

Brazing processes may also be classed according to the brazing alloy and the brazing temperature range; for example, copper brazing, silver brazing and nickel alloy brazing.

BRAZING SHEET

Brazing filler metal in sheet form. See STANDARD WELDING TERMS.

BRAZING, Silver

A low-temperature brazing process in which the filler metal used is essentially an alloy of silver and copper. *See* SILVER SOLDERING *and* SILVER ALLOY BRAZING.

BRAZING TECHNIQUE

The details of a brazing operation which, within the limitations of the prescribed brazing procedure, are controlled by the brazer or brazing operator. See STANDARD WELDING TERMS.

BRAZING TEMPERATURE

The temperature to which the base metal is heated to enable the filler metal to wet the base materials and form a brazed joint. See STANDARD WELDING TERMS.

BRAZING TEMPERATURE RANGE

The temperature range within which brazing can be accomplished.

BRAZING WIRE

A filler metal of, for example, silver or copper alloy (brass or bronze) used in brazing.

BRIDGING

A term applied to a weld which is made by spanning the weld metal over a groove, leaving a void in the center of the joint. While this weld may have the outside appearance of a good weld, it may actually have low strength.

BRINELL TEST FOR HARDNESS

A test for determining the hardness of metals by applying a known load to the surface of the material to be tested with a hardened steel ball of known diameter. The diameter of the resulting impression in the metal is measured. The Brinell hardness number is calculated as the quotient of the applied load divided by the area of the surface of the impression, which is assumed to be spherical. If P is the applied load (measured in kilograms), D is the diameter of the steel ball (measured in millimeters) and d is the diameter of the impression (measured in millimeters), then

$$\text{B.H.N.} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

in which B.H.N. is the Brinell hardness in kilograms per square millimeter. *See* HARDNESS TESTING.

BRITISH THERMAL UNIT (B.T.U.)

The British Thermal Unit is the quantity of heat required to raise the temperature of one pound of pure water one degree Fahrenheit.

BRITTLENESS

A characteristic of a metal or material that is the opposite of ductility. A brittle material is resistant to formation, not malleable, and easily cracked or broken. Brittle materials exhibit very little permanent deformation before fracture, and overloading in service causes sudden failure. Glass is an example of a brittle material; however, glass is somewhat elastic because it will bend a little and return to its original shape when the load is removed. If overloaded, it will fracture in a brittle fashion.

White cast iron and gray cast iron are examples of brittle metals. Table B-3 lists the order of brittleness of several common elements and metals; (1) is the most brittle and (14) is the least brittle, or most ductile.

Table B-3
Order of Brittleness

(1) White cast iron	(8) Brass
(2) Gray cast iron	(9) Structural steel
(3) Hardened Steels	(10) Zinc
(4) Bismuth	(11) Monel® Metal
(5) Manganese	(12) Tin
(6) Bronzes	(13) Copper
(7) Aluminum	(14) Iron

BRITTLE NUGGET

A nonstandard term used to describe a faying plane failure in a resistance weld peel test.

BRONZE

A large group of copper, zinc, and tin alloys. In general, these constituents are distributed in the following range: copper, 70% to 90%; zinc, 1% to 25%, and tin 1% to 18%. Manganese and phosphorus are sometimes added to act as deoxidizing agents. Bronze alloys have been used since ancient times for making castings, coins, and ornaments.

BRONZE FACING

See BRONZE SURFACING.

BRONZE SURFACING

The deposition of a thin layer of bronze on cast iron or steel to provide corrosion resistance or to reduce sliding friction. Bronze is used to build up worn surfaces to restore them to original size. Bronze surfacing is frequently used to repair pistons, valves, and other sliding surfaces on pumps, engines, and machines.

Many bronze alloys are available. Those of the softer type (phosphor bronzes) are intended to wear more than the mating surface, and the harder type (hard aluminum bronzes) are intended to wear less than the mating surface.

Bronze surfaces can be deposited with the oxyacetylene process; however, most surfaces are deposited by shielded metal arc welding and submerged arc welding. Shielded metal arc welding electrodes are available for use with direct current, electrode positive (DCEP) and alternating current. These are basically flat-position electrodes, but can be used in the vertical position by skilled welders. Electrodes and wires available for these applications are listed in ANSI/AWS A5.13, *Specification for Solid Surfacing Welding Rods and Electrodes.*

Base Metal Preparation

It is important that the base metal and filler metal are thoroughly clean before overlay welding is started. All foreign matter, such as grease, rust, oxides, paint, and other impurities should be completely removed. Both should be free of moisture to prevent porosity in the deposit of aluminum bronze and other bronzes.

Minimum Penetration

Penetration must be minimized when overlaying iron base metals. Excessive dilution of the overlay with base metal, particularly cast iron, may result in a deposit so hard that it is essentially unmachineable.

Deposition by stringer bead is not recommended, because this technique tends to increase penetration and dilution of the deposit with base metal. In general, the largest size electrode consistent with the mass and thickness of the base metal should be used. The electrode should be manipulated in a rapid weaving motion to deposit a bead width three to five times the diameter of the electrode.

In controlling the weave, the operator should take particular care that the molten edges of the bead do not solidify in a way that causes undercutting and entraps slag. This can be avoided by hesitating slightly at the edges of the bead and keeping the frequency of the weave fast enough to maintain a completely molten pool of deposited weld metal. This relatively wide weaving motion also enables the operator to control the molten metal to minimize slag inclusions, impurities and porosity. While the angle of the electrode in relation to the work surface is not critical, inclining the electrode slightly back in the direction of welding will float the molten slag back over the deposited weld metal. This will protect the deposit from oxidation while cooling and prevent the slag from rolling ahead of the weld metal as it fuses with the base metal. It minimizes any tendency for slag inclusions and poor fusion.

Slag Cleaning

All slag should be completely removed from the surface of deposited metal, especially between beads of overlay work and layers of multi-layer deposits. Generally, the deposit should be wire-brushed thoroughly after removing the slag and before making the next deposit. Careful attention to cleaning can avoid slag inclusions and porosity in the weld deposit.

BRONZE WELDING

A nonstandard term when used for BRAZE WELDING.

BRUSHES, Arc Welding Generators

A brush is the sliding connection which completes a circuit between a fixed and a moving conductor. Arc welding generator brushes are designed to function under the conditions of varying output of arc welding.

BRUSHES, Weld Cleaning

Rotary or manual brushes, usually made of stiff wire, are used to remove loose particles of dirt, slag, spatter, and other foreign materials from the weld, to eliminate any possibility of inclusion of these foreign particles in the weld beads. *See* WELD CLEANING.

BUCKLING

Distortion caused by the heat of a welding process. *See* EXPANSION AND CONTRACTION.

BUILDING CONSTRUCTION CODES

The latest edition of the ANSI/AWS D1.1 *Structural Welding Code—Steel* should be used to design, fabricate, inspect, and repair welded steel structures.

The building codes of most cities include a definite standard covering structural welding. Most of these standards have been specified from the ANSI/AWS D1.1 *Structural Welding Code—Steel.* The first AWS Code of this type was published in 1928.

In 1988 the first edition of the Bridge Welding Code, ANSI/AASHTO/AWS D1.5 was published, covering fabrication of steel highway bridges by welding.

The ANSI/AWS D1.1 *Structural Welding Code* does not include such design considerations as arrangement of parts, loading, and computation of stresses for proportioning the load-carrying members of a structure. It is assumed that such considerations are covered elsewhere in a general code or specification, such as the American Institute of Steel Construction (AISC) *Specification for the Design, Fabrication and Erection of Structural Steel Buildings,* or other specifications prescribed by local building codes and by the owner. *See* Appendix 2.

BUILDUP

A surfacing variation in which surfacing material is deposited to achieve the required dimensions. See STANDARD WELDING TERMS. *See also* BUTTERING, CLADDING, BRONZE SURFACING *and* HARDFACING.

Buildup, or padding, refers to metal deposited by an arc welding process in which parallel beads are deposited adjacent to one another, and fused to one another as well as to the base metal. It is used for buildup operations, filling in large cavities when heavy sections are being welded, or forming a shape such as a box or lug by the deposition of weld metal. It is very important that each bead be completely fused to adjacent and underlying passes where several layers of metal are deposited.

Beads are normally deposited parallel to the long dimension of the weld or surface being built up. When building up a vertical surface, it is recommended that a series of beads be deposited across the bottom first, then vertical beads are deposited down from the top to complete the work. If build-up is done on a surface which tapers down to a thin edge, the current must be carefully reduced to avoid destroying the shape of the thin edge.

Two causes of poor results are failing to clean the metal surface thoroughly, and depositing beads too far apart in an attempt to reduce the number of passes required.

BUILD-UP SEQUENCE

A nonstandard term for CROSS-SECTIONAL SEQUENCE. *See also* JOINT BUILDUP SEQUENCE; BLOCK SEQUENCE; *and* LONGITUDINAL SEQUENCE.

BUNSEN BURNER

A gas torch used mainly for laboratory work, in which the combustible gas is mixed with air before the zone of combustion is reached. The air is introduced through a tube at the base of the burner, and the mixture burns at the mouth of the tube with an intense blue flame. The temperature of the flame depends on the type of gas and the pressure used.

BURIED ARC

A CO_2 gas metal arc welding (GMAW) process in which the metal transfer occurs below the surface of the base metal. Relatively high current and voltage are necessary for this welding technique, which is used only for mild steel applications. The welding current depends on the diameter of the wire; for example, a 1.14 mm (0.045 in.) diameter mild steel wire would be run at 400 to 425 amps and 35 to 37 volts. Under such conditions, the arc force digs a crater in the base metal which acts as a crucible for molten metal during welding. *See* GAS METAL ARC WELDING.

BURNBACK

An arc outage in which electrode feed is interrupted. Burnback in gas metal arc welding usually causes the filler wire and the electrical contact tube to melt together. This condition stops the wire from feeding through the contact tube and stops the welding operation. A burnback may cause weld defects. *See* STUBBING.

BURNBACK TIME

A nonstandard term for MELTBACK TIME.

BURNER

A nonstandard term when used for OXYFUEL GAS CUTTER. Also, a name sometimes applied to a welder who does flame cutting.

BURNING

A nonstandard term when used for OXYFUEL GAS CUTTING.

Also, a term applied to metal which is heated sufficiently high, or close to the melting point, to cause permanent damage to the material. The damage may be caused by the melting of some phases, oxidation of some alloying elements, loss of prior heat treatment, or excessive grain growth.

This term has also been used in reference to lead burning and paint burning.

BURNING IN

A nonstandard term for FLOW WELDING.

BURNOFF RATE

A nonstandard term when used for MELTING RATE.

BURNS, Treatment of

Injuries from dry heat, such as a welding flame, are called burns, and those from moist heat (steam) are called scalds. Both are painful, and both are dangerous when extensive or deep. Burns and scalds require medical attention. Shock often follows burns or scalds even when the injury is comparatively slight; it causes death in severe cases.

Relief of pain is the object of treating slight burns, where the skin is reddened but not destroyed. *See* Appendix 12.

BURN-THROUGH

A nonstandard term when used for excessive melt-through or a hole through a root bead. *See* MELT-THROUGH.

BURN-THROUGH WELD

A nonstandard term for a SEAM WELD or a SPOT WELD.

BUS

A shortened term for *Bus Bar.*

BUS BAR

A heavy, (usually uninsulated) bar of electrically conductive material, such as copper or aluminum, which serves as a main electrical conductor in a power plant, building or factory.

BUTANE

(Chemical symbol: C_4H_{10}). A flammable gaseous paraffin hydrocarbon present in petroleum and natural gas, sometimes used in oxyfuel (flame) cutting. Butane is colorless, with a slightly unpleasant odor. Butane is available as a liquefied compressed gas in cylinders. Molecular weight, 58.123; specific gravity 2.110 at 20°C (68°F); liquid density, 4.81 lb/gal at 21°C (70°F); critical temperature, 152°C (305.6°F); critical pressure, 43.3 kPa (6.28 psia). *See* OXYFUEL GAS CUTTING *and* PROPANE.

BUTTERING

A surfacing variation that deposits surfacing metal on one or more surfaces to provide metallurgically compatible weld metal for the subsequent completion of the weld. See STANDARD WELDING TERMS. *See also* BUILDUP; CLADDING, *and* HARDFACING.

Buttering is a form of surfacing in which one or more layers of weld metal are deposited on the groove face of one member (for example, a high alloy weld deposit on steel base metal which is to be welded to a dissimilar base metal).

BUTTING MEMBER

A joint member that is prevented, by the other member, from movement in one direction perpendicular to its thickness dimension. For example, both members of a butt joint, or one member of a T-joint or corner joint. See STANDARD WELDING TERMS. *See* Figure B-15. *See also* NONBUTTING MEMBER.

BUTT JOINT

A joint between two members aligned approximately in the same plane. See STANDARD WELDING TERMS. *See* Appendix 5 (A).

BUTTON

The part of a weld, including all or part of the nugget, that tears out in the destructive testing of spot, seam, or projection welded specimens. This term is sometimes applied to a spot weld nugget. See STANDARD WELDING TERMS.

BUTTON WELDING

A term applied to gas metal arc spot welding.

BUTT RESISTANCE WELD

The two modes of resistance butt welding are flash welding and upset welding. In flash welding, pieces having essentially the same cross section are brought together slowly, and an electrical voltage is applied. On contact, heating and flashing occur and continue as the pieces move together, until the entire cross section is molten. At this time the pieces are forced together under pressure to squeeze out the molten metal.

In upset welding, pieces of essentially the same cross section are brought together under pressure; then voltage is applied, causing electric current to flow, heating the contact area. Current flow and pressure continue until the joint area is heated to the plastic range and a hot forge type weld is formed. No melting

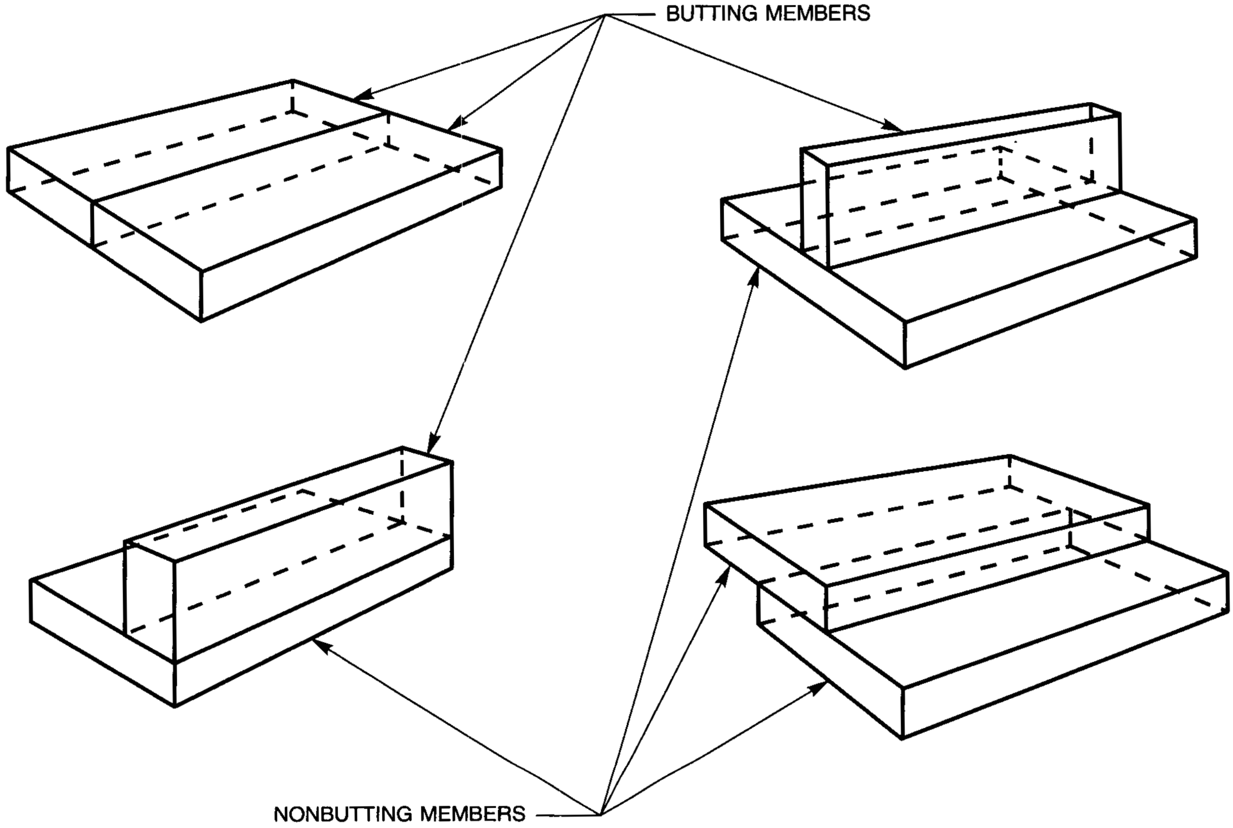


Figure B-15—Butting and Nonbutting Members

occurs in this type of weld. *See* RESISTANCE WELDING, FLASH WELDING, *and* UPSET WELDING.

BUTT WELD

A nonstandard term for a weld in a butt joint.

A butt weld is one in which two plates, surfaces, or bars are brought together edge to edge, or end to end, to form a seam or junction, and welded. Two butt-welded plates form a flat plane; two bars butt-welded form a single straight bar.

BY-PASS

A passage in a cutting torch connecting the oxygen supply and the preheating oxygen tube.

C

C.G.S.

Abbreviation for centimeter-gram-second units; the centimeter is the unit of length, the gram is the unit of weight, and the second is the unit of time.

C.P.

Abbreviation for constant potential. *See* CONSTANT VOLTAGE POWER SOURCE.

CABLE AND CABLE CONNECTORS

Two cables, an electrode cable and a workpiece cable, are required to complete the electrical circuit between the welding machine and the workpiece. The correct size and the quality of cable are basic to welding operations. If the cable is too small for the current, it will overheat and could cause rapid deterioration of the cable insulation. It will also cause a voltage drop which could affect the welding conditions.

Copper Cable Construction

The cable most frequently chosen for welding applications is a neoprene-covered, multiple-strand copper cable specifically developed for welding service. Neoprene, a synthetic rubber, is used as the outer jacket because of its superior toughness, flexibility, and resistance to heat, abrasion, and oil or grease.

Size of Workpiece Cable

In arc welding, the work forms part of the electrical circuit, so it is essential that the workpiece cable be the same size as the electrode cable. The workpiece cable does not need to be as flexible as the electrode cable, since it stays in one spot most of the time.

The shortest cable possible should be used. If the distance from the machine is too great, the voltage drop becomes so large that it affects the amount of electrical energy transmitted to the welding arc. If the work has to be located at a considerable distance from the welding machine, it is important that the connecting cable be larger in diameter than if the distance is short. The cable size must be selected for length as well as amperage. Table C-1 shows recommended copper cable sizes for distances from 7.5 to 38 m (25 to 125 ft) from the welding machine (distance = total length of electrode and workpiece cables divided by two) and currents from 100 to 600 amp.

Aluminum Cable

One of the advantages of aluminum cable is that it weighs less than half that of copper, although the diameter must be about 30% larger to compensate for its greater resistivity.

If the duty cycle is medium to high, a good rule of thumb is to increase the size of aluminum cable by one size or number of the American Wire Gauge (AWG) rating over the size of copper cable normally used. As an example, if 1/0 copper cable is used for an application, it can be replaced by 2/0 aluminum cable.

Table C-1
Recommended Copper Welding Cable Sizes

Power Source		AWG Cable Size for Combined Length of Electrode and Workpiece Cables				
Rating in Amperes	Duty Cycle %	0 to 15 m (0 to 50 ft)	15 to 30 m (50 to 100 ft)	30 to 46 m (100 to 150 ft)	46 to 61 m (150 to 200 ft)	61 to 76 m (200 to 250 ft)
100	20	6	4	3	2	1
180	30	4	4	3	2	1
200	60	2	2	2	1	1/0
300	60	1/0	1/0	1/0	2/0	3/0
400	60	2/0	2/0	2/0	3/0	4/0
500	60	2/0	2/0	3/0	3/0	4/0
600	60	2/0	2/0	3/0	4/0	*

*Use two 3/0 cables in parallel.

To obtain the lowest resistivity, electrolytic aluminum is used for welding cable. This grade of aluminum cable is only half as strong as copper, so to achieve the same flexibility and resistance to breaking, the aluminum wire is semi-annealed, while the copper wire can be dead soft.

To assure a good connection, it is important to thoroughly clean the aluminum conductor prior to making either a soldered or mechanical joint.

Connections

Every welding circuit has at least four cable connections and possibly more. All are extremely important. If a cable connection is inadequate, the resulting voltage drop in the electrical circuit will affect the quality of welding as seriously as an inadequate cable.

The four necessary connections are those connecting the two cables to the welding machine; cable to a device for the electrode to receive the welding current; and cable to workpiece clamp.

Many of the difficulties encountered in welding can be traced to the workpiece cable. If a welder attempts to "get by" with an inefficient contact between the workpiece cable and the workpiece, the result will be unsatisfactory welding and lost time.

Although there are several ways in which the workpiece cable can be connected to the work, the prime requisite is to ensure a positive means of contact. Regardless of which connection is used, it must provide suffcient contact surface held firmly in place to complete the electrical circuit. Cleanliness of the contact area is of utmost importance. A dirty contact can allow arcing between the workpiece connector and the work, which not only heats the workpiece connection, but results in poor arcing characteristics between the electrode and the work.

The welding machine frame should be connected to an earth ground, or a person accidentally touching it may receive a noticeable shock. The cable connecting the power supply frame to ground should not be confused with the workpiece cable and its connection.

Checking Power Loss

Voltage drops due to poor connections in a welding circuit may also show up in the welding machine, misleading the welding operator by disguising the exact source of trouble. Before assuming that a welding machine is at fault, the operator should check the cable and cable connections to assure that they are tight. Loose connections in the machine, or overloaded usage, can cause a transformer winding or insulation to burn. A visual inspection of the entire welding circuit should be made to check for cable breaks or shorts, followed by checking the lugs and terminals bolted to the machine studs for tightness and possible corrosion at the contact points.

CADMIUM

(Chemical symbol: Cd). A malleable, ductile, toxic, bivalent metallic element added to plating to protect against corrosion, and used in bearing metals. It is also used in low-friction alloys, solders, brazing alloys, and nickel-cadmium storage batteries. Cadmium is found in nature as a carbonate or sulphide of certain zinc ores. Cadmium has an atomic weight of 112.41; atomic number, 48; specific gravity, 8.65; melting point, 321°C (610°F).

CADMIUM FUMES

See WELDING FUMES.

CALCIUM

(Chemical symbol: Ca). A silvery, metallic element that occurs in nature in shells, limestone and gypsum. In the field of welding, calcium is commonly associated with carbon to form calcium carbide. Calcium has a strong affinity for oxygen and becomes coated with an oxide film when exposed to air. When heated in nitrogen, it forms calcium nitride. It decomposes readily in water with the evolution of hydrogen and formation of calcium hydroxide. Atomic number, 20; atomic weight, 40.07; melting point, 810°C (1490°F); specific gravity, 1.54.

CALCIUM CARBIDE (CaC_2)

Historical Background

In 1836, English chemist Edmund Davy observed that a by-product incidental to the production of potassium decomposed water and produced a gas which contained acetylene. In 1862, a German chemist, Wohler, discovered that acetylene could be produced from calcium carbide which he had made by heating a mixture of charcoal and an alloy of zinc and calcium to a very high temperature. Like Davy's material, it decomposed water and yielded acetylene. He also reported that the ignited gas produced a brilliant, smoky flame. But it was a French chemist, Berthellot, who in 1862 thoroughly described the reactions. Unfortunately, for the next thirty years only a few chemists observed the acetylene flame, and none of them saw any commercial potential.

However, with the development of the electric arc furnace, Thomas Willson, an electrical engineer in Spray, North Carolina, attempted to produce metallic calcium from lime and coal tar. Instead of calcium metal, he produced a dark molten mass which cooled to a brittle solid. When he discarded it in a stream, a large quantity of gas was suddenly liberated. On being ignited, the gas produced a bright but smoky flame. It was not the clean hydrogen flame which would have been produced by the reaction of calcium and water, but obviously because of the soot, was a rich hydrocarbon. Repeating the smelt and analyzing the solid, which showed it to contain calcium carbide, Willson sent a specimen with a letter to Lord Kelvin in Glasgow on September 16, 1892. This dated document secured Willson the honor of being the first to produce calcium carbide on a commercially promising scale.

During the same time, others in French and German laboratories had been studying and describing carbides, but none were able to produce them on a commercial scale. Thus, as the result of an accident, the industrial possibilities of calcium and acetylene were recognized for the first time. The practicality of using acetylene as a means of illumination was demonstrated in 1892, and with the establishment of the Willson Illuminating Company in Spray, in the spring of 1895, the first factory to manufacture calcium carbide came into being.

Calcium Carbide Production

Calcium carbide is produced in electric arc furnaces which attain temperatures of about 2760 to 3900°C (5000 to 7000°F). The arc established between two electrodes is used to heat a mixture of lime and coke, causing the following changes to occur:

$$CaO + 3C \rightarrow CaC_2 + CO$$

Quicklime + coke yield calcium carbide + carbon monoxide

To obtain high quality acetylene, it is necessary to use quicklime that is essentially 99% pure, and low-ash coke. The phosphorus and sulfur levels of both must also be very low.

The solidified calcium carbide resembles dark brown or black or bluish black stone; its density is 2.24 times greater than water. It will not burn except at very high temperatures in the presence of oxygen. It is not affected by organic solvents and it is unaffected by shock. It can be stored indefinitely if sealed from air. It is odorless, but gives off a smell due to the presence of small amounts of acetylene produced by the interaction of moisture in the air. In the presence of that moisture, it slowly slakes to a dry lime.

Gas Production

The value of calcium carbide comes from the reaction which occurs when placed directly in contact with water according to the following equation:

$$CaC_2 + 2\,H_2O \rightarrow Ca(OH)_2 + C_2H_2$$

Carbide + water yield slaked lime + acetylene

One kg (2.2 lb) of calcium carbide will produce 0.33 m^3 (11.5 ft^3) of acetylene at room temperature.

CALESCENT

See CURIE POINT.

CALORIE

A unit of heat. The amount of heat required to raise the temperature of one gram of water one degree Celsius.

CALORIZING

A process of coating a metal with a fine deposit of aluminum similar to galvanizing with zinc. It is used primarily as a means of protecting steel from oxidation at elevated temperatures, rather than from the more familiar types of corrosion.

CAP

A nonstandard term for the final layer of a groove weld.

CAPACITANCE

The property of an electric non-conductor that permits the storage of energy as a result of electric displacement when opposite surfaces of the non-conductor are maintained at a difference of potential.

CAPACITOR

A condenser. An element of an electrical circuit used to store charge temporarily; the primary purpose is to introduce capacitance in an electric circuit. It usually consists of two metallic plates separated by a dielectric.

CAPACITOR DISCHARGE STUD WELDING

See ARC STUD WELDING.

CAPACITY

The capability of holding or carrying an electric charge. Capacity is measured in farads or microfarads.

CAPACITY REACTANCE

The measure of the opposition to the passage of alternating current through a condenser as expressed in ohms.

CAPILLARY ACTION

The force by which liquid, in contact with a solid, is distributed between closely fitted faying surfaces of the joint to be brazed or soldered. See STANDARD WELDING TERMS.

Capillary action is the phenomenon by which adhesion between the molten filler metal and the base metals, together with surface tension of the molten filler metal, distribute the filler metal between parts of the brazed or soldered joint.

CARBIDE

A binary compound of the element, carbon, with a more electropositive element.

Among the commercially important carbides are silicon (i.e., the abrasive, Carborundum), iron (the strengthening constituent in steel), and calcium (used to produce acetylene). As a class, they are hard, opaque solids. *See* CALCIUM CARBIDE.

CARBIDE TOOLS

See BRAZING, CARBIDE TOOLS.

CARBON

(Chemical symbol: C). A nonmetallic element that occurs in many inorganic and all organic compounds. An element of prehistoric discovery, carbon is widely distributed in nature. It is found native in diamond and graphite, and as a constituent of coal, petroleum, asphalt, limestone and other carbonates. In combination, it occurs as carbon dioxide and as a constituent of all living things. Carbon is unique in forming an almost infinite number of compounds. It has an atomic weight of 12; atomic number, 6; melting point, above 3500°C (6300°F); specific gravity, amorphous 1.88, graphitic 2.25, diamond 3.51.

The addition of carbon to iron produces steel; carbon is the principal hardening agent in steel. In most cases, alloy steels containing carbon up to about 0.20% are considered easily weldable. Alloy steels containing over 0.20% carbon are generally considered heat-treatable steels, and are heat treated by quenching and tempering to obtain the best combinations of strength and toughness or ductility. In some cases, these steels are used in the as-rolled condition. As the principal hardening element in most alloy steels, carbon controls the strength and hardness of the steel, while alloying additions are used to increase hardenability and improve toughness.

CARBON ARC BRAZE WELDING (CABW)

A braze welding process variation that uses an arc between a carbon electrode and the base metal as the heat source. See STANDARD WELDING TERMS.

CARBON ARC BRAZING

A nonstandard term for TWIN CARBON ARC BRAZING.

CARBON ARC CUTTING (CAC)

An arc cutting process that uses a carbon electrode. See STANDARD WELDING TERMS.

Carbon arc cutting is primarily used for foundry work and in scrap yards. In carbon arc cutting, the intense heat of the arc melts a crevice through the parts being cut. A jagged cut results. In addition to the irregular appearance of the cut, considerable metal is wasted due to the width of the cut. Carbon arc cutting has largely been replaced by air carbon arc cutting. *See* AIR CARBON ARC CUTTING.

CARBON ARC WELDING (CAW)

An arc welding process that uses an arc between a carbon electrode and the weld pool. The process is used with or without shielding and without the application of pressure. See STANDARD WELDING TERMS. *See also* BENARDOS PROCESS, GAS CARBON ARC WELDING, SHIELDED CARBON ARC WELDING, *and* TWIN CARBON ARC WELDING.

Carbon arc welding is, for all practical purposes, an obsolete process. Like the gas-tungsten arc process (GTAW), it uses non-consumable electrodes, either carbon or graphite. Unlike GTAW, however, the electrodes erode rapidly. And unlike GTAW, which has the great advantage of inert gas shielding, fluxes were often used to protect the weld metal and some of the filler wires used were coated with suitable fluxes. Carbon contamination is a potential problem and must be carefully avoided when igniting the arc with a scratch start, or by accidental contact while using very short arcs. Because of the poor shielding and potential for carbon contamination, the process was used most frequently for welding copper and its alloys, and cast irons.

Historical Background

Carbon arc welding is presently used only to a very limited extent, but much was learned about shielding during the early development of arc welding (circa 1925) when CAW was popular.

Welders using the carbon arc to fusion-weld iron and steel learned to control the nature of the welding atmosphere by resorting to simple methods. As an example, the oxidizing effect of air aspirated into the arc was reduced by inserting a string of combustible material into the arc alongside the electrode to combine with at least some of the oxygen in the arc area. If the string consisted of tightly rolled-up paper, it burned to form water vapor and carbon dioxide, both of which are more protective of the molten steel than oxygen. The string was fed into the upper part of the arc, the narrowest part which contained the largest amount of air. By removing a large portion of the uncombined oxygen from the arc, the combustible material sometimes permitted welding to be performed without a flux. When more effective protection was needed in carbon arc welding, the string of combustible material was impregnated with slag-forming ingredients. As the string burned, these ingredients melted and performed their functions right at the point where they were most needed. The nature of the slag and flux varied with the metal being welded. For steels, minerals such as clay and asbestos were used for forming the slag, and fluorspar was favored as the flux. From this simple beginning, shielding the arc with gases and protecting the molten metal with slag and flux developed into a highly refined and complex technology. Reference: George E. Linnert, *Welding Metallurgy,* Vol. 1, 4th Edition, 722-23. Miami, Florida: American Welding Society, 1994.

CARBON ARC WELDING, Shielded

A carbon arc welding process in which the molten filler and weld metal are effectively protected from the air by a supplementary shielding gas.

CARBON BLOCKS AND PASTE

Carbon in the form of blocks, rods and carbon compositions, or paste, have been used to support the workpiece in welding operations. Carbon sheets or blocks are available in various sizes, and can be shaped as needed.

In a joining operation, the parts to be welded may be small and must be jointed at such an angle that much time and patience is required to fit up the parts before the actual welding can begin. Often, just as the welding torch is applied, the parts which have been balanced very sensitively are blown apart, and they are much too hot to pick up and re-position without first allowing them to cool. This sequence may occur three or four times before the welder is successful in fusing the two parts.

This type of job can be simplified by imbedding the ends of the parts to be joined in carbon paste to maintain alignment. Just two daubs of carbon paste on top of a fire brick are adequate to hold most parts in the correct position. The welding can then be done in a minute or two, thus saving much time and frustration. See BACKUP BARS AND PLATES.

CARBON DIOXIDE

(Chemical formula: CO_2). A colorless, odorless, noncombustible gas used in several welding processes; supplied in cylinders, shipped at its vapor pressure of 5722 kPa (830 psig) at 21°C (70°F). Molecular weight: 44.011; specific gravity: 1.522 at 21°C (70°F); critical pressure: 1183 kPa (171.6 psia).

CARBON DIOXIDE WELDING

Carbon dioxide is used either alone or as an additive to argon in shielding gases used with the gas metal arc welding (GMAW) process when fabricating steels.

Solid Wire GMAW

When CO_2 is used alone for shielding with solid filler wires, the arc tends to produce excessive spatter unless it is kept very short. To avoid porosity, the filler wires must be specially deoxidized. However, when the arc length is properly controlled, the gas offers many advantages, such as high welding speeds, deep penetration and low cost. For these reasons, it is often the gas of choice, particularly for mechanized applications. Its use is restricted to mild steels, because both carbon and oxygen pick-up in the welds can be problems with stainless steels or low-alloy steels when toughness or control of weld composition are requirements.

Carbon dioxide is also used as an additive to argon. A mixture of 25% CO_2 and 75% argon is used to improve the arc stability and weld quality for the short circuiting modification of the GMAW process. Lower amounts, 6% to 8% CO_2, are used with argon to stabilize the spray transfer mode when welding carbon steels and low-alloy steels. Still lower concentrations of 1% or 2% CO_2 are used to stabilize the spray arc mode when welding stainless steels.

Flux-Cored Arc Welding

The effects of CO_2 on the welding arc and control of weld deposit composition are completely different when CO_2 is used to shield flux-cored wires. Because of arc stabilizers in the wire cores, the arcs can be very stable and free of spatter. Also, carbon pick-up can be controlled, allowing the gas to be used alone to deposit acceptable welds in stainless steels. However, since better control of the arc and carbon is obtained by using a mixture of 25% CO_2 and 75% argon, this mixture is frequently used for shielding cored wires.

CARBON ELECTRODE

A nonfiller metal electrode used in arc welding and cutting, consisting of a carbon or graphite rod, which may be coated with copper or other materials. See STANDARD WELDING TERMS.

CARBON ELECTRODE HOLDER

Any form of holder for gripping carbon or graphite electrodes of 12 to 38 mm (1/2 to 1-1/2 in.) diameter. *See* ARC WELDING.

CARBON ELECTRODE PROCESS

See BENARDOS PROCESS *and* ARC WELDING.

CARBON EQUIVALENT

Carbon is the most important of all alloying additions to steels because of the effects it produces on the microstructure as the welds cool from the very high temperatures associated with the deposition of weld metal. This applies as much to the heat-affected zone (HAZ) of the plate as it does to the weld metal. In addition, when carbon equivalents are of concern, they are generally related to the HAZ.

Two of the most troublesome problems associated with fabricating steels are hydrogen-induced cracking and poor toughness or ductility. Both are aggravated by a microstructure called martensite. Since martensite is very hard, its presence can be inferred by measuring the hardness of the HAZ, particularly in the coarse-grained regions which are close to the weld deposit. Carbon has a profound and direct effect on hardness. Other alloying elements also affect hardness, although not to the same degree. In total, they affect the facility with which a given hardness can be obtained in an alloy steel. This is called hardenability.

However, the most important use of this concept has not been in predicting hardness, but predicting the minimum preheat temperature needed to avoid the formation of the hard martensite. Since martensite is produced at higher cooling rates, anything that can be done to reduce cooling rates can be beneficial toward avoiding that microstructure or a high hardness. Preheat is important because it has a very strong effect on the rate at which welds cool. Weldability, energy input and cooling rates are important variables.

Investigators have measured the effects of alloy content on the preheat temperatures needed to prevent hydrogen-induced cracking or poor toughness, and have determined the relative importance of the alloying elements on that temperature. This is another measure of carbon equivalence (CE). One example follows:

$$\mathrm{CE} = \mathrm{C} + \frac{\mathrm{Mn} + \mathrm{Si}}{6} + \frac{\mathrm{Cr} + \mathrm{Mo} + \mathrm{V}}{5} + \frac{\mathrm{Ni} + \mathrm{Cu}}{15}$$

The minimum preheat temperature needed to avoid hydrogen-induced cracking has been shown to have a value of:

$$\mathrm{PHmin} = 200\,\mathrm{CE} - 20$$

where PH is preheat temperature in degrees Celsius.

CARBON, Free

See CARBON.

CARBON GRADIENT

Carbon gradient is the variation in carbon content from the external face of a carburized metal article to the unaltered core. A steep gradient is to be avoided whenever possible. A reverse form of carbon gradient (lowest carbon content near the outer shell) is produced by decarburization.

CARBONIZATION

Coking or driving off the volatile matter from fuels such as coal and wood. (Carbonization should not be confused with carburizing.)

CARBONIZING FLAME

See CARBURIZING FLAME.

CARBON MONOXIDE

(Chemical formula: CO). A colorless, odorless, toxic gas formed by the incomplete combustion of carbon or carbon compounds. Carbon monoxide fumes may result from welding operations, and the welding operator must avoid breathing them. If natural ventilation is not adequate to remove the fumes, a suction system should be placed near the source to evacuate them.

Molecular weight: 28.010. Specific gravity: 0.968 at 21°C (70°F). Critical temperature: –140.2°C (–220.4°F); critical pressure: 3499.2 kPa (507.5 psia). It condenses into a liquid which boils at –192°C (–314°F) and solidifies at –206°C (–339°F).

CARBON STEEL

A steel containing various percentages of carbon. The classification "carbon steel" is generally accepted for all commercial irons and plain steels. Low-carbon steel is defined as having a maximum of 0.15% carbon content. Mild steel is described as having 0.15 to 0.35% carbon. Medium-carbon steel contains 0.35 to 0.60% carbon, and high-carbon steel contains from 0.60 to 1.0% carbon.

Carbon primarily controls the response of steel to hardening heat treatments; however, other alloying elements such as manganese, silicon, sulfur, and copper may be added. These elements may impart properties to the steel that are also important.

CARBON TEMPER

See TEMPER CARBON.

CARBORUNDUM

A trade name for a silicon carbide abrasive.

CARBURIZING

Adding carbon to the surface of iron-base alloys by heating the metal below its melting point while in contact with carbonaceous solids, liquids or gases.

CARBURIZING FLAME

A reducing oxyfuel gas flame in which there is an excess of fuel gas, resulting in a carbon-rich zone extending around and beyond the cone. See STANDARD WELDING TERMS. *See* Figure A-1. *See also* NEUTRAL FLAME, OXIDIZING FLAME, *and* REDUCING FLAME.

In an oxyacetylene flame, a carburizing flame is one in which there is an excess of acetylene. The flame has a sharply defined inner cone and a bluish outer flame, but between these, surrounding the cone, is an intermediate white cone. The length of this intermediate or excess-acetylene cone may be considered to be a measure of the amount of excess acetylene in the flame. This flame is sometimes called *excess acetylene*, or *reducing*.

A carburizing flame is used in hardfacing and similar processes to obtain a fusion or bond between base metal and weld metal without deep melting of the base metal.

CARRIER GAS

The gas used to transport powdered material from the feeder or hopper to a thermal spraying gun or a thermal cutting torch. See STANDARD WELDING TERMS.

CASCADE SEQUENCE

A combined longitudinal and cross-sectional sequence in which weld passes are made in overlapping layers. See STANDARD WELDING TERMS.

A welding sequence developed in shipyards to minimize the defects that might be caused by thermal cracking in the root pass. Subsequent beads are stopped short of a previous pass, creating a cascade effect. *See* BLOCK SEQUENCE WELDING.

CASCADE WELDING

See CASCADE SEQUENCE.

CASE

A thin layer of metal just below or at the surface of a plate with distinctively different structure or properties from the main body or core.

CASE HARDENING

Case hardening involves either carburizing or nitriding the surface of iron-base alloys to increase wear resistance. This is commonly accomplished in heat-treating furnaces with the parts immersed in appropriate sources of those elements. However, for small, noncritical jobs, it is possible to carburize parts with a welding torch.

The method requires a strongly carburizing flame, which is used to heat the surface to be hardened. It is best to use the white cone of the flame. The rate of carburization can be accelerated by turning the oxygen off occasionally, allowing a carbon soot to form on the surface. The depth of the case is determined by the time the part is heated and the maximum temperature achieved. Melting should be avoided. Hardening is assured by quenching the parts in water immediately after being treated.

CASSETTE

A light-proof holder to contain the sensitive film used during exposure to X-rays or gamma rays in weld inspection.

CAST BRASS

A form of brass generally known as common brass. It may contain up to 75% copper, but the average composition is two parts of copper to one part zinc. Cast brass often contains a small amount of lead.

CASTING STRAINS

Strains accompanied by internal stresses resulting from uneven solidification and uneven cooling of a casting and the relief of such stresses by yielding.

Such strains are similar to welding strains which result from the solidification and cooling of weld metal.

CAST IRON

A large family of alloys, generally containing more than 2% carbon and between 1% and 3% silicon. Unlike steels, they are not malleable when solid, and most have low ductility and very poor resistance to impact loading. However, cast irons are very useful when intricate or inexpensive castings are required, and they provide a high damping capacity (the ability of a material to absorb vibration) which can be important for precision machinery. Cast irons have a low melting temperature, are very fluid when molten, and shrink very little during solidification.

Unlike steels, cast irons contain free graphite grains, and it is the shape and distribution of the free graphite grains which have the strongest effect on the properties of the cast iron. Also important is the matrix in which they occur. The microstructure of the matrices depends on the alloys present in the metal, and the rate at which it solidifies and cools. If this sequence is very rapid, the dissolved carbon does not have enough time to nucleate as graphite during solidification; while the matrix transforms to harder microstructure. Subsequent heat treatments are also important to temper the very hard structures.

Silicon is added to cast iron primarily to control the solubility of carbon, and therefore the characteristics of the graphite. Additionally, silicon serves as a deoxidizer, promotes fluidity, and decreases shrinkage. Sulfur might be present in the alloy but is not added intentionally, since it causes hot cracks and can produce porosity if present in high concentrations. Phosphorous is also undesirable, because it produces a hard, brittle compound; its low melting temperature contributes to hot-cracking problems. However, phosphorous increases the fluidity of these irons, which is a desirable characteristic when casting very thin sections. Manganese is added to tie up the sulphur as a high-melting compound in order to reduce the problem of hot cracking. Manganese is also used to control the microstructure of welds, improving the strength and ductility as well as machinability.

Types of Cast Irons

The four basic types of cast iron are gray, white, ductile, and malleable.

The gray cast irons contain flake graphite, which imparts a gray surface in fractures, and are the most common of the cast irons. The gray irons are readily machinable.

The white cast irons exhibit crystalline, whitish fractures because the carbon remains in solution during solidification, producing massive carbides in a pearlitic matrix. They are very brittle and hard, but very wear-resistant.

The ductile irons are also known as nodular irons. They contain alloys which cause the graphite to nucleate as spheres. These nodules are encased in a layer of ferrite and are in a pearlitic matrix, making them very ductile. Some nodules exhibit elongations of up to 18%.

Malleable cast irons are produced by heat treating specially alloyed white cast irons. Heat treating results in the development of graphite nodules (temper carbon) in a ferrite matrix. Malleable cast irons are used when good strength, toughness, and casting and machining properties are required.

CAST IRON, Arc Welding

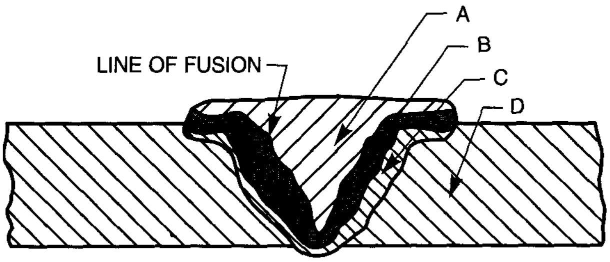
Most welds in cast irons are made with an arc welding process such as shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW). The high energy concentration associated with these processes allows highly localized fusion of both the cast irons and the electrodes. But this results in high cooling rates and localized thermal expansion, neither of which is desirable. Even so, reliable, high-quality welds can be produced when proper procedures and suitable filler metals are used. Prior to the development of the SMAW processes, the carbon arc welding (CAW) process was used extensively for welding cast irons. Few, if any, shops still consider CAW as a viable technique.

Welding Considerations

Because of the considerable differences in the composition and microstructure of the cast irons, it is essential to identify the type of cast iron before welding begins. Some insight about the type of iron can be determined from the appearance of fractures, an examination of the microstructure, or from hardness measurements. A chemical analysis would also be helpful. When no information is obtainable, the iron could be assumed to be gray cast iron because of its general use, and the procedures selected on that basis.

The selection of the filler metal, the energy input, and the preheat are very important to successful welding. Selection of the welding process is also important in establishing the procedures and materials to be used.

When welding cast iron with a steel electrode, there are four important zones in the vicinity of the weld: the weld metal area, the alloyed weld metal zone, the heat-affected zone, and the original cast iron. *See* Figure C-1. In C-1, Section A is deposited steel, unaffected by dilution. Section B is also steel deposited from the electrode, but changed from a soft steel to a rather high-carbon steel. This is due to alloying with carbon from the cast iron.



A — Steel deposited but unaffected.
B — Steel deposited and hardened by absorption of carbon.
C — Cast iron which has been hardened.
D — Original cast iron.

Figure C-1—Steel Electrode Deposit on Cast Iron

Cast iron which was brought up to melting temperature, then chilled by the cold mass of the casting, is shown as Section C, the heat-affected zone. The result is a metal which is extremely hard and brittle. This hardening is due to rapid cooling, which prevents the iron carbide from changing into iron and graphite. The metal in this area is white iron; the controlling component is cementite.

Section D is the original cast iron.

Failure of a welded joint of the type shown in Figure C-1 will usually occur in the cast iron adjacent to the line of fusion, because the hardened cast iron is more brittle than the high-carbon steel on the steel side of the line of fusion.

A specific reference is ANSI/AWS D11.2, *Guide for Welding Iron Castings*, published by the American Welding Society.

Preheat

Preheating to slow the rate at which the welds cool is important to the success of welding cast irons. It is not a question of whether to use preheat or not, but what the temperature should be, and how it should be distributed. Preheat prevents cracks caused by thermal stresses, reduces residual stresses, distortion, and hardness in the HAZ. It burns off undesirable organic contaminants such as oils and greases. As a general rule, to prevent cracking, the minimum preheat temperature should be about 40°C (100°F) for malleable irons; between 150 and 260°C (300 and 500°F) for gray irons, depending on the alloy content; between 200 and 315°C (400 and 600°F) for ductile irons, depending on the alloy content, and above 315°C (600°F) for white irons to prevent the formation of martensite. The filler metal is an important consideration in preheating, with lower temperatures being acceptable with weaker welds. The temperature selected and the distribution of heat within a casting are also dependent on the complexity of the shape and size of the casting, (with the more complex shapes and larger sizes requiring more heat), and the need to produce compressive stresses in the vicinity of the weld joint. Slow cooling of the casting after welding is also necessary. Very slow cooling can be accomplished by burying the casting in sand or other material or, at the very least, covering it with a heat resistant fabric to minimize radiation and convective cooling.

Thermal Stresses

When a section of metal is heated or cooled, the expansion or contraction which takes place will produce stresses. This can be visualized by comparing this effect to that produced by driving a wedge between the sections at the point of heat application. The greatest stress is exerted at a time when the metal is just below the point of fusion, or at the time contraction has taken place. The effect of these stresses is illustrated in Figure C-2. Assume that Item 1 is to be welded at the point marked "W" and that the casting section at the point of welding is 13 by 2.5 cm (5 by 1 in.). An application of welding heat at the point "W" continues to expand the metal at this point until a point just below the fusion is reached. This expansion causes the free end to move outward in order to accommodate the greater bulk of material at the weld, just as if a wedge were being driven into the metal. After the metal solidifies, this greater bulk begins to recede or contract and continues to do so until a point is reached at which the casting has cooled to ambient temperature. With this contraction there is a corresponding movement of the free end of the casting. If, instead of the casting having the flat section shown in Item 1, it takes the form of that shown in Item 2, where

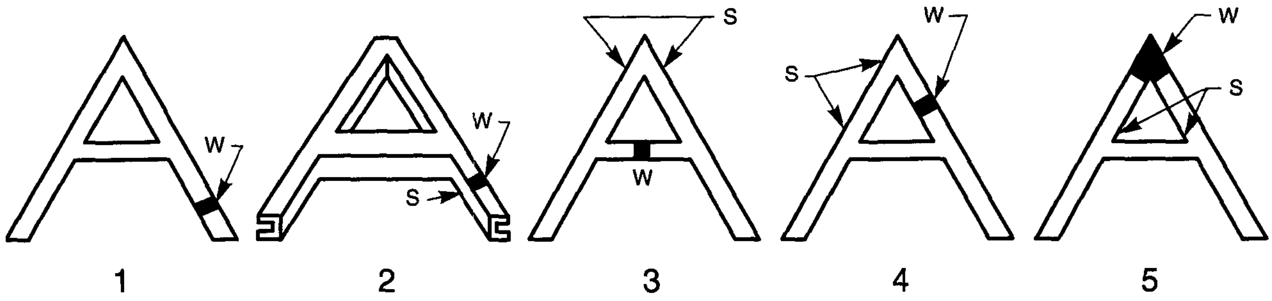


Figure C-2—Stresses Set Up During Welding

the leg section is similar to three sides of a square, the leg, instead of being free to move, is held more rigidly, causing considerable strain on the lower side of the section and opposite the weld.

Contraction Strains. On cooling, contraction takes place as in the previous example, causing a severe strain in the lower section. If the casting is solid and the section so heavy that the welding heat does not penetrate all the way through, there is the same expansion and contraction with the accompanying stresses and strains which often result in warpage and breakage. Items 3, 4 and 5 in Figure C-2 show similar examples; the points "W" representing the places of welding and the points "S" where the greatest strain is exerted. Breakage from expansion and contraction stresses does not always occur at the point of greatest stress application, but at a point where the strength of the section is less than that required to withstand the stress applied at that point. An example of this is shown in Item 3, where the weld is made in the cross member between the legs, and the strain is distributed about the apex of the angle formed at the junction of the legs. If the section of the apex is heavy enough to withstand the energy exerted, the breakage, if any, would then take place in the leg sections and at a point which is less able to withstand the applied stress at that particular point. A close study of the construction of each particular casting is necessary so that proper precautions and care can be exercised when designing the joint, preparing it for welding, and completing the weld.

Special Techniques

The reliability of welds in cast irons can be improved with several techniques. One involves a mechanical method called *studding*, in which studs are positioned as needed in the weld joint to reinforce the welded joint. (*See* CAST IRON STUDDING *and* ARC STUD WELDING).

Another technique involves weld face grooving, in which staggered grooves are cut along the faces of joints to accept stringer welds. They prevent potential cracks from propagating in completed welds.

Peening can be very helpful in reducing residual tensile stresses. It is most effective when used on welds which are at red heat, but not below 540°C (1000°F). Peening can be accomplished by hand with a ball peen hammer or with an air hammer.

Preventing Cracks. Cracking can also be reduced by depositing the welds in a specific sequence and direction. In welding castings with irregular sections, the area of least strain (the heavy sections) should be welded first, and the area of the greatest strain (the light sections) should be welded last. When welding areas of the various sections, the direction of the weld should be from the heavy section toward the light section, and always toward a corner or edge when possible.

Joint Preparation

Sound, clean cast iron is an essential requirement for joints to be repaired by welding. Sometimes the weld zone is impregnated with sand and other contaminants which accumulated while the cast component was in use. All foreign materials must be removed, including casting skins, sand, rust, paint, or oil. All of the defective metal must be removed before the welds are made. Sufficient metal must be removed to provide the welder with a large enough opening to achieve full penetration in the root and side walls. The presence of contaminants might not be detected until after some weld metal has been deposited. If such a condition is found, that metal as well as more of the casting must be removed so that sound weld metal can be deposited.

Cracks are often pinned by drilling holes at the ends of the cracks. This reduces the high stress concentrations at the cracks and keeps them from propagating while preparing the joint for welding and while welding. Air carbon arc is the most common process used for removing defects and opening the joints. Following this, the heat-affected zone (HAZ) should be removed by grinding.

The type of weld groove to be prepared depends on many factors, such as accessibility, anticipated application, the type of cast iron, thickness, the welding process and the filler metal. For example, when using high-nickel fillers, adjustments need to be made for the "sluggishness" of this material, meaning a wider root opening and larger groove angle.

Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) is probably the most widely used process for arc welding cast irons because of its versatility, because it offers the greatest selection of filler metal compositions, and because it can be used in all positions. The SMAW process also has a number of other advantages, such as reasonable deposition rates, low distortion and a narrow heat-affected zone.

Filler Metals for SMAW

Gray Iron Rods. These rods can match the compositions of the castings to be welded, including those with high carbon levels. They are used in the flat position at high currents to produce large fluid puddles. To avoid hot cracking, the arc current should not be interrupted quickly, but should be decreased slowly to fill the crater and allow it to solidify without cracking. Gray iron rods produce welds which can match the color of the casting as well as its mechanical properties.

Mild Steel Electrodes. Mild steel electrodes such as E7018 are used to repair defects in castings when color match is important, but easy machining is not. To keep the weld hardness down, it is important to minimize dilution and discourage procedures which cause high cooling rates. Another problem is associated with the large shrinkage differences with mild steel and cast iron: the resultant stresses can be severe enough to cause cracking in the HAZ. To avoid them, preheat is essential.

Nickel Alloy Electrodes. Nickel-alloy electrodes have a special place in the fabrication of cast irons. Nickel offers a number of advantages. First, it has a very low solubility for carbon, so carbon dissolved in the weld metal as the result of dilution is rejected as graphite during solidification. This minimizes shrinkage in the weld metal which, in turn, reduces residual stresses in the weld joint. Additionally, the nickel-rich alloys are soft, easy to machine and offer high resistance to hot cracking when restrained.

There are four basic categories of nickel-base electrodes:

(1) *High-nickel*—containing about 85% nickel and alloyed with carbon, silicon, manganese and copper. They are used in applications where the diluted weld metal must be machined.

(2) *Nickel-iron*—a 50/50 mix of nickel and iron containing the same alloy additions as the high-nickel electrodes. The welds are stronger and more ductile, making them more useful for welding ductile or high-strength gray irons. They are effective for joining cast irons to dissimilar alloys, such as carbon steel or nickel base alloys. Stainless steels should be buttered with a high-nickel electrode first to keep chromium carbide from forming in the final weld. This alloy has the lowest coefficient of thermal expansion, making it more useful for welding heavy sections.

(3) *Nickel-manganese-iron*— a 40/40 mix of nickel and iron, containing about 12% manganese. This alloy has the good combination of strength, ductility and cracking resistance. It is used for welding the nodular irons, and in surfacing applications where wear resistance is important.

(4) *Nickel-copper*—a 60/40 nickel copper alloyed with a little silicon and manganese. These electrodes are used only in applications where dilution can be kept very low, because the addition of iron can cause weld cracking.

Copper Alloy Electrodes. Copper alloy electrodes are used for braze welding cast irons. (*See* BRAZE WELDING). The most commonly used of these are strengthened with either tin or aluminum. The copper alloy electrode containing aluminum is considerably stronger, but both offer the advantages of being very soft and ductile when hot. This allows it to yield while cooling, relieving stresses that could cause cracking. The strength increases rapidly as the alloys cool to ambient temperature.

Technique for Deep Welds

When the weld is deep enough to require that several layers be deposited, a special technique is used. This technique utilizes a coated electrode in combination with a filler rod of silicon bronze. The first layer is always made with the electrode alone; the silicon bronze is not added until subsequent layers. The operator uses one hand to maintain the arc with the electrode and feeds the bronze wire into the pool with the other hand. The filler rod is held close to the arc and is added by intermittently bringing its end into contact with the pool behind the electrode. Care has to exercised so that the feed rod will not make contact with the electrode. *See* CAST IRON; CAST IRON, Oxyacetylene Welding, *and* CAST IRON, Malleable.

Gas Metal Arc Welding (GMAW)

The GMAW process is most commonly used with the spray-arc mode of metal transfer, a high-energy technique. Producing a large heat-affected zone (HAZ) and deep penetration, it is more likely to cause weld or HAZ cracking. The buried-arc mode, which is sometimes used for welding carbon steels with CO_2-rich gases, also produces a deeply penetrating weld. In the globular mode, however, using argon-rich gases and currents below that at which spray occurs, the weld penetration is very low. Unfortunately, this mode cannot be used in any position except the flat or, possibly, for horizontal fillet welds. The short-circuiting mode allows low penetration welds to be made in all positions; seemingly an ideal combination for welding cast irons. However, due to the very low energy associated with this mode, lack-of-fusion defects must be expected when welding thicknesses greater than 6 mm (1/4 inch).

Filler Metals. The variety of electrodes available for GMAW is not as extensive as those available for SMAW. This is because small diameter wires are required for the gas shielded processes, meaning that the alloys must have reasonably good ductility in order to be drawn. For this reason, high-carbon, nickel-rich wires cannot be made economically. It is possible to use the same alloys designed for welding steels. They provide an excellent color match; however, they must be used with care, and because dilution causes the welds to be very hard, they cannot be machined. Preheat is essential.

When dilution must be tolerated and the welds must be machined, alloys containing 95% or more nickel are required. Nickel-iron wires are also available, but they deposit hard welds which are crack sensitive. The same nickel-manganese-iron alloy used for SMAW offers the same high strength and crack resistance for GMAW welding. Copper-tin and copper-aluminum wires can also be used and, with globular or short-circuiting transfer, these wires can be used for braze welding. *See* BRAZE WELDING.

Flux-Cored Arc Welding

Like the solid wires used for the GMAW process, the cored wires used with this modification of GMAW must be ductile. However, since alloys can be incorporated in the core, many compositions can be produced without causing either drawing or feeding difficulties. In addition, some of the cored wires can incorporate constituents which provide protection to the arc and weld pool, eliminating the need for shielding gases. These are the self-shielded cored wires, some of which offer the advantages of high deposition rates and low penetration at relatively low welding currents. They can be used to great advantage for welding heavy sections of cast irons. Some also have basic slags which increase the tolerance for sulfur, thereby reducing the possibility of hot cracking.

Filler Metals. Wires containing 70/30 nickel-iron compositions are available for welding heavy castings. Although these wires are effective for welding thick sections, the welds produced are generally too hard to be machined. Nickel-iron-manganese electrodes with a 60/40 ratio of Ni/Fe deposit stronger and more ductile welds which are machinable. They also can be used to weld cast irons to dissimilar metals.

CAST IRON, Braze Welding

Cast iron braze welding can be used for the repair of breaks in iron castings, from very small castings to those weighing several tons. The term *brazing* includes metal arc processes and oxyacetylene braze welding.

Castings must be thoroughly clean and free of graphite; they must be preheated before brazing is applied. Joints are prepared for brazing in the same way as for welding. *See* CAST IRON; ARC WELDING, JOINT PREPARATION; *and* PREHEAT.

When braze welding, a "black heat" is all that is necessary (instead of the dull red heat necessary when fusion-welding with the torch and cast iron rods). There are a number of bronze welding rods on the market which may be used for brazing cast iron.

Procedure

A flux should be used when braze welding cast iron with the oxyacetylene process. The torch flame should be either neutral, slightly carburizing or slightly oxidizing, depending on the recommendations of the rod manufacturer for the type of rod and the specific application.

One of the principal factors in cast iron braze welding is good "tinning". This is accomplished by careful cleaning and preparation, the use of a good tinning flux, and by heating the metal to the correct heat, a "black heat" adjacent the area to be welded.

It is good practice to position the pieces being braze welded so that the weld is made uphill. A short length of seam, about 5 cm (2 in.), is heated with the torch, the rod is dipped into the flux, and this area tinned. It is easy to recognize when the bronze is tinning well because of the manner in which it flows over the hot casting. If it does not flow readily, tinning is not being properly accomplished; the flux should be placed so that the metal ahead of the molten film of bronze is covered. If tinning becomes difficult, as is sometimes the case with an old casting, it is often possible to file the surface with a coarse file while the surface is hot so that the bronze will adhere.

After a two-inch section of the joint has been welded, another two-inch section is tinned, and subsequently built up until the joint is completed. Any tendency of the bronze to become liquid and run can always be prevented by drawing the torch away immediately. This enables the welder to control the bronze pool and to make an acceptable weld.

When braze welded in this manner, the strength of this joint is such that if the weld is broken, pieces of the bronze will actually pull areas of the cast iron out of the cast iron base metal, indicating that the weld is stronger than the cast iron base.

CAST IRON, Hard Spots

A cast iron weld will very often contain hard spots, or will be hard in some places and soft in others. The chief cause of this is the chilling of the metal from the molten state.

When molten cast iron is suddenly cooled, the dissolved carbon remains in the iron as such, but when cooled slowly the carbon separates from the iron in the form of graphite. A fracture in a suddenly cooled metal would show white iron, and on testing with a file, would prove to be very hard; a fracture in slowly cooled metal would show gray iron and would be soft.

Sudden cooling of cast iron makes it hard. When a cold welding rod is plunged into the pool of molten metal under the flame, the rod chills the metal it comes in contact with, and causes small round hard spots in the metal. These hard spots make it difficult to machine or finish the weld. To overcome this problem, the rod should be red hot before it is brought in contact with the melted iron. As an example, when welding a tooth or boss on a gear wheel or other large casting, if the casting is cold and the filler rod is added, the metal cools immediately on being welded, and results in a hard, chilled weld, which lacks strength and is impossible to machine.

Hard, porous and unacceptable welds can also result from using an incorrect flux or an excessive quantity of flux, impurities in the filler rod, or rods low in silicon.

CAST IRON, Malleable

Malleable cast iron is capable of being bent, extended or shaped to some extent. For example, if a malleable casting is placed in a vise and an attempt is made to break it, it will bend before breaking. If castings are subjected to great strains and rough usage, malleable cast iron is required. Malleable cast iron can be distinguished from gray cast iron if a fracture is broken clear through the casting. The malleable iron has a clearly discernible white, steely skin extended slightly from the surface of the casting toward the center. A fracture showing the interior of a gray iron casting lacks the bright skin at the surface.

Annealing. Malleable iron castings are not used in the as-cast condition. They must be annealed to make them malleable. The castings are packed for annealing in different ways, depending on the product desired. For example, *black heart* castings are made by tightly packing the white iron castings in the annealing boxes, surrounding them with mill scale (oxide of iron), and covering them. They are then placed in the annealing furnaces and maintained at 730 to 815°C (1350 to 1500°F) for approximately 60 hours. During this time, the carbon in the iron changes from the chemically combined form, separating from the iron and becoming interspersed among the grains of the iron as very fine particles of a coke-like carbon called *temper carbon.* While this change is occurring, the mill scale, or iron oxide, surrounding the castings in the annealing boxes combines with the carbon in the surface of the castings, decarburizing the surface metal, thus changing it into a grade of steel. If a black heart malleable casting is broken by blows from a sledge hammer, the fracture shows a bright steel skin for a slight depth around the surface of the casting, and a black interior.

Pipe Fittings. Many pipe fittings, and some other types of castings which do not require great strength, are made in all black form, and are called *all-black malleable* castings. These castings are packed in the annealing boxes in an inert medium like sand. The packing prevents warping of the castings while they are heated at red heat in the annealing boxes. In some cases, no packing at all is used.

White Heart Castings. Another grade of malleable castings is known as *white heart* castings, and are more common in Europe than in the United States. They are packed in mill scale or iron ore, and are decarburized throughout the casting so that the fracture is white.

Shrinkage in Malleable Castings. The shrinkage of malleable castings is important to welders. Gray iron shrinks about 10.4 mm/m (1/8 in./ft) during solidification and cooling. White iron shrinks about 21 mm/m (1/4 in./ft). Cast steel shrinks about 26 mm/m (5/16 in./ft). An interesting observation is that during the annealing of white cast iron, it regains about half of its shrinkage, growing in size during the annealing process so that the net shrinkage of malleable castings is about the same (10.4 mm/m [1/8 in./ft]) as that of gray iron castings.

Welding Malleable Castings

Considering the changes in the iron which take place during the annealing process, it follows that if the torch or the arc is applied to the malleable iron and the temperature of the section to be welded is actually raised to the point of fusion, the entire structure of the casting is altered, and the weld section reverts approximately to white iron. Therefore, an ordinary fusion weld on a malleable casting produces a weld area which does not have the strength or the toughness of the rest of the casting, may not even be as strong as a gray iron casting, and would also be hard and brittle. Any weld which requires actual fusion of the base metal of the casting might be counter to the objective of annealed castings. This is usually what takes place, and the fusion welding process is not recommended.

Arc Welding, Malleable Iron

When arc welding is used for malleable cast iron, the procedure is generally very much the same as for cast iron, however, special precautions are necessary because malleable iron and cast iron have very different characteristics. Malleable iron is affected by the heat of fusion to a greater extent. If the casting must have malleable characteristics when the weld is completed, there is no alternative but to heat treat it again, as it was first treated to make it a malleable casting.

Joint Preparation. In preparing the joint for arc welding, the joint opening should be chipped out, or ground to either a single- or double-V opening, depending on the thickness of the metal. A single-V should extend to within about 1.6 mm (1/16 in.) from the bottom, and when the two pieces are placed together, there should be about 1.6 mm (1/16 in.) between the edges at the point where the bevels meet. The groove angle should be approximately 90°.

The surfaces of the V should be thoroughly wire-brushed, or sandblasted if equipment is available. If the casting is covered with grease or oil, a solvent should used to clean it.

Temperature Control. It is important that the casting be kept as cool as possible: first, to prevent change in the form of the carbon, and second, to prevent strains in the casting itself. The arc should never, at any time, be held on the casting long enough to heat the metal to a red heat.

Cleaning Weld Beads. Before welding a second bead over one already made, the first bead should be thoroughly cleaned: wire-brushed until the steel is bright and free from any particles of the coating or of the slag. Cleanliness is an absolute necessity, otherwise foreign particles may become embedded, causing a pocket or hole.

When using a steel electrode, the weld is a likely to be hard, too hard for machining. However, this is not important when making an average repair on a malleable casting, because machining is not usually required. If machining is required, it is better to use a bronze electrode.

If the casting is heavy and the section is thick, it may be better to drill and tap holes at various points and insert threaded studs.

Electrodes for SMAW

Electrodes made of phosphor-bronze and heavily coated to shield the molten metal from the air can be used in making malleable iron welds. The work should be prepared and cleaned in exactly the same way as for other types of welding, and the electrodes should be used with DCEP. A 4 mm (5/32 in.) electrode can be used with a current from 70 to 170 amp, and 24 to 28 arc volts. If a 4.8 mm (3/16 in.) electrode is used, current should be from 90 to 220 amp, with voltage from 24 to 28 volts. It is desirable to hold the electrode at approximately 90° to the work. It may be necessary to reduce the current somewhat as the work progresses and the heat increases. It should be remembered that with these rods, as with others, the casting must not be heated too hot: the lowest current required to achieve fusion should be used.

Monel® alloy electrodes may also be used to produce machinable welds of high strength. Because of the higher melting point of Monel®, about 1360°C (2480°F), higher currents are needed to produce proper flow and fusion. Each layer or bead is moderately peened to diminish stresses, and thoroughly cleaned between beads.

Oxyacetylene Torch Brazing

To make a repair weld in a malleable casting, the crack or break must be chipped or ground out to form a V to an included angle of approximately 60°. The surfaces of the V should be vigorously wire-brushed to clean them thoroughly. If the casting is completely broken, the parts should be placed in correct alignment, and supported on the welding table to prevent sagging or warping out of shape. It is a good practice to use a bronze rod with a rather low melting point. Heating malleable iron to the point of fusion will change its characteristics, so the temperature should be kept as low as possible to avoid overheating.

Temperature Control. The melting temperature of a bronze welding rod is about 885°C (1626°F); a manganese-bronze welding rod will melt at approximately 925°C (1700°F). Therefore, it is necessary to heat the casting only to the melting temperature of the particular rod being used, which is about a red heat, in order to flow the bronze over the metal. It will adhere to the surface, or "tin" the metal.

Flux. As in most brazing, a suitable flux is needed. The flux should be a malleable iron flux, so designated on the label, and not the type of flux used for brazing cast iron. The object of the flux is to clean the surface of the casting, so that the metal will "tin" readily.

Tinning. The most important part of any braze is the initial *tinning*, or coating, of the base metal with the bronze. If this coating readily flows over the metal at the right temperature, the balance of the weld can be built up to the top of the V. In this respect, malleable iron does not differ from gray iron castings, except that it is critical not to overheat the malleable castings. Gray castings can be placed in a preheating furnace and preheated without any danger of changing the structure of the metal, but greater attention must be given to preventing such changes when heating malleable castings.

When braze welding malleable castings, a short section of the V should be tinned as described, and this section should be built up to completion as rapidly as possible. The next section should then be tinned and completed, continuing with short increments until the entire braze is completed.

Penetration. When braze welding a small casting with the oxyacetylene torch, the welder is often tempted to fit the two parts together in alignment, and to flow the bronze on the surface, believing that the braze metal will penetrate the depth of the break and adhere to it. This procedure may work in a furnace brazing process in which castings are heated for a long time until the heat penetrates evenly to the center of the casting. The bronze spelter used for this purpose penetrates entirely to the bottom of the casting, and such repairs are very strong when properly made. It is difficult, however, to heat the center of a small malleable casting sufficiently with the torch without overheating the surface. As a rule, any attempt to torch-braze in this manner will result in fusing only to the surface skin of the casting, with no appreciable fusing at the center. It is usually a better practice to form a V in the casting and tin a weld from the bottom up to make sure that all portions of the weld actually adhere to the iron surface.

As a general rule, whether an arc or a torch is used to weld malleable iron, bronze welding rods and electrodes are preferred because of the lower temperature at which they can be applied, to avoid fusion of the malleable iron during the process.

CAST IRON, Oxyacetylene Welding

Welding cast iron with a torch and cast iron welding rods can readily be accomplished.Preheating the weld area or the entire casting is required, except when very small castings are involved. *See* PREHEAT.

The same techniques for cleaning and preparing the casting for welding that are used for other processes are used with gas welding. *See* CAST IRON, ARC WELDING.

Procedure

The cast iron weld joint is prepared and preheated. A neutral oxyacetylene flame is used, along with a cast iron welding flux, which is essential to break down the surface oxide and increase the flowing qualities of the metal. Assuming that the weld is to be made on a V-joint, the torch is applied to the edges of the V, and the cast iron welding rod is heated and dipped into the flux, which adheres to it. The sides of the V are melted down, and the molten rod is added to the puddle.

A short section of the weld is built up in this manner; successive sections are added until the weld is finished. With cast iron, it is often good practice to begin at the center of a weld and back the torch out to the edge of the weld. Then the flame is always pointing toward the completed weld, and as the edge is approached, the metal can be controlled to good advantage. The edge can be built up square, or to the appropriate shape. If the torch is pointing toward the edge, the hot metal is likely to be driven over the edge by the force of the flame and will produce a weld with a ragged, incomplete finish.

Manipulating the torch helps finish the weld. If the torch is withdrawn momentarily from the hot puddle, the weld metal will instantly solidify, enabling the welder to control the metal and make a neat, square edge weld. The opposite side of the weld can be completed using the same procedure.

Porosity

Porosity in a weld is formed by gas entrapment during solidification. The cavities or holes (blowholes) which appear in the molten puddle during welding are usually the result of overheating the metal, or holding the flame in one place too long, thus driving the gases produced by the flame into the molten cast iron. Porosity can also be caused by gas produced in the metal during overheating. If gases are allowed to remain in the metal, the weld will be porous and will lack strength.

Porosity in cast iron welds can be avoided in many cases by correct manipulation of the torch. The flame should be directed so that it is not pointed at the molten puddle for more than a moment, then it is quickly moved to a colder part of the seam, or to the rod as it is held in the molten metal.

Standards for welding cast iron are contained in ANSI/AWS D11.2, *Guide for Welding Iron Castings.*

CAST IRON PIPE WELDING

See PIPE WELDING.

CAST IRON SOLDERING

Soldering cast iron presents many problems, the most difficult of which is properly tinning the cast iron surface to be soldered. If plating facilities are available, it is best to copper plate the parts that are to be soldered. If not, a substitute tinning process can be developed by thoroughly cleaning the surfaces and copper plating them with a solution of copper sulphate. This solution should be made up of 30 ml (1 oz) copper sulphate and 15 ml (1/2 oz) acid added to 240 ml (8 oz) of water. The parts to be soldered are either brushed with the solution or dipped in it. They are then rinsed and allowed to dry before soldering.

Some welders prefer to prepare cast iron for soldering by tinning it with half-and-half solder, 50% tin and 50% lead. A grinder is used to remove all of the scale from the surface so that it is clean and bright. The ground surface is then cleaned of grease by dipping it in a lye solution, then rinsed and dipped in muriatic acid. The surface is then treated with rosin and tinned with half-and-half solder. The casting may have to be dipped in acid several times before it becomes thoroughly tinned. Rubbing the surface of the iron casting with a piece of zinc while the surface is covered with acid will facilitate the tinning. The tinned surface can then be soldered with the half-and-half solder.

CAST IRON STUDDING

Steel can be welded to cast iron if the workpieces are free to align themselves after contraction strains which result during cooling. Studding can be done when the weld is in a position in which the parts are not free to align themselves. A steel weld made to cast iron appears acceptable until just about the time it is being most admired during cooling, when it invariably cracks along the edge of the weld. This is easily explained when we consider that steel has approximately four times the strength of cast iron. The definite location of the break comes about because the cast iron adjacent to the weld has become chilled cast iron, no matter whether it was originally so or not, and a sharp demarcation of structure, together with a possible layer of weaker cast iron, invariably causes the break to take place in this layer of cementite. Studding is recommended for large castings where strength is required.

Properly aligned and spaced holes are drilled carefully so that they are not drilled all the way through the casting. The holes are tapped for the correct threading and the headless stud bolts are screwed into these holes; they should project from 3.2 mm to 6 mm (1/8 to 1/4 in.) above the surface of the casting.

Studs can be ordinary steel headless stud bolts, and are welded with a low-carbon steel electrode. While shielded metal arc welding is usually chosen for the studding procedure, any process which uses this electrode can be used. The thickness and spacing of the studs should be proportioned so that the studs will have at least the full strength of the cast iron section. The space between the studs should be about 2-1/2 times the diameter of the stud, and they should be staggered. They should also have a reasonably fine thread.

Strength

Since steel has four times the strength of cast iron, the problem is to proportion the studs so that the ratio of the cross section of the steel to the cross section of the remaining cast iron is something less than four to one at any one section that will be subjected to cooling strains at the same time. Simply stated, this means large studs for large sections and smaller studs for smaller sections. Steam-tight joints on cast iron can be made with the efficient use of studs.

Another good application of studding is the use of large studs as an anchor or nucleus for breaks in castings such as gear teeth. One to three of these large anchor studs, together with some small regular studs appropriately distributed, will provide the necessary weld strength to the cast iron, as well as strength to withstand some shear and thrust strains. The weld, built up to size and machined off, finishes into a perfect wearing or bearing surface. This method of studding is also applied to cast steel, in cases where the original section has not been adequate to withstand the strains.

Studding Methods

Following are procedures to produce studded welds to repair breaks in cast iron:

(1) Grind or chip the crack to form a V from one surface, if only one surface is accessible for welding, or half way from both faces if both are accessible, saving enough pieces of the original assembly to keep the piece securely clamped in alignment. Before any of the welding is done, the stud holes are to be drilled and tapped with a bottoming tap, and the studs screwed in tightly, completely filling the hole for a depth of at least four times the diameter of the studs. A convenient way of doing this is to have rods threaded for their entire length, screw these in tightly, and saw them off 3.2 to 6 mm (1/8 to 1/4 to in.) above the surface of the work, depending on accessibility. A narrow V should have the studs closer to the work than a more open one.

(2) Weld around the studs so that they are part of the cast iron; then weld between the studs crosswise or diagonally until the entire surface of the V and the adjacent surface forming the underside of the pad is completely covered before proceeding with the main filling in of the weld. Add metal one bead at a time so that no large section of the weld solidifies from the molten state at any one time.

Welding the stud to the cast iron makes the stud an integral part of the casting. Welding from stud to stud diagonally or crosswise draws the fractured surfaces together to their original contact if a small amount of the original break has been left intact at the bottom of the V. This can be done in most instances, but not if pieces are broken out and lost, in which case they must be replaced by a casting or forging.

In this steel studding process for cast iron, especially for cylinders and similar work, machining is often necessary after welding. The hard stratum of metal directly under the weld prevents ordinary cutting operations, so it must be ground. There are other means of taking care of this hardened layer for machining on the surface; one of the methods is to finish the machined part with a nickel-copper electrode, which has the property of merging with the cast iron so that no hard layer of cementite is formed. This nickel-copper electrode was developed for repairing scored cylinders and similar applications.

CAST IRON THERMITE

A thermite mixture containing additions of ferrosilicon and mild steel. *See* THERMITE WELDING.

CAST IRON, White

A cast iron in which the carbon is in combined form rather than in the form of graphite. It is hard, brittle and highly resistant to abrasive wear, and can be machined only with great difficulty with special cutting tools. A freshly made fracture has a silvery white color. *See* CAST IRON.

CAST STEEL

Any object made by pouring molten steel into a mold. *See* STEEL, CAST.

CATHODE

The negative terminal of a power supply; the electrode when using direct current electrode negative (DCEN). In an electrolytic cell, the cathode is the source of electrons.

CAULKING

Plastic deformation of weld and adjacent base metal surfaces by mechanical means to seal or obscure discontinuities. See STANDARD WELDING TERMS.

CAULK WELD

A nonstandard term for SEAL WELD.

CAUSTIC EMBRITTLEMENT STRESS

Corrosion cracking of mild steel in contact with alkaline solutions; sometimes called *boiler embrittlement.* The failure is usually intergranular and usually occurs with concentrated sodium hydroxide when specific impurities such as silicates act as accelerators. Stresses above the elastic limit are especially conducive to the problem.

Caustic embrittlement is a form of stress corrosion responsible for occasional boiler failures. The objective in hot water and steam boiler operations is to avoid handling acidic water because of metal loss by uniform corrosion. Therefore, small amounts of alkali (caustic soda) are added to the water periodically to keep the PH at about 10.5, at which level there will be practically no corrosion on plain steel. However, if an excess of alkali is added, such water at elevated operating temperatures can cause stress corrosion cracking. In these situations, the steel does not become embrittled; its still-solid grains remain ductile. Instead, intergranular attack penetrates the steel, weakening the steel section and reducing its capacity to act in a ductile manner. This intergranular attack is recognized as stress corrosion cracking that has developed by an anodic mechanism.

CELSIUS (C)

A thermometric scale on which the interval between the freezing point and the boiling point of water is divided into 100 degrees, with 0 representing the freezing point and 100 representing the boiling point. This scale was devised in 1730 by Anders Celsius, a Swedish astronomer. Celsius has replaced Centigrade as the metric unit of temperature.

CEMENTITE

(Chemical symbol: Fe_3C) A carbide of iron which occurs as a micro-constituent of steel and cast iron. It is the normal form of carbon which occurs in steel. Cementite may occur interspersed with ferrite, or in a free form as a network, or in plates. On prolonged heating, particularly if there has been distortion of the steel, it is possible to get decomposition of cementite into free carbon and iron. *See* CAST IRON, Hard Spots *and* METALLURGY.

CENTIGRADE

See CELSIUS.

CENTIMETER (cm)

A unit of linear measure in the metric system equal to 1/100 of a meter, or 0.3937 (slightly over 3/8) inch.

CERAMICS

Ceramics are inorganic nonmetallic materials separable into two broad categories: traditional ceramics and advanced ceramics. A common characteristic of ceramic materials is that they are manufactured from powders which are formed to a desired shape, and then heated to high temperature with or without the application of external pressure to achieve a final densified part.

Traditional ceramics include clay products, refractories, silicate glasses, and cements. They are most commonly made from inexpensive, readily available, naturally occurring minerals. These materials typically have low densities (or relatively high porosity contents) and normally are not used in applications where joining by techniques other than cementing is practical.

Advanced ceramics, by comparison, are made from powders that are chemically processed or synthesized and in which properties such as particle size distribution and chemical purity are closely controlled. Within the family of advanced ceramics are materials developed for their exceptional mechanical properties. This subset of advanced ceramics is often referred to as *structural ceramics,* and it includes monolithic materials such as aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and silicon-aluminum oxynitrides (sialons), as well as ceramic composites like Al_2O_3 containing SiC whiskers or SiC containing titanium diboride (TiB_2) particles. Care is taken during the manufacture of structural ceramics to ensure that chemical composition is controlled and that high densities (or relatively low porosity contents) are achieved.

The technological interest in structural ceramics is directly related to their unique properties when they are compared to metals. Many ceramics are characterized by high strength, not only at room temperature but at elevated temperatures as well. Silicon carbide, for example, can maintain a tensile strength in excess of 200 MPa (29 ksi) at 1530°C (2800°F), the melting point of iron. Other ceramics, like Si_3N_4 and certain ceramic composites, also maintain high strength at high temperatures. Besides high strength, other properties that make ceramics attractive candidates for applications usually reserved for metallic alloys include excellent wear resistance, high hardness, excellent corrosion and oxidation resistance, low thermal expansion, high electrical resistivity, and high strength-to-weight ratio. Structural ceramics are being used or considered for use as cutting tools, bearings, machine tool parts, dies, pump seals, high temperature heat exchangers, and a variety of internal combustion and turbine engine parts. Typical properties for some metals and structural ceramic materials are given in Table C-2.

Ceramic joining, especially ceramic-to-metal joining, has been the subject of much developmental research over the years. However, with high interest in using ceramics as structural components in demanding applications, such as internal combustion engines, turbine engines, and heat exchangers, there is a heightened interest in ceramic joining technologies. The development of more effective joining techniques for structural ceramics could also have a great impact on their use in mass-produced components.

One of the most important functions of joining techniques is to provide the means for economic fabrication of complex, multi-component structures. Development of effective ceramic joining techniques will be especially significant because of limitations on component manufacturing due to ceramic processing techniques and to the materials themselves. For example, deformation of densified ceramics to form complex shapes is practically impossible because most ceramic materials are brittle even at elevated temperatures. Also, in some development programs like those for advanced heat engines, some complex parts are being made as monoliths by difficult processing schemes or by extensive machining of densified billets.

While this approach to component manufacturing is acceptable for development purposes, it is impractical for mass production because of high costs. The difficulty of machining ceramics also makes it costly. By reducing the complexity of individual parts, significant reductions in machining cost can be expected. Effective methods of joining ceramics may eliminate machining altogether in some cases.

Effective ceramic joining techniques also can play an important role in improving the reliability of ceramic structures. Because ceramics are brittle materials, they are very sensitive to flaws resulting from the quality of raw materials used in their production and to the characteristics of various processing techniques, including machining. A single flaw can cause the rejection or, or if undetected, the failure of a ceramic part. Rather than dealing with complicated monolithic parts, it is easier to inspect and detect flaws in simple-shaped components before they are joined to form complex structures.

The electronics industry has the largest fraction of advanced ceramics actually in use. Also, while the

Table C-2
Typical Properties of Some Pure Metals and Structural Ceramics[a]

Material	Strength[b]		Modulus of Elasticity		Coefficient of Linear Thermal Expansion		Electrical Resistivity, μΩ·cm	Thermal Conductivity, W/(m·K)
	MPa	ksi	GPa	ksi	μm/m/°C	in./in./°F		
Al	34	4.9	62	8992	23.6	13.10	2.6548	221.75
Cu	69	10.0	110	15 954	16.5	9.17	1.6730	393.71
Fe	130	18.9	196	28 427	11.7	6.50	9.71	75.31
Mo	345	50.0	324	46 992	4.9	2.72	5.20	142.26
Ni	152	22.0	207	30 023	13.3	7.39	6.84	92.05
Ti	207	20.0	116	16 824	8.4	4.67	42.00	21.90
Al_2O_3	300	43.5	380	55 114	6.8	3.78	10^{20}	27.20
SiC	500	72.5	480	69 618	4.2	2.33	10^{7}	62.80
Si_3N_4	1000	145.0	304	44 091	3.2	1.78	$>10^{20}$	10.00
ZrO_2	700	101.5	205	29 733	9.7	5.39	$>10^{17}$	2.00

a. Values given are typical values for each material at or near room temperature. Property values of both metals and ceramics can vary significantly with composition.

b. Yield strengths are given for metals; modulus of rupture strengths are given for ceramics.

development of materials like zirconium oxide, silicon nitride, and silicon carbide has been rigorously pursued in recent years, aluminum oxide is still the most widely used structural ceramic with a sizable commercial electronics market.

Reference: American Welding Society, Welding Handbook, Vol 3, 8th Edition. Miami, Florida, 1996.

CERAMIC ROD FLAME SPRAYING

A thermal spraying process variation in which the surfacing material is in rod form. See STANDARD WELDING TERMS.

CERTIFIED WELDER

A welder who passes qualification tests based on standards developed by the American Welding Society. Test results are recorded and maintained by the American Welding Society. Information, study material, and test dates and sites are available from the Certification Department of the American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126.

CHAIN INTERMITTENT WELD

An intermittent weld on both sides of a joint in which the weld increments on one side are approximately opposite those on the other side. See STANDARD WELDING TERMS. *See* Figure C-3.

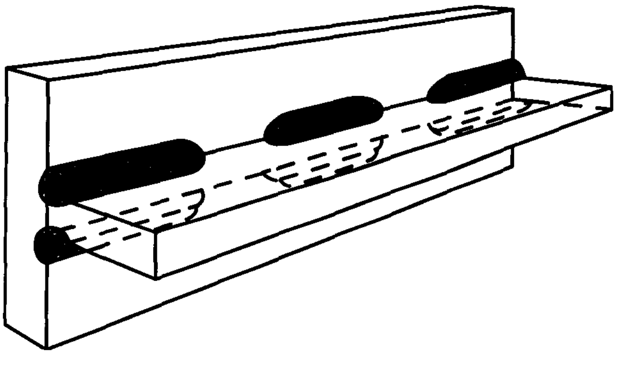


Figure C-3—Chain Intermittent Fillet Weld

CHAMFER

See EDGE PREPARATION *and* WELD JOINT.

CHAMFERING

The preparation for welding of a contour, other than for a square groove weld, on the edge of a member.

CHARLES' LAW

At a constant volume, the pressure of a perfect gas is directly proportional to the absolute temperature; or at a constant pressure the volume is directly proportional to the absolute temperature. This is expressed as follows:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \text{ and } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

in which T_1 and T_2 are the initial and final temperatures, respectively. (The absolute temperature in degrees Fahrenheit is [460 + T] where T is the observed temperature in degrees F).

CHARPY TEST

An impact test used to determine the notch toughness of materials. In its most common form, it has been given the designation *Charpy V-notch.* The specimens are 55 mm long and have a square cross section of 10 mm. A two millimeter notch is ground on one surface at half the length. The specimen is positioned with the ends of the notched surface straddling two supports and is struck opposite the notch by a wedge-shaped hammer at the end of a pendulum. The energy absorbed in breaking the specimen is calculated from data about the mass and length of the pendulum, the initial height of the hammer and the height of the hammer after the fracture. The test is performed at a number of temperatures, the results of which provide information about the overall toughness of the metal and the temperature at which it can be expected to fail in a brittle manner. A typical Charpy testing machine is shown in Figure C-4.

CHART OF WELDING PROCESSES

See Appendix 3.

CHEMICAL DIP BRAZING

A dip brazing process in which the filler metal is added to the joint before immersion in a bath of molten chemicals. *See also* ALUMINUM BRAZING.

CHEMICAL ELEMENTS

All matter is composed of one or a combination of two or more of over a hundred elements which make up the periodic table. About 20 of these are used in the manufacture of carbon and alloy steels. Some are used because of the specific properties they impart to steel when alloyed with it; others are included to rid the steel of impurities or to render impurities harmless.

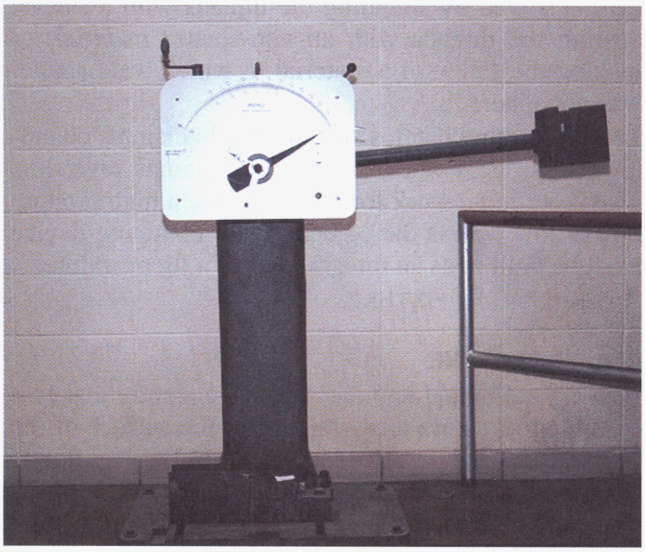


Figure C-4—Typical Charpy Testing Machine

The elements of the periodic table, their chemical symbols and atomic numbers are listed in Appendix 14.

CHEMICAL FLUX CUTTING

A nonstandard term for FLUX CUTTING.

CHILL CAST PIG

Pig iron cast in metal molds or chills. If a machine is used the product is called *machine cast pig*.

CHILL RING

A nonstandard term when used for BACKING RING.

CHILL TIME

A nonstandard term when used for QUENCH TIME.

CHIPPING

A method of removing surface defects with a chisel, so that the defects will not be worked into the finished product. Chipping is often used simply to remove metal, for example when preparing a joint for welding. *See* CHIPPING HAMMER.

Chipping is used to remove scale, rust, or other foreign materials from the workpiece. It can also be used between beads to remove slag, and after welding to ensure a neatly finished weld. Chipping is often used in combination with wire-brushing to prepare surfaces.

If defects and foreign matter are removed by gas cutting, the terms *de-seaming* or *de-scarfing* are used.

CHIPPING HAMMER

A tool for removing slag, scale or unwanted metal when preparing a surface for welding or finishing a weld.

A chipping hammer may be equipped with either drift or chisel ends, chisels on each end set at right angles to each other, or with adjustable chisels. Cleaning a surface with a chipping hammer is accompanied by a peening action which helps knock off particles of slag or scale, but also has a tendency to compact the weld metal slightly. Peening results in higher density of the weld and improves soundness and strength. The peening is usually followed by a vigorous brushing with a stiff wire brush.

CHOKE COIL

A coil of low resistance and high inductance which will oppose changes in electric current but allow regular, steady currents to flow through easily. Choke coils are also known as *reactors* or *reactance coils*.

CHROMIUM

(Chemical symbol: Cr). A lustrous, hard, very brittle, steel-gray metallic element used to harden steel alloys, to produce stainless steels, and in corrosion-resistant plating. Melting point: 1615°C (2939°F); boiling point: 2200°C (3992°F); atomic number: 24; atomic weight, 5.996.

Chromium is of great technical importance in metallurgy because of its hardening effect on steel, and because of its corrosion resistant properties. It is unaffected by the action of air at ordinary temperatures and is also resistant to chemicals.

A material containing chromium is difficult to weld because of the formation of chromium oxide. This oxide forms a coating on the surface during welding, but the coating can be removed by grinding or by using special fluxes.

Chromium is one of the basic ingredients used in producing stainless steels. As an ingredient in alloy steel, chromium is a hardening element which also tends to increase the strength of the steel. When the percentage is from 12% to 30%, chromium increases the corrosion and oxidation resistance of the steels; this holds true at both high and low temperatures. There is little loss of strength in chrome steels at temperatures up to 480°C (900°F). *See* STAINLESS STEEL.

CIRCULAR ELECTRODE

See STANDARD WELDING TERMS. *See* RESISTANCE WELDING ELECTRODE.

CLAD BRAZING SHEET

A metal sheet on which one or both sides are clad with brazing filler metal. See STANDARD WELDING TERMS. *See also* CLAD METAL.

CLADDING

A surfacing variation that deposits or applies surfacing material, usually to improve corrosion or heat resistance. See STANDARD WELDING TERMS. *See also* BUILDUP, BUTTERING, HARDFACING; THERMAL SPRAYING, *and* EXPLOSION WELDING.

CLAD METAL

A laminar composite consisting of a metal or alloy, with a metal or alloy of different chemical composition applied to one or more sides by casting, drawing, rolling, surfacing, thick chemical deposition, or thick electroplating. See STANDARD WELDING TERMS.

CLAD STEEL

See STEEL, Clad.

CLAMP

A device used to join, grip, support, fasten, or hold parts in alignment.

Clamps are vitally important to all welders and welding operations, and there are many types of clamps in use in welding shops and manufacturing plants. Some of these devices are made in the shop for use with special welding tables or faceplates, and may be merely "dogs" or "wedges". There are also hook bolts, three-point bearing clamps, lever clamps, swinging strap clamps, and cam-operated clamps made for specific welding applications. The C-clamp will be found in every shop, augmented by specially designed pliers, hand vises, toggle clamps, angle clamps and other clamping devices.

When selecting a clamp for use in welding, or any other operation requiring pieces to be held in alignment, the following are important considerations:

(1) The size and shape of the workpiece
(2) Condition of the workpiece
(3) Strength of the clamp
(4) Ease and speed with which clamps can be attached or detached
(5) Means and point of applying pressure
(6) Frequency of set-up
(7) Method of preventing the clamp from loosening during use.

The clamping device should be made so that weld spatter will not cause it to malfunction. The problem of weld spatter adhering to the threads of a C-clamp can be solved by shielding the threads with a sleeve, coating the threads with an anti-spatter material, or making the screw of a material to which weld spatter will not adhere.

Quick-acting clamps such as toggle clamps, clamping pliers, hand vises, and some C-clamps save time when setting up work for welding. When high production at low cost is the objective, the clamping device must be built in as an integral part of a jig or fixture. *See also* JIG *and* FIXTURE.

CLEAVAGE PLANE

A crystallographic plane which frequently makes it possible to fracture a crystal so that the surface of the fracture is smooth and plane and always parallel to some definite crystallographic plane. A substance may cleave on more than one crystallographic plane.

CLOSED JOINT

See CLOSED ROOT.

CLOSED ROOT

A term applied to a joint which has the root edges or surface in contact during welding; a design in which there is no space between the roots of the parts being joined.

CLUSTER POROSITY

A localized array of porosity having a random geometric distribution. See STANDARD WELDING TERMS.

COALESCENCE

The growing together or growth into one body of the materials being welded. See STANDARD WELDING TERMS.

COAL GAS

A gas produced by high-temperature distillation of bituminous coal. With a Btu value of about 680 Btu per cu ft, coal gas was used as a preheating medium in some flame cutting applications before natural gas became generally available.

COATED ELECTRODE

A nonstandard term for COVERED ELECTRODE or LIGHTLY COATED ELECTRODE.

COATING

A nonstandard term when used for THERMAL SPRAY DEPOSIT.

COATING DENSITY

A nonstandard term when used for SPRAY DEPOSIT DENSITY RATIO.

COBALT

(Chemical symbol: Co). A hard metallic element, similar to nickel in appearance but with a bluish hue. It is used for magnetic alloys, high-temperature alloys in steel, and for pigments in glass and ceramics.

Cobalt is malleable, ductile and weakly magnetic. It oxidizes very slowly in moist air. In the metallic form, cobalt does not have many uses, however, when combined with other elements, it is used in hardfacing materials, and also as an alloying agent in steel when high strength or hardness at high temperatures is required. It imparts the quality known as *red hardness.*

Atomic number: 27; atomic weight: 58.9332; melting point: 1467°C (2673°F); specific gravity: 8.5.

COBALT-60

A radioactive isotope of cobalt used for weld inspection. It is used in shops or in field applications where radiographs are needed. Cobalt-60 is more commonly used than radium even though radium allows shorter exposure times. *See* RADIOGRAPHIC EXAMINATION.

CODES

A systematically arranged, comprehensive set of rules and standards for welding applications, mandatory where the public interest is involved. For example, there are codes for manufacturing equipment and consumer products, for building construction, automotive, aircraft and rail car construction, bridges, power plants, pressure vessels, and piping systems. There are also codes for installation, operation and maintenance. *See* Appendix 16.

COEFFICIENT OF LINEAR EXPANSION

The increase in dimensions of an unrestrained material caused by being heated. As a corollary, thermal coefficients of contraction measure the shrinkage of a material when cooled; generally expressed per degree Celsius or degree Fahrenheit change in temperature.

The thermal expansion of various metals differ. For example, copper expands about 0.1 in. per ft when the temperature is raised 1000°F. A gray iron casting expands much less than copper: 0.067 in. per ft per 1000°F. When this rate of expansion is applied to a cast iron bar 10 ft long, the expansion will be approximately 0.6875 in. when the temperature is raised 1000°F. Under similar conditions, a 10-ft aluminum bar will expand nearly 1.5 in.; a bronze bar, 0.781 in.; and a steel bar slightly more than 0.75 in. *See* Table C-3.

Table C-3
Expansion of Metals

Metal	Linear Expansion per Foot of Length, per 1000°F Rise in Temperature in.
Zinc	0.169
Aluminum, Cast	0.148
Tin	0.139
Silver	0.129
Bronze	0.119
Brass, Cast	0.115
Copper	0.106
Nickel	0.083
Wrought Iron	0.078
Steel	0.076
Cast Iron	0.067

Distortion

Differences in the amount of thermal expansion due to changes in temperature are responsible for the distortion commonly found in completed welds. When the hot regions in the vicinity of the weld are restrained from expanding by stiff, colder metal around them, they can deform plastically. These dimensional changes are reflected as distortion after the weldment cools. Stresses due to thermal contraction can be sufficiently severe to cause brittle metals such as cast irons to crack.

COEXTRUSION WELDING (CEW)

A solid-state welding process that produces a weld by heating to the welding temperature and forcing the workpieces through an extrusion die. See STANDARD WELDING TERMS. *See also* COLD WELDING.

COHESION

In a weld, cohesion is the result of perfect fusion and penetration, with the molecules of the parent metal and the added material thoroughly integrated or joined. *See* ADHESIVE BONDING, *and* DEPTH OF FUSION.

COIL WITHOUT SUPPORT

A filler metal package consisting of a continuous length of welding wire in coil form without an internal *support. It is appropriately bound to maintain its shape. See* STANDARD WELDING TERMS.

COIL WITH SUPPORT

A filler metal package consisting of a continuous length of welding wire in coil form wound on a simple cylinder without flanges. See STANDARD WELDING TERMS.

COLD CHISEL

A chisel made from steel for cutting metal. Cold chisels are usually made from a 0.70 to 0.80 carbon tool steel. A steel of this type should be forged at 870°C (1600°F) and hardened at 760 to 782°C (1400 to 1440°F) to get the combination of toughness and hardness required.

COLD CRACK

A crack which develops after solidification is complete. See STANDARD WELDING TERMS.

Cold cracking, commonly called *delayed cracking,* occurs some time after a fusion weld has been made and has fully solidified, often well after it has cooled to room temperature. The origin of this type of transgranular cracking is embrittlement of susceptible microstructure (most commonly untempered ferrous martensite) by diffusible atomic or nascent hydrogen in the presence of a tensile internal (i.e., residual) or applied stress. The fact that this type of cracking can take considerable time to occur gives it the name "delayed cracking." *See also* UNDERBEAD CRACK *and* HYDROGEN EMBRITTLEMENT.

COLD LAP

A nonstandard term when used for INCOMPLETE FUSION or OVERLAP.

COLD SOLDERED JOINT

A joint with incomplete coalescence caused by insufficient application of heat to the base metal during soldering. See STANDARD WELDING TERMS.

COLD SHORTNESS

A little-used expression applied to a metal to describe the characteristic of brittleness at ordinary or low temperatures.

COLD WELDING (CW)

A solid-state welding process in which pressure is used to produce a weld at room temperature with substantial deformation at the weld. See STANDARD WELDING TERMS. *See also* DIFFUSION WELDING, FORGE WELDING, *and* HOT PRESSURE WELDING.

A characteristic of the cold welding process is the absence of heat, either applied externally or generated by the welding process itself. A fundamental requisite for satisfactory cold welds is that at least one of the metals to be joined is highly ductile and does not exhibit extreme work-hardening. Both butt and lap joints can be cold welded.

Cold welding involves two concurrent steps: (1) distorting the contact surfaces of two ductile metals to rupture their surface oxide layers, thus exposing clean metal, and (2) applying enough pressure across those surfaces to allow interatomic bonding. The oxides and other surface contaminants become scattered as minute particles within the joint. Although most commonly used to join sheets of nonferrous metals such as aluminum and copper, cold welding also allows dissimilar metals and other shapes to be joined.

In all cases, however, the contacting surfaces must be clean of surface contaminants and then deformed sufficiently to force the surface oxides to rupture and intimate contact of the surfaces to be made. Since work hardening is inevitable, the joints are somewhat stronger than might be expected. When joining sheet metals these objectives can be accomplished with dies. The ends of bars also can be joined by using strong clamping shoes, powerful hydraulic forces and containment dies to deform the ends. Even tubes can be cold welded by positioning one tube inside the other and pulling them between a drawing die and a mandrel to cause the needed surface deformation.

Materials for Cold Welding

Materials with face-centered cubic (FCC) lattice structure are best suited for cold welding, provided they do not work-harden rapidly. Soft tempers of metals such as aluminum and copper are most easily cold welded. It is more difficult to weld cold worked or heat treated alloys of these metals. Other FCC metals that may be cold welded readily are gold, silver, palladium and platinum.

Dissimilar Metal Welds

Joining copper to aluminum by cold welding is a good application of the process, especially where aluminum tubing or electrical conductor grade aluminum is joined to short sections of copper to provide transition joints between the two metals. Such cold welds are characterized by substantially greater deformation of the aluminum than the copper because of the difference in the yield strengths and work-hardening behaviors of the two metals.

Numerous dissimilar metals may be joined by cold welding, whether or not they are soluble in one another. In some cases, the two metals may combine to form intermetallic compounds. Since cold welding is carried out at room temperature, there is no significant diffusion between dissimilar metals during welding. The alloying characteristics of the metals being joined do not affect the manner in which the cold welding operation is carried out. However, the interdiffusion at elevated temperatures can affect the choice of postweld thermal treatments and the performance of the weld in service.

Welds made between metals that are essentially insoluble in each other are usually stable. Diffusion can form an intermetallic compound at elevated service temperatures. In some cases, this intermetallic layer can be brittle and cause a marked reduction in the ductility of the weld. Such welds are particularly sensitive to bending or impact loading after an intermetallic layer has formed.

Applications

Butt Joints. Cold welding is commonly used to produce butt joints in wire, tubing, and simplè extruded shapes of like and unlike metals. A major application is in the manufacture of aluminum, copper, gold, silver, and platinum wire. The most common use is to join successive reels of wire for continuous drawing to smaller diameters. Diameters ranging from 0.06 to 12.7 mm (0.0025 to 0.50 in.) have been successfully welded.

Lap Welds. Lap welds can be used for joining aluminum sheet or foil to itself and also to copper sheet or foil. Commercial uses of lap welding include packaging applications, as well as electrical applications, which is probably the major use for cold welding. It is especially useful in the fabrication of electrical devices in which a transition from aluminum windings to copper terminations is required. The range of electrical applications covers large distribution transformers to small electronic devices. A variation of cold lap welding is applied to the sealing of commercially pure aluminum, copper, or nickel tubing.

Surface Preparation

The contacting surfaces must be clean of surface contaminants. Dirt, absorbed gas, oils, (even fingerprints) or oxide films on the surfaces interfere with metal-to-metal contact and must be removed to obtain strong welds. Rotary brushes of 0.1 mm (0.004 in.) diameter stainless steel wire, brushing at a surface speed of about 15 m/s (3000 ft/min) is recommended. Chemical and abrasive cleaning methods are not satisfactory because the chemical residue or abrasive particles in or on the surface may prevent the formation of a sound weld.

Equipment

Pressure for welding may be applied to overlapped or butted surfaces with hydraulic or mechanical presses, rolls, or special manually or pneumatically operated tools. A hand tool of the toggle cutter type is suitable for very light work; common manually operated presses can be used for medium size work. Heavy work requires power operated machines. The rate of pressure application does not usually affect the strength or quality of the weld.

Pressure required to effect a weld depends on the working area of the dies. Pressures are generally slightly above the flow point of the material, and range from 186 to 276 MPa (27 000 to 40 000 psi) for aluminum, and from two to four times as much for copper. Time during which the pressure is applied is not critical; good welds can be made with either slow squeeze or impact. Hand welding by impact on an anvil is quite feasible, provided correct penetration of the die can be achieved.

Given a suitable arrangement of workpieces and dies, the application of pressure forces the work surfaces into close contact while the flow takes place, welding them solidly together. The work hardening that necessarily takes place is an advantage, because it tends to balance the loss in strength resulting from the decrease in the cross section.

The term *cold welding* is also applied to the self-diffusion property of a material. For example, two sheets or strips of silver in contact with one another will adhere at temperatures ranging from 200 to 400°C (400 to 750°) at pressures up to 310 MPa (45 000 psi). Lead and other materials have this same quality.

COLD WORK

The plastic deformation of metals at a temperature below that at which recovery and recrystallization take place. Cold work generally refers to the plastic deformation of metals at ordinary temperature. Cold work causes metals to harden, thereby becoming stronger but less ductile.

COLLAR

The reinforcing metal of a nonpressure thermite weld. See STANDARD WELDING TERMS.

COLLARING, Thermal Spraying

Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit. See STANDARD WELDING TERMS. *See* Figure C-5.

COMBINED CARBON

The carbon in steel and cast iron which is in the form of iron carbide (Fe_3C) as distinguished from graphite and tempered carbon. *See* METALLURGY.

COMBUSTIBLE

Capable of burning. Any substance which will unite with oxygen is combustible.

COMBUSTION

The process of burning, or oxidation producing heat and light. In welding, the term is extended to a flame consuming fuel, oil, or gas, and includes oxidation, as when metals are heated in air or oxygen.

COMMUTATION

Changing alternating current produced in the armature windings into direct current using a commutator.

COMMUTATOR

A device by which alternating current produced in a generator is changed into direct current. A series of bars or segments connected to armature coils of a dynamo so that rotation of the armature, in conjunction with fixed brushes, will result in unidirectional current output in the case of a generator, and in the reversal of the current into the coils in the case of a motor.

COMMUTATOR-CONTROLLED WELDING

The making of multiple groups of resistance spot or projection welds sequentially with the same welding contactor through the use of a commutating device. See STANDARD WELDING TERMS.

COMPANION PANEL

A nonstandard term when used for SPRAY TAB.

COMPLETE FUSION

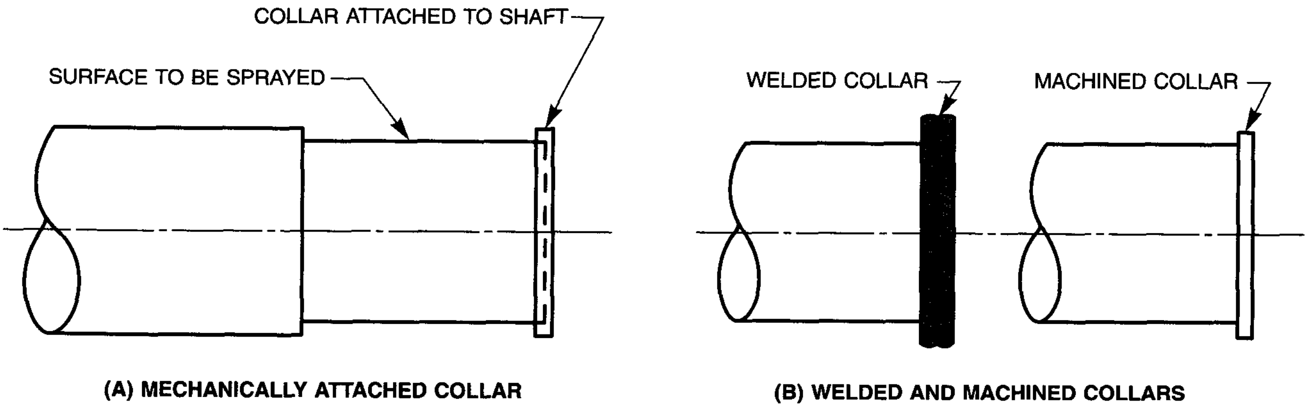
Fusion over the entire fusion faces and between all adjoining weld beads. See STANDARD WELDING TERMS. *See also* INCOMPLETE FUSION.

COMPLETE JOINT PENETRATION (CJP)

A joint root condition in a groove weld in which weld metal extends through the joint thickness. See STANDARD WELDING TERMS. *See also* COMPLETE JOINT PENETRATION WELD, INCOMPLETE JOINT PENETRATION, PARTIAL JOINT PENETRATION WELD, *and* JOINT PENETRATION.

COMPLETE JOINT PENETRATION WELD

A groove weld in which weld metal extends through the joint thickness. See STANDARD WELDING TERMS. *See also* COMPLETE JOINT PENETRATION, INCOMPLETE JOINT PENETRATION, PARTIAL JOINT PENETRATION WELD, *and* JOINT PENETRATION.



(A) MECHANICALLY ATTACHED COLLAR

(B) WELDED AND MACHINED COLLARS

Figure C-5—Collaring as Used in Thermal Spraying

COMPOSITE

A material consisting of two or more discrete materials with each material retaining its physical identity. See STANDARD WELDING TERMS. *See also* CLAD METAL, COMPOSITE ELECTRODE, *and* COMPOSITE THERMAL SPRAY DEPOSIT.

Composites are combinations of materials, like fiberglass, in which two or more structurally complimentary substances such as metals, ceramics, glasses and polymers are combined to produce structural or functional properties which are not possible with the individual components.

An application is the production of low-cost aluminum metal matrix composites for high-performance structural components. Silicon carbide whiskers (small crystalline materials) have been used to reinforce the aluminum matrix, resulting in a structure that is lighter in weight and equal to or greater in strength than conventional materials. The reinforced composites have applications in aerospace projects, and potential military applications such as track vehicle tread shoes (*See* Figure C-6), power train parts, and missile structures. *See also* POLYMERIC COMPOSITE.

Figure C-6—Armored Vehicle Track Shoes Cast from an Aluminum Metal Matrix Composite will be Assembled into Treads for Field Tests on Vehicles such as this M551 Sheridan Light Tank

COMPOSITE ELECTRODE

A generic term for multi-component filler metal electrodes in various physical forms such as stranded wires, tubes, and covered wire. See STANDARD WELDING TERMS.

An example of a composite electrode is a flux cored electrode which utilizes a tubular electrode with deoxidizing and alloying powders in the core. *See also* COVERED ELECTRODE, FLUX CORED ELECTRODE, METAL CORED ELECTRODE, *and* STRANDED ELECTRODE.

COMPOSITE JOINT

A joint in which welding or another thermal process is used in conjunction with mechanical joining.

COMPOSITE STRUCTURE

A structure in which more than one material is used.

COMPOSITE THERMAL SPRAY DEPOSIT

A thermal spray deposit made with two or more dissimilar surfacing materials that may be formed in layers. See STANDARD WELDING TERMS.

COMPOUND GENERATOR

A generator that has shunt and series field coils acting together to produce a constant voltage, although current output may vary.

COMPRESSION TESTING

See TUBE TESTING.

COMPUTERIZATION OF WELDING INFORMATION

Two documents have been developed by ANSI/AWS in cooperation with the American Society of Nondestructive Testing (ASNT) on the computerization of material property data. These documents are used to identify, define and document welds and weld properties and nondestructive test data; also used to produce a Procedure Qualification Record. Reference: ANSI/AWS A9.1, *Standard Guide for Recording Arc Welds in Computerized Material Property and Nondestructive Examination Databases;* and ANSI/AWS A9.2, *Standard Guide for Describing Arc Welds in Computerized Material Property and Nondestructive Examination Databases.*

Computerized access to ANSI/AWS D1.1-96 *Structural Welding Code—Steel* is available on a compact disk (CD-ROM).

Sources of information on electronic databases and computer programs include the following: ASM International (**www.asm-intl.org/**), American Welding Institute, (**www.awi.org/**) American Welding Society (**http://www/amweld.org/**); Battelle Memorial Institute (**www.itaiep.doc.gov/sabit/batelle.html/**), and Edison Welding Institute (**http://www.ewi.org**).

CONCAVE FILLET WELD

A fillet weld having a concave face. See STANDARD WELDING TERMS. *See* Appendix 11.

CONCAVE ROOT SURFACE

The configuration of a groove weld exhibiting underfill at the root surface. See STANDARD WELDING TERMS. *See* Figure C-7.

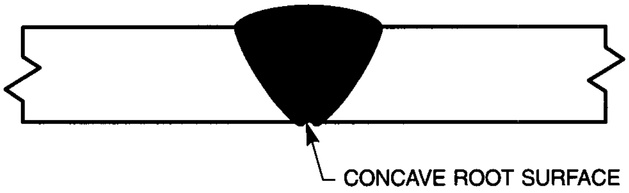


Figure C-7—Example of a Concave Root Surface

CONCAVE WELD

A weld in which the top layer ends below the plane of the surrounding material in a butt joint, or beneath a plane of 45° for a fillet weld. Although considered to be undesirable for many applications because of the reduced throat section and because of the increased possibility of hot cracking, properly fused concave fillet welds can be beneficial for resistance to fatigue in service. The absence of mechanical discontinuities in these welds minimizes crack initiation due to concentrated residual stresses.

CONCAVITY

The maximum distance from the face of a concave fillet weld perpendicular to a line joining the weld toes. See STANDARD WELDING TERMS. *See* Appendix 11.

CONCENTRIC CABLE

A number of wires wound spirally around a central conductor or cable and insulated from the conductor or cable.

CONCURRENT HEATING

The application of supplemental heat to a structure during welding or cutting. See STANDARD WELDING TERMS.

CONDENSER

A device consisting of two conductors separated by an insulating material, capable of holding an electric charge. *See* CAPACITOR.

CONDENSER DIELECTRIC

The insulating material between condenser plates or conductors.

CONDENSER PLATE

One of the conductors forming a condenser.

CONDUCTIVITY

The reciprocal of resistivity. For any solid or liquid conductor, it measures the amount of electricity transferred across a unit area per unit voltage.

CONDUCTOR

A wire or part through which a current of electricity flows; a carrier of electric current.

CONDUIT

A pipe, tube or duct for enclosing electric wires or cables.

In gas metal arc, flux cored arc, and submerged arc welding, a flexible metal tube which conducts electrode wire from a spool or reel to the welding torch. Some conduits are lined with a material such as Teflon to reduce friction and improve wire feeding.

CONE

The conical part of an oxyfuel gas flame adjacent to the tip orifice. See STANDARD WELDING TERMS. *See* Figure A-1.

CONICAL SEAT

A joint in the torch head which receives and securely fastens an interchangeable tip and forms a gas-tight seal.

CONNECTED LOAD

The sum of the power usage rating of all the lamps, motors, welders, heating devices, etc., drawing from a particular electric circuit.

CONNECTION

A nonstandard term when used for a welded, brazed, or soldered joint.

CONNECTOR

A device used to connect or join one circuit or terminal to another.

CONSTANTAN

An alloy composed of 40% nickel and 60% copper. Constantan is a high-resistance alloy used in winding resistance coils, and as a thermocouple alloy.

CONSTANT CURRENT POWER SOURCE

An arc welding power source with a volt-ampere relationship yielding a small welding current change from a large arc voltage change. See STANDARD WELDING TERMS. *See also* WELDING POWER SOURCE.

A constant current power source has a "drooping" output characteristic; the output voltage decreases as welding current increases. This type of power supply is used with shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW).

CONSTANT POTENTIAL WELDER

See CONSTANT VOLTAGE POWER SOURCE.

CONSTANT VOLTAGE POWER SOURCE

An arc welding power source with a volt-ampere relationship yielding a large welding current change from a small arc voltage change. See STANDARD WELDING TERMS. *See also* WELDING POWER SOURCE.

A constant voltage power source is capable of providing a range of variations in welding current while maintaining nearly constant voltage. Constant voltage (sometimes called *constant potential power sources)* have a relatively flat volt-ampere output curve. They have a lower open circuit voltage than machines with the drooping characteristic required for SMAW.

These characteristics are achieved by low impedance transformer design, in which the primary and secondary coil relationships have a very tight magnetic or inductive coupling.

Gas Metal Arc Welding

With the development of solid-state devices which can handle high power, the constant voltage output is more easily and economically achieved electronically. This is particularly true of the inverter type power supplies.

Constant voltage welders were developed initially for submerged arc welding. However, their desirable characteristics were noted and quickly adapted for the gas metal arc welding (GMAW) process. The interaction of the drooper power supply and wire feed speed made it difficult to set proper welding conditions. With a constant voltage output, however, setting the welding conditions is far simpler, since the power supply determines the voltage and the wire feed speed determines the current. Additionally, the self-regulating feature provided by the constant voltage machines make it easier for welding operators to maintain a constant arc length with GMAW. These desirable "welder friendly" characteristics apply equally to SAW.

CONSTRICTED ARC

A plasma arc column that is shaped by the constricting orifice in the nozzle of the plasma arc torch or plasma spraying gun. See STANDARD WELDING TERMS.

CONSTRICTING NOZZLE

A device at the exit end of a plasma arc torch or plasma spraying gun, containing the constricting orifice. See STANDARD WELDING TERMS. *See* Appendix 10.

CONSTRICTING ORIFICE

The hole in the constricting nozzle of the plasma arc torch or plasma spraying gun through which the arc plasma passes. See STANDARD WELDING TERMS. *See* Appendix 10.

CONSTRICTING ORIFICE DIAMETER

See STANDARD WELDING TERMS. *See* Appendix 10.

CONSTRICTING ORIFICE LENGTH

See STANDARD WELDING TERMS. *See* Appendix 10.

CONSUMABLE ELECTRODE

An electrode that provides filler metal. See STANDARD WELDING TERMS.

CONSUMABLE ELECTRODE WELDING

All arc welding processes in which the electrode supporting the arc is melted and becomes a significant part of the weld deposit.

CONSUMABLE GUIDE ELECTROSLAG WELDING

An electroslag welding process variation in which filler metal is supplied by an electrode and its guiding member. See STANDARD WELDING TERMS.

CONSUMABLE INSERT

Filler metal that is placed at the joint root before welding, and is intended to be completely fused into the joint root to become part of the weld. See STANDARD WELDING TERMS.

CONTACT ARC WELDING

A technique used with the shielded metal arc welding (SMAW) process in which heavily coated iron powder electrodes are dragged in the joint. The core rod of these electrodes becomes recessed in the coating during welding, forming a relatively deep cone. Since the coating is a poor conductor, it can be in contact the weld pool without shorting the arc.

The contact arc welding technique permits automatic maintenance of the arc, and results in the following advantages: easily started arc, constant arc length, improved welds, and reduction of welder fatigue.

Contact arc welding was developed by Dr. van der Willigen of Holland in 1944. Among the classifications of electrodes developed to take advantage of this procedure are E7014, E7024 and E7027.

CONTACT BAR

An electric terminal used in a seam welding machine to apply electric current and mechanical pressure to the workpieces.

CONTACT JAW

An electric terminal used in a flash welding machine to securely clamp the workpieces and conduct electric current to the workpieces.

CONTACTOR

A device which opens and closes an electrical circuit.

CONTACT POINT

An electric terminal used in a spot welding machine to apply electric current and mechanical pressure to the workpieces. The contact point insert is a small disc of metal inserted in a contact, projecting beyond its surface.

CONTACT RESISTANCE, Resistance Welding

Resistance to the flow of electric current between two workpieces or an electrode and a workpiece. See STANDARD WELDING TERMS.

CONTACT ROLLER

An electric terminal used in a seam welding machine to apply electric current and mechanical pressure to the workpieces.

CONTACT TUBE

A device that transfers current to a continuous electrode. See STANDARD WELDING TERMS. *See* Appendix 10.

CONTACT TUBE SETBACK, Flux Cored Arc Welding and Gas Metal Arc Welding

The distance from the contact tube to the end of the gas nozzle. See STANDARD WELDING TERMS. *See* Appendix 10. *See also* ELECTRODE SETBACK.

CONTACT WELDING

See CONTACT ARC WELDING.

CONTINUOUS COOLING DIAGRAM

When steels cool from high temperatures at which they have an austenitic microstructure, they can transform into a number of very different microstructures, such as ferrite, pearlite, bainite and martensite. The type of structure formed depends on the composition of the steel and the rate at which it cools. The type of structure can be predicted with a continuous cooling diagram similar to the one illustrated in Figure C-8.

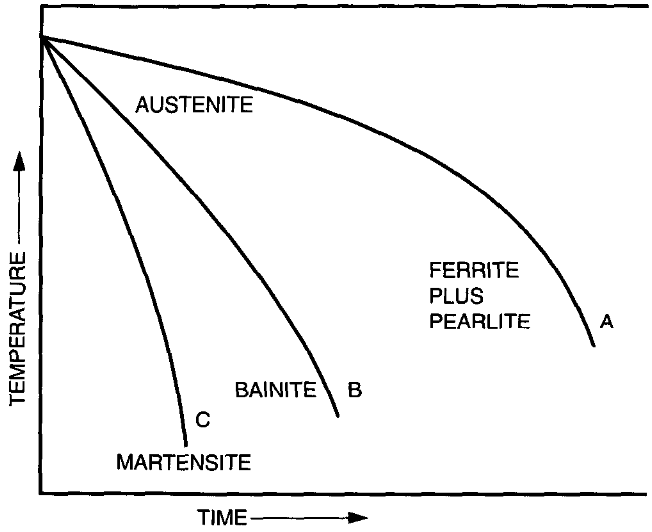


Figure C-8—Simplified Continuous Cooling Diagram

With very slow cooling rates (A), a mixture of ferrite and pearlite is likely, and forms at a relatively high temperature. These are the lowest strength steels and are very ductile. At higher cooling rates (B), but lower temperatures, bainite can be formed. Bainite has higher strength and has considerable notch toughness. At still higher rates (C), and the lowest temperature, martensite can be expected. Martensite is very strong but tends to be brittle in the as-quenched condition. In most cases, the martensite is considered to be undesirable because it lacks toughness and because it is prone to hydrogen-induced cracking. By using low-hydrogen welding processes, however, the martensitic welds can provide very high strengths when that property is desired.

CONTINUOUS SEQUENCE

A longitudinal sequence in which each weld pass is made continuously from one end of the weld to the other. See STANDARD WELDING TERMS.

CONTINUOUS WAVE LASER

A laser having an output that operates in a continuous rather than a pulsed mode. A laser operating with a continuous output for a period greater than 25 milliseconds is regarded as a continuous wave laser. See STANDARD WELDING TERMS.

CONTINUOUS WELD

A weld that extends continuously from one end of a joint to the other. Where the joint is essentially circular, it extends completely around the joint. See STANDARD WELDING TERMS.

CONTRACTION

The shrinkage of heated metal during cooling. *See* EXPANSION AND CONTRACTION, Arc Welding.

CONTROLLED ATMOSPHERE WELDING

Welding performed in an enclosure in which the conventional atmosphere has been replaced by an inert gas or a vacuum.

CONTROLLER

A device that controls the action of electrical machines connected to it.

CONVERTER

A machine that changes a-c electrical energy into dc, or dc into ac.

CONVEX FILLET WELD

A fillet weld having a convex face. See STANDARD WELDING TERMS. *See* Appendix 11.

CONVEXITY

The maximum distance from the face of a convex fillet weld perpendicular to a line joining the weld toes. See STANDARD WELDING TERMS. *See* Appendix 11.

CONVEXITY RATIO

The ratio of the reinforcement of a fillet weld to the theoretical throat of the weld. *See* FILLET WELD.

CONVEX ROOT SURFACE

The configuration of a groove weld exhibiting root reinforcement at the root surface. See STANDARD WELDING TERMS. *See* Figure C-9.

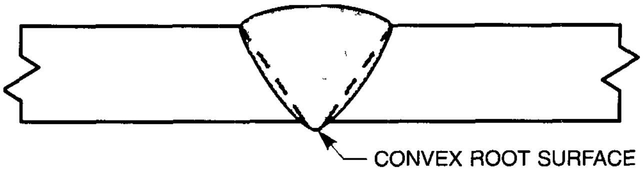


Figure C-9—Example of a Convex Root Surface

COOLING RATE

The rate at which designated points in a weld cool through well-defined temperature bands where metallurgical changes can occur. The rates of cooling depend on a number of factors, such as the thickness of the material being welded, its thermal conductivity, the preheat or interpass temperature, and the energy input used to make the weld. The effects these variables have on the cooling rate of steel are generally measured at 590 or 700°C (1100 or 1300°F), temperatures at which significant metallurgical changes are expected to occur while cooling. The maximum cooling rates occur in heavy sections, generally thicker than about 25 mm (1 in.). In thinner sections the cooling rates will be less because the heat sink provided has been reduced.

In very thin sheet, the cooling rate due to a heat sink will be very low and most of the cooling will be due to radiation or convection. *See* CRITICAL COOLING RATE, PREHEAT, *and* INTERPASS TEMPERATURE, Welding.

COOL TIME, Resistance Welding

The time interval between successive heat times in multiple-impulse welding or in the making of seam welds. See STANDARD WELDING TERMS.

COPPER

(Chem. symbol: Cu). A lustrous, reddish brown metallic element which is malleable, ductile, and an excellent conductor of heat and electricity. It is extremely tough, but very ductile. When heated to just under its boiling point, the metal becomes so brittle that it can be powdered. Copper is very resistant to atmospheric oxidation and corrosion. Copper has an atomic weight of 63.5; atomic number, 29; melting point, 1082°C (1980°F); boiling point, 2310°C (4190°F); specific gravity, 8.4.

Copper is widely used for electrical conductors and for the manufacture of electrical equipment. It is used in water tubing, valves, fittings, heat exchangers, chemical equipment and bearings. Copper is the electrical conductivity standard of the engineering world, with a rating of 100% IACS (International Annealed Copper Standard). Copper and most copper alloys can be welded, brazed and soldered.

COPPER ACETYLIDE

An unstable substance which forms when acetylene comes in contact with copper. This substance is likely to explode spontaneously and cause fire. ***Copper tubing must not be used to convey acetylene.***

COPPER ALLOYS

Copper is used extensively as an ingredient of bronze, brass and other nonferrous alloys. Molten copper has the distinctive characteristic of expanding on solidification.

Historical Background

Dr. R. H. Thurston's work on the strength of bronzes included an exhaustive series of tests on the strength and ductility of the copper-zinc series during the period 1875 to 1881.

In 1876, approximately five years before the publication of Dr. Thurston's work, John A. Tobin of the U.S. Engineer Corps patented the alloy known as *Tobin bronze*, a high-strength yellow bronze of approximately 60% copper, 1% tin, and 39% zinc composition.

Classification

Because there are hundreds of copper alloys in common use, they are classified in several general groups, based on (1) a similarity of the characteristics of the elements added to copper, and (2) a similarity in the reaction to the various welding processes of the alloys in a given group.

Copper and copper alloys are classified into nine major groups:

(1) Coppers—99.3% Cu minimum
(2) High-copper alloys—up to 5% alloying element
(3) Copper-zinc alloys (brass)
(4) Copper-tin alloys (phosphor bronze)
(5) Copper-aluminum alloys (aluminum bronze)
(6) Copper-silicon alloys
(7) Leaded coppers
(8) Copper-nickel-zinc alloys (nickel-silver)
(9) Special alloys

Copper and Copper Alloy Designations

Copper alloys are divided into the wrought and cast alloy categories shown in Table C-4. The Unified Numbering System (UNS) uses a five-digit number (following the prefix letter C to designate copper alloys) to classify metals. Copper alloys 1xxxx to 7xxxx are wrought alloys, and 8xxxx and 9xxxx are cast alloys. An alloy manufactured in both a wrought form and cast form can have two UNS numbers, depending on method of manufacture. Copper and copper alloys have commonly used names, such as oxygen-free copper, beryllium copper, Muntz metal, phosphor bronze, and low-fuming bronze; these names have been replaced with UNS numbers.

The following physical properties of copper alloys are important to welding, brazing, and soldering: melting temperature range, coefficient of thermal expansion, and electrical and thermal conductivity. Physical properties for some of the most widely used copper alloys are listed in Table C-5. The table includes data for electrical and thermal conductivity, and illustrates that when alloying elements are added to copper, electrical and thermal conductivity decrease drastically. The electrical and thermal conductivity of an alloy will significantly affect the welding procedures used for the alloy.

Base Metals

Copper alloy base metals are available as (1) sheet metal and plates, (2) pipes and tubes, (3) rods and shafts, (4) wire and cable, (5) bars and extruded architectural shapes, and (6) castings.

Alloying Elements

Copper is capable of alloying with at least thirty of the known elements. Seventeen of these elements, used singly or in combination and in varying proportions, combine with copper in a large number of commercial copper alloys with a wide range of properties. Zinc is the most important commercial alloying element and is used in proportions from 1% to 50% to make approximately fifteen different commercial brasses.

Aluminum. Copper-aluminum alloys may contain up to 15% aluminum as well as additions of iron, nickel, tin, and manganese. The solubility of aluminum in copper is 7.8%, although this is slightly increased with the addition of iron. Alloys with less than 8% aluminum are single phase, with or without iron additions. When the aluminum is between 9 and 15%, the system is two-phase and capable of either a martensitic or a eutectoid type of transformation. Increasing amounts of aluminum increase tensile strength, increase yield strength and hardness, and decrease elongation of the alloy. Aluminum forms a surface refractory oxide that must be removed during welding, brazing, or soldering.

Arsenic. Arsenic is added to copper alloys to inhibit the dezincification corrosion of copper-zinc alloys in

Table C-4
Classification of Copper and Copper Alloys

Category	Description	Range of UNS Numbers[a]
	Wrought alloys[b]	
Copper	Copper—99.3 percent minimum	C10100–C15760
High-copper alloys	Copper—96 to 99.2 percent	C16200–C19750
Brasses	Copper-zinc alloys	C20500–C28580
Leaded brasses	Copper-zinc-lead alloys	C31200–C38590
Tin brasses	Copper-zinc-tin alloys	C40400–C49080
Phosphor bronzes	Copper-tin alloys	C50100–C52400
Leaded phosphor bronzes	Copper-tin-lead alloys	C53200–C54800
Aluminum bronzes	Copper-aluminum alloys	C60600–C64400
Silicon bronzes	Copper-silicon alloys	C64700–C66100
Miscellaneous brasses	Copper-zinc alloys	C66400–C69950
Copper-nickels	Nickel—3 to 30 percent	C70100–C72950
Nickel-silvers	Copper-nickel-zinc alloys	C73150–C79900
	Cast alloys[c]	
Coppers	Copper—99.3 percent minimum	C80100-C81200
High-copper alloys	Copper—94 to 99.2 percent	C81300–C82800
Red brasses	Copper-tin-zinc and copper-tin-zinc-lead alloys	C83300–C83810
Semi-red brasses		C84200–C84800
Yellow brasses		C85200–C85800
Manganese bronze	Copper-zinc-iron alloys	C86100–C86800
Silicon bronzes and silicon brasses	Copper-zinc-silicon alloys	C87300–C87900
Tin bronzes	Copper-tin alloys	C90200–C91700
Leaded tin bronzes	Copper-tin-lead alloys	C92200–C94500
Nickel-tin bronzes	Copper-tin-nickel alloys	C94700–C94900
Aluminum bronzes	Copper-aluminum-iron and copper-aluminum-iron nickel alloys	C95200–C95900
Copper-nickels	Copper-nickel-iron alloys	C96200–C96900
Nickel-silvers	Copper-nickel-zinc alloys	C97300–C97800
Leaded coppers	Copper-lead alloys	C98200–C98840
Special alloys		C99300–C99750

a. Refer to ASTM/SAE Publication DS-56/HS 1086, *Metals and Alloys in the Unified Numbering System*, 6th Ed., 1933. ASTM, Philadelphia, PA., and Society of Automotive Engineers, Warrendale, Pa.

b. For composition and properties, refer to *Standards Handbook, Part 2—Alloy Data, Wrought Copper and Copper Alloy Mill Products*, 8th Ed., New York: Copper Development Association, Inc., 1985.

c. For composition and properties, refer to *Standards Handbook, Part 7—Data/Specifications, Cast Copper and Copper Alloy Products*, New York: Copper Development Association, Inc., 1970.

Table C-5
Physical Properties of Typical Wrought Copper Alloys

		Melting Range		Coefficient of Thermal Expansion at 200–300°C (68–572°F)		Thermal Conductivity at 20°C (68°F)		Electrical Conductivity, % IACS
Alloy	UNS No.	°C	°F	µm/ (m·°K)	µin./ (in.·°F)	W/ (m·°K)	BTU/ (ft·h·°F)	
Oxygen-free copper	C10200	1066–1088	1948–1991	17.6	9.8	370	214	101
Beryllium-copper	C17200	866–982	1590–1800	17.8	9.9	107–130	62–75	22
Commercial bronze	C22000	1021–1043	1870–1910	18.4	10.2	188	109	44
Red brass	C23000	988–1027	1810–1880	18.7	10.4	159	92	37
Cartridge brass	C26000	916–955	1680–1750	20.0	11.1	121	70	28
Phosphor bronze	C51000	955–1049	1750–1920	17.8	9.9	69	40	15
Phosphor bronze	C52400	943–999	1550–1830	18.4	10.2	50	29	11
Aluminum bronze	C61400	1041–1046	1905–1915	16.2	9.0	67	39	14
High-silicon bronze	C65500	971–1027	1780–1880	18.0	10.0	36	21	7
Manganese bronze	C67500	866–888	1590–1630	21.2	11.8	105	61	24
Copper-nickel, 10%	C70600	1099–1149	2101–2100	17.1	9.5	38	22	9
Copper-nickel, 30%	C71500	1171–1238	2140–2260	16.2	9.0	29	17	4.6
Nickel-silver, 65–15	C75200	1071–1110	1960–2030	16.2	9.0	33	19	6

water. Arsenic additions to copper alloys do not cause welding problems unless the alloy also contains nickel. Arsenic is detrimental to the welding of copper alloys that contain nickel.

Beryllium. The solubility of beryllium in copper is approximately 2% at 870°C (1600°F) and only 0.3% at room temperature. Therefore, beryllium easily forms a supersaturated solution with copper that will precipitate in an age-hardening treatment. Because thermal conductivity and melting point decrease with increased beryllium content, the higher beryllium content alloys are more easily welded. Beryllium forms a refractory oxide that must be removed for welding, brazing, or soldering. The welding operator must carefully avoid exposure to beryllium fumes.

Boron. Boron strengthens and deoxidizes copper. Boron deoxidized copper is weldable with matching filler metals, and other coppers are weldable with filler metals containing boron.

Cadmium. The solubility of cadmium in copper is approximately 0.5% at room temperature. The presence of cadmium in copper up to 1.25% causes no serious difficulty in fusion welding because it readily evaporates from copper at the welding temperature. A small amount of cadmium oxide may form in the molten metal, but it can be removed by using a flux.

Cadmium-copper rod is RWMA (Resistance Welding Manufacturers Association) Class 1 alloy. The small amount of cadmium strengthens pure copper while maintaining very high conductivity. This combination of properties makes this material ideal for electrodes used for resistance welding high-conductivity alloys such as aluminum. Because of federal restrictions regarding the use of heavy metals in manufacturing, cadmium-alloyed copper has been essentially replaced by an over-aged chromium copper. The welding operator must carefully avoid exposure to cadmium fumes.

Chromium. The solubility of chromium in copper is approximately 0.55% at 1038°C (1900°F) and less than 0.5% at room temperature. The phase that forms during age hardening is almost pure chromium. Like aluminum and beryllium, chromium can form a refractory oxide on the molten weld pool that makes oxyfuel gas welding difficult unless special fluxes are used. Arc welding requires a protective atmosphere over the molten weld pool.

Iron. The solubility of iron in copper is approximately 3% at 1040°C (1900°F) and less than 0.1% at room temperature. Iron is added to aluminum bronze, manganese bronze, and copper-nickel alloys to increase strength by solid solution and precipitation hardening. Iron increases the erosion and corrosion resistance of copper-nickel alloys. Iron must be kept in solid solution or in the form of an intermetallic to maintain the desired corrosion resistance benefit, particularly in copper-nickel alloys. Iron also acts as a grain refiner. Iron has little effect on weldability when used within the alloy specification limits.

Lead. Lead is added to copper alloys to improve machinability or bearing properties and the pressure tightness of some cast copper alloys. Lead does not form a solid solution with copper and is almost completely insoluble (0.06%) in copper at room temperature. Lead is present as pure, discrete particles and is still liquid at 327°C (620°F). Leaded copper alloys are hot-short and susceptible to cracking during fusion welding. Lead is the most detrimental alloying element with respect to the weldability of copper alloys. The welding operator must carefully avoid exposure to lead fumes.

Manganese. Manganese is highly soluble in copper. It is used in proportions of 0.05 to 3.0% in manganese bronze, deoxidized copper, and copper-silicon alloys. Manganese additions are not detrimental to the weldability of copper alloys. Manganese improves the hot working characteristics of multi-phase copper alloys.

Nickel. Copper and nickel are completely solid soluble in all proportions. Although copper-nickel alloys are readily welded, residual elements may lead to embrittlement and hot cracking. There must be sufficient deoxidizer or desulfurizer in the welding filler metal used for copper-nickel to provide a residual amount in the solidified weld metal. Manganese is most often used for this purpose.

Phosphorus. Phosphorus is used as a strengthener and deoxidizer in certain coppers and copper alloys. Phosphorus is soluble in copper up to 1.7% at the eutectic temperature of 650°C (1200°F), and approximately 0.4% at room temperature. When added to copper-zinc alloys, phosphorus inhibits dezincification. The amount of phosphorus that is usually present in copper alloys has no effect on weldability.

Silicon. The solubility of silicon in copper is 5.3% at 816°C (1500°F) and 3.6% at room temperature. Silicon is used both as a deoxidizer and as an alloying element to improve strength, malleability, and ductility. Copper-silicon alloys have good weldability, but are hot-short at elevated temperatures. In welding, the cooling rate through this hot-short temperature range should be fast to prevent cracking.

Silicon oxide forms on copper-silicon alloys at temperatures as low as 204°C (400°F). This oxide will interfere with brazing and soldering operations unless a suitable flux is applied prior to heating.

Tin. The solubility of tin in copper increases rapidly with temperature. At 788°C (1450°F), the solubility of tin is 13.5%; at room temperature, it is probably less than 1%. Alloys containing less than 2% tin may be single-phase when cooled rapidly.

Copper-tin alloys tend to be hot-short and to crack during fusion welding. Tin oxidizes when exposed to the atmosphere, and this oxide may reduce weld strength if trapped within the weld metal.

Zinc. Zinc is the most important alloying element used commercially with copper. Zinc is soluble in copper up to 32.55% at 927°C (1700°F) and 37% at room temperature. A characteristic of all copper-zinc alloys is the relative ease that zinc will volatilize from the molten metal with a very slight superheat.

Zinc is also a residual element in aluminum bronze and copper-nickel, and may cause porosity or cracking, or both.

COPPER ALLOY WELDING

Copper and copper alloys can be joined by welding, brazing, and soldering processes. Table C-6 summarizes the application of the most commonly used processes for major alloy classifications. The following information concerns some of the more important copper alloys and their weldability by various processes.

Copper Alloys, Weldability

Copper presents a unique welding problem because of its combined properties of (1) a relatively high melting temperature, 1083°C (1981°F), and (2) very high thermal conductivity. This means that a lot of energy is lost due to the very deep heat sink encountered by the arc. Fortunately, the problem is reduced by the alloys, because they can lower the thermal conductivity by as much as 70%, while simultaneously lowering the melting temperature by as much as 195°C (350°F). Heat losses due to high thermal conductivity can be reduced by controlling the preheat and interpass temperatures.

Arc Welding. Copper and most copper alloys can be joined by arc welding. Welding processes that use gas shielding are generally preferred, although shielded metal arc welding (SMAW) can be used for many noncritical applications.

Table C-6
Applicable Joining Processes for Copper and Copper Alloys

Alloy	UNS No.	Oxyfuel Gas Welding	SMAW	GMAW	GTAW	Resistance Welding	Solid-State Welding	Brazing	Soldering	Electron Beam Welding
ETP Copper	C11000–C11900	NR	NR	F	F	NR	G	E	G	NR
Oxygen-Free Copper	C102000	F	NR	G	G	NR	E	E	E	G
Deoxidized Copper	C12000 C123000	G	NR	E	E	NR	E	E	E	G
Berylium-Copper	C17000–C17500	NR	F	G	G	F	F	G	G	F
Cadmium/ Chromium Copper	C16200 C18200	NR	NR	G	G	NR	F	G	G	F
Red Brass—85%	C23000	F	NR	G	G	F	G	E	E	—
Low Brass—80%	C24000	F	NR	G	G	G	G	E	E	—
Cartridge Brass—70%	C26000	F	NR	F	F	G	G	E	E	—
Leaded Brasses	C31400–C38590	NR	NR	NR	NR	NR	NR	E	G	—
Phosphor Bronzes	C50100–C52400	F	F	G	G	G	G	E	E	—
Copper-Nickel—30%	C71500	F	F	G	G	G	G	E	E	F
Copper-Nickel—10%	C70600	F	G	E	E	G	G	E	E	G
Nickel-Silvers	C75200	G	NR	G	G	F	G	E	E	—
Aluminum Bronze	C61300 C61400	NR	G	E	E	G	G	F	NR	G
Silicon Bronzes	C65100 C65500	G	F	E	E	G	G	E	G	G

E = Excellent G = Good F = Fair NR = Not Recommended

Argon, helium, or mixtures of the two are used as shielding gases for gas tungsten arc welding (GTAW), plasma arc welding (PAW), and gas metal arc welding (GMAW). In general, argon is used when manually welding material that is either less than 3.2 mm (1/8 in.) thick, or has low thermal conductivity, or both. Helium or a mixture of 75% helium and 25% argon is recommended for mechanized welding of thin sections and for manual welding of thicker sections or alloys having high thermal conductivity. Small additions of nitrogen or hydrogen to the argon shielding gas may be used to increase the effective heat input.

The SMAW process can be used to weld a range of thicknesses of copper alloys. Covered electrodes of copper alloys for SMAW are available in standard sizes ranging from 2.4 to 4.8 mm (3/32 to 3/16 in.). Other sizes are available in certain electrode classifications. Submerged arc welding (SAW) has been used for welding copper alloys, although the use of this process is not widespread.

Arc welding should be done in the flat position when practical. In positions other than flat, particularly in the overhead position, GTAW or SMAW is preferred. For the vertical and overhead positions with some copper alloys, GMAW with pulsed power and small diameter electrodes is also suitable. Higher thermal conductivity and thermal expansion of copper and its alloys result in greater weld distortion than in comparable steel welds. The use of preheat, fixtures, proper welding sequence, and tack welds can minimize distortion or warping.

Gas Tungsten Arc Welding. The GTAW process can be used without filler metal to make square-butt joints on copper thinner than 3.2 mm (1/8 in.). Heavier sections, up to about 12 mm (1/2 in.), require the joints to be opened up and, therefore, filler metals are required. In many situations, the use of pulsed GMAW should be considered for thicknesses above 3.2 mm (1/8 in.). With the exception of the oxidizable alloys, direct-current straight polarity (DCEN) is the preferred type of current for GTAW.

Although argon shielding can be used, helium-rich gases are more suitable because they produce more heat at the work surface for a given welding current. When oxides might form on the surface of the base metal, especially with beryllium copper, alternating current is a better choice because of the cleaning action produced during the DCEP half cycle. In this case, argon-rich gases must be used.

Available as filler metals are copper, phosphor-, aluminum- and silicon-bronzes and copper-nickel. Filler metal specifications include: ANSI/AWS A5.6, *Specifications for Covered Copper and Copper Alloy Arc Welding Electrodes*; A5.7, *Specifications for Copper and Copper Alloy Bare Welding Rods and Electrodes*; and A5.27, *Specification for Copper and Copper Alloy Rods for Oxyfuel Gas Welding.*

Gas Metal Arc Welding. The GMAW process is an excellent choice for welding thicknesses of copper and its alloys which are greater than 3.2 mm (1/8 in.). It offers the advantages of high energy concentration at the weld pool, a reasonable deposition rate, and ease of use. Single-V joints are used with thicknesses up to 12 mm (1/2 in.), while double-V joints are preferred for thicker section sizes. Argon-rich gases are the rule. Helium in amounts up to 80% or 90% can be added to increase the heat input without affecting the desirable spray-arc transfer. Although very effective, the spray transfer is associated with a driving arc and fluid pool which preclude its use except in the flat or horizontal positions. The pulsed-spray mode allows welds to be made in all positions and also in thinner section sizes. A large range of alloy systems is available as filler metals. (*See* ANSI/AWS A5.7, *Specifications for Copper and Copper Alloy Bare Welding Rods and Electrodes.*)

Shielded Metal Arc Welding. Compared to the gas shielded methods, SMAW requires larger joint openings, higher welding currents, higher preheat and interpass temperatures, and more welder skill. In spite of the disadvantages, it still is being used by job shops which rely heavily on the process for welding other metals. Available as filler metals are copper; phosphor, aluminum and silicon bronzes, and copper-nickel. (*See* ANSI/AWS A5.6, *Specifications for Covered Copper and Copper Alloy Arc Welding Electrodes.*)

Plasma Arc Welding. The PAW process offers some unique advantages for welding copper and its alloys. Most important is the electrical energy concentration which is produced. This allows higher welding speed and reduces the size of the heat-affected zone (HAZ). Also, the high velocity plasma protects the tungsten electrode from the fumes produced by volatile alloys such as zinc and tin. Because of the high speeds and narrow welds, it lends itself nicely to mechanization. When filler metals are required, those used with the GTAW process are recommended. A precautionary note: The plasma arc process often uses hydrogen in the plasma gas to increase the energy concentration.

This must be avoided because the hydrogen can cause embrittlement due to the formation of water vapor when it reduces the oxides of copper which can be found in copper alloys.

Submerged Arc Welding. The SAW process is typically used for making mechanized welds in thick sections.

References for information on copper include the following:

ASTM/SAE Publication DS-56/HS 1086, *Metals and Alloys in the Unified Numbering System,* 6th Edition, 1993. ASTM, Philadelphia, Pa., and Society of Automotive Engineers, Warrendale, Pa.

American Welding Society. Welding Handbook, 8th Edition, Vol. 3, *Materials and Applications*, Miami, Florida. 1996.

American Welding Society. ANSI/AWS A5.6, *Specification for Covered Copper and Copper Alloy Arc Welding Electrodes*, Miami, Florida, Latest Edition.

For composition and properties, refer to *Standards Handbook, Part 2-Alloy Data, Wrought Copper and Copper Alloy Mill Products;* 8th Edition: Copper Development Association, Inc., New York. 1985.

For composition and properties, refer to *Standards Handbook, Part 7-Data/Specifications, Cast Copper and Copper Alloy Products*: Copper Development Association, Inc., New York. 1970.

Manufacturers of copper alloy base metals, rods, fluxes and electrodes are an excellent source of information on material specification, recommended welding procedures, and safe handling for the particular metals and supplementary materials used in joining the copper alloys.

Safe Practices

In addition to safe practices required for the welding, brazing or soldering process used on copper, a good ventilation system must be provided when welding copper alloys. This is particularly important when welding beryllium copper, or when using a beryllium-copper welding rod. The dust, fumes and mist of beryllium compounds in virtually every form are highly toxic. Because no safe maximum concentration has been established, extreme precaution should be taken to reduce dust, fumes and mist to zero. An effective high velocity ventilating system should be used regardless of the degree of contamination. The welding operator should also be protected with clothing, gloves and a breathing mask of the most improved type. *See* Appendix 12.

COPPER BACK-UP BARS

See BACKUP BARS AND PLATES.

COPPER WELDING

See COPPER ALLOY WELDING.

CORD, Thermal Spraying

Surfacing material in the form of a plastic tube filled with powder that has been extruded to a compact, flexible cord with characteristics similar to a wire. See STANDARD WELDING TERMS.

CORE

The iron or steel in the center of a coil in magnets, transformers, generators or motors through which magnetic lines of force pass.

CORE LOSS

The power loss in a machine due to eddy currents and hysteresis losses.

CORED SOLDER

A solder wire or bar containing flux as a core. See STANDARD WELDING TERMS.

CORE TRANSFORMER

Transformer with the windings placed on the outside of the core.

CORNER-FLANGE WELD

A nonstandard term for an edge weld in a flanged corner joint.

CORNER JOINT

A joint between two members located approximately at right angles to each other in the form of an L. See STANDARD WELDING TERMS.

A corner joint is formed by the angular placement of an edge of one base metal part on an edge or surface of another base metal part so that neither part extends beyond the outer surface plane of the other part.

CORONA, Resistance Welding

The area sometimes surrounding the nugget of a spot weld at the faying surfaces which provides a degree of solid-state welding. See STANDARD WELDING TERMS.

CORRECTIVE LENS

A lens ground to the wearer's individual corrective prescription. See STANDARD WELDING TERMS.

CORROSION

Gradual chemical or electro-chemical attack by atmospheric contaminants, moisture or other agents. It occurs in many forms, such as general pitting, and crevice and intergranular corrosion. It is evidenced most obviously as rust on steels or pits on aluminum. *See* STRESS-CORROSION CRACKING.

Causes: Wrong type of electrode diminishes corrosion resistance of the weld as compared to the parent metal; improper weld deposit for the corrosive media; the metallurgical effect of welding; and improper cleaning of the weld.

Corrections: Proper use of electrodes that provide equal or better corrosion resistance than the parent metal. When welding 18-8 austenitic stainless steel, the analysis of the steel and the welding procedure should be correct to avoid carbide precipitation: this condition can be corrected by annealing at 1040 to 1150°C (1900 to 2100°F).

CORROSION EMBRITTLEMENT

The embrittlement produced in some alloys due to exposure to a corrosive which attacks the grain boundaries. Such corrosion can be particularly troublesome in the coarse grained regions of weld heat-affected zones.

CORROSIVE FLUX

A flux with a residue that chemically attacks the base metal. It may be composed of inorganic salts and acids, organic salts and acids, or activated rosin. See STANDARD WELDING TERMS.

COSMETIC PASS

A weld pass made primarily to enhance appearance. See STANDARD WELDING TERMS.

CO_2 WELDING

A nonstandard term for gas metal arc welding with carbon dioxide shielding gas.

COVALENT BOND

A primary bond arising from the reduction in energy associated with overlapping half-filled orbitals of two atoms. See STANDARD WELDING TERMS.

COVERED ELECTRODE

A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization, and can serve as a source of metallic additions to the weld. See STANDARD WELDING TERMS. *See also* SHIELDED METAL ARC WELDING, Covered Electrodes.

The core of the covered electrode consists of either a solid metal rod of drawn or cast material or one fabricated by encasing metal powders in a metallic sheath. The core rod conducts the electric current to the arc and provides filler metal for the joint.

The electrode covering consists of metal and alloy powders, pulverized minerals, and organic materials such as cellulose and silicate binders. The primary functions of the electrode covering are to provide arc stability and to shield the molten metal from the atmosphere with gases created as the coating decomposes from the heat of the arc. Other characteristics contributed by the electrode covering include alloying the weld metal, producing slags to protect and shape the weld pool and providing a dam to help support weld metal in vertical joints.

The shielding medium and the ingredients in the covering and the core wire control the mechanical properties, chemical composition, and metallurgical structure of the weld metal, as well as the arc characteristics of the electrode. The composition of the electrode covering varies according to the type of electrode.

COVER GLASS

A clear glass used to protect the lens in goggles, face shields and helmets from spatter material.

COVER LENS

A nonstandard term for a round cover plate.

COVER PLATE

A removable pane of colorless glass, plastic-coated glass, or plastic that covers the filter plate and protects it from weld spatter, pitting, or scratching. See STANDARD WELDING TERMS.

CRACK

A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement. See STANDARD WELDING TERMS. *See* Appendix 9.

CRACKING OF WELD METAL

Causes: Joint too rigid; welds too small for size of parts joined; poor welds; improper joint preparation; unsuitable electrode.

Corrections: Design the structure and develop a welding procedure to eliminate rigid joints; increase weld size to handle the load; make a full size weld in short sections; develop a welding sequence that leaves the ends of the joint free to move as long as possible; proper fusion; preheating; prepare uniform joints.

CRANKSHAFT JOURNAL REBUILDING

Automotive industry metallurgists have developed superior crankshafts that eliminate most problems of the past. However, if it is necessary to repair an older, badly worn crankshaft journal, it can be built up with either SMAW, GTAW, or GMAW. Before welding, it is usually good practice to turn the worn surface and shoulder down evenly, so that when the weld metal is added it will be of uniform thickness and structure. The shoulder should be turned down to solid base metal and rebuilt with weld metal.

Because of its low heat input, GMAW is probably the fastest and least expensive method of rebuilding crankshaft journals. The short-arc method of GMAW deposits a steel bond on the crankshaft which is equal to the shaft in density. The alloy of the shaft mixes with the welding wire to form a homogeneous deposit which blends with the original metal.

The shaft can be built up with GMAW and an automatic welding head. The shaft is centered in a lathe and turned. The welding head is attached in a fixed position, then indexed over the weld zone. The welding wire is fed automatically to the arc.

The weld deposit is made while the crankshaft rotates in the lathe at 2 rpm. Welding is done uphill, using a high-tensile steel electrode, 0.8 mm (.030 in.) diameter, with a 75% argon-25% carbon dioxide shielding gas mixture. Distortion is held to 0.13 mm (0.005 in.), and the average weld time for rebuilding a journal is three to five minutes. Shielded metal arc welding can also be used with either bare or coated electrodes.

CRATER

A depression in the weld face at the termination of a weld bead. See STANDARD WELDING TERMS.

CRATER CRACK

See STANDARD WELDING TERMS. *See* Appendix 9.

Radial cracks formed in weld craters as the weld pool solidifies and shrinks. They are caused by low melting constituents which are segregated in the pool during solidification and cause the metal to tear due to shrinkage stresses. When possible, they should be eliminated by allowing the arc to dwell in the crater for a short time instead of removing the electrode quickly. In this way, the crater can fill up and reduce the shrinkage forces. Also helpful with gas tungsten arc welding (GTAW) is a technique which allows the current to decay slowly at the end of a weld to reduce the solidification rate.

CRATER FILL CURRENT

The current value during crater fill time. See STANDARD WELDING TERMS.

CRATER FILL TIME

The time interval following weld time but prior to meltback time during which arc voltage or current reach a preset value greater or less than welding values. Weld travel may or may not stop at this point. See STANDARD WELDING TERMS.

CRATER FILL VOLTAGE

The arc voltage value during crater fill time. See STANDARD WELDING TERMS.

CREEP

The flow, or plastic deformation, of metals when held for long periods of time at stresses below their normal yield strength. The effect is particularly noticeable when the temperature during stressing approaches the recrystallization temperature of the metal.

Creep may produce effects of consequential magnitude at normal temperatures as well as at elevated temperatures, depending on the material and the degree to which freedom from continuing deformation can be tolerated.

In addition to determination of creep rate at elevated temperatures, timed testing includes measurement of time for fracture, when sufficient load is applied, and measurement of stress relaxation by creep. These additional tests *are called creep rupture, stress rupture, notched-bar rupture* and *relaxation tests*. Standard practices for most of these long time tests can be found in ASTM E139, *Conducting Creep, Creep Rupture and Stress Rupture Tests of Metallic Materials.* These tests are conducted with a relatively slow heating rate.

CREEP, (Regulator)

Any increase in the outlet pressure of a regulator; a term applied to gas regulators which may "creep" (because of slow pressure increases) when the seat does not close against the inlet nozzle, allowing gas to enter the regulator beyond the pressure desired. A creeping regulator is detected by movement of the indicator in a low-pressure gauge.

In gas welding, with the valves on the torch closed, regulator creep occurs when the hand on the dial does not remain stationary, but indicates a higher pressure than it did while operating the torch. A creep of a few pounds is allowable, but when the creep reaches 50 pounds beyond the operating pressure, using the creeping regulator is dangerous, since the pressure in the body of the regulator may burst the diaphragm or the gauge.

CRITICAL COOLING RATE

When steels cool from high temperatures at which they have an austenitic microstructure, they can transform to a number of very different microstructures, such as pearlite, bainite and martensite. The structure formed depends on the composition of the steel and the rate at which it cools. With very slow cooling rates, a mixture of ferrite and pearlite is likely. This is relatively weak but very ductile. At higher cooling rates, bainite will form. It is very strong and very tough. At still higher rates, martensite can be expected. This structure is very strong but tends to be brittle. In most cases, the martensite is considered to be undesirable, so high cooling rates must be avoided. However, heavily alloyed steels are called *hardenable* because they will produce martensite at low cooling rates, so the critical cooling rates for steels with high hardenability are much lower than those for steels with low hardenability. With knowledge of these critical cooling rates, and using the cooling rate equations, welding personnel can determine what the welding procedures should be to avoid undesirable microstructures, or to obtain those that are specified. *See* CONTINUOUS COOLING DIAGRAM, METALLURGY, *and* MARTENSITE.

CRITICAL PRESSURE

The pressure sufficient to cause a gas to be liquefied when at its critical temperature.

CRITICAL RANGE (Temperature)

The range of temperature in steels in which the reversible change from austenitic (stability at high temperatures) to ferrite and cementite (stability at low temperatures) occurs. The upper limit varies with the carbon content. The lower limit for slow heating and cooling is about 700°C (1292°F).

CRITICAL TEMPERATURE

The preferred metallurgical term is *transformation temperature.* It is the temperature at which a phase change can occur. Sometimes it is used to denote the limiting temperature of a transformation range. Such transformations are expected with all metals and their alloys, and when reversible, transformations on heating occur at higher temperatures than during cooling.

In the case of steels, some of the critical temperatures are identified as:

Ac_1—The temperature at which austenite begins to form during heating

Ac_3—The temperature at which the transformation of ferrite to austenite is completed during heating

Ar_1—The temperature at which austenite completes transformation to ferrite on cooling

Ar_3—The temperature at which austenite begins to transform to ferrite on cooling

Ms—The temperature at which austenite begins to transform to martensite on cooling. Note that this transformation is not reversible. On heating, martensite first transforms to ferrite.

The critical temperature is customarily associated with the following phenomena: hardening when quenched; loss of magnetism; absorption of heat; formation of coarse grain on cooling.

On heating a metal, the eutectoid change at approximately 720°C (1328°F) is known as Ac_1 (lower critical temperature), while the final temperature of transformation to austenite (upper critical temperature) is known as Ac_3. On cooling, the temperatures are somewhat lower due to hysteresis, and are known as Ar_3 (corresponding with Ac_3) and Ar_1 (corresponding with Ac_1) respectively.

CROSS MAGNETISM

The magnetic lines of force produced in an armature that are at right angles to those produced by the field coils.

CROSS-SECTIONAL SEQUENCE

The order in which the weld passes of a multiple-pass weld are made with respect to the cross section of the weld. See STANDARD WELDING TERMS. *See also* BLOCK SEQUENCE *and* CASCADE SEQUENCE.

CROSS WIRE WELDING

A common variation of projection welding wherein the localization of the welding current is achieved by the intersection contact of wires, and is usually accom-

panied by considerable embedding of one wire into another. See STANDARD WELDING TERMS.

A typical cross wire resistance weld is shown in Figure C-10. *See also* PROJECTION WELDING *and* RESISTANCE WELDING.

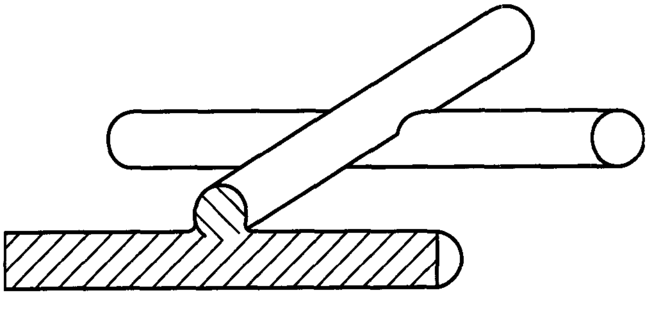


Figure C-10—Section of a Typical Cross Wire Weld

CRYOGENICS

Cryogenics is the science of very low temperatures and their phenomena. The definition for cryogenic temperatures has changed during the years as it became easier to produce cryogenic products. In about 1950, the definition of a cryogenic temperature was −73°C (−100°F). Now it has been reduced to −128°C (−200°F). Carbon dioxide, which boils at −78°C (−109°F) is no longer considered a cryogenic gas.

The commercial gas components in air, boiling temperatures at atmospheric pressure, and volume fraction in air are shown in Table C-7.

Table C-7
Commercial Components of Air

Gas	Boiling Point °C	Boiling Point °F	Fraction Volume
Nitrogen	−196	−320	78%
Oxygen	−183	−297	21%
Argon	−186	−303	1%
Neon	−246	−411	15 ppm
Krypton	−153	−244	1 ppm
Xenon	−108	−163	0.1 ppm

The welding industry relies heavily on cryogenic technology, because oxygen is needed for oxyfuel welding and cutting, and argon is needed for the GMAW and GTAW processes. These gases, along with nitrogen, are produced in air separation plants using a process developed by Dr. Karl von Linde about 1890. By 1910, air separation plants, although small, became relatively common in the United States.

Air separation plants have increased in size to the extent that a single plant can produce 2800 tons of oxygen per day. Air separation plants use high volume, low pressure pumps, turbo-expanders and reversing exchangers to drop the incoming air temperature below the −198°C (−325°F) needed to liquefy it. The liquid is then separated by fractional distillation in bubble towers; the liquid oxygen is removed at the bottom and the cooler nitrogen from the top. The separation and purification processes continue until the gases listed in Table C-7 are produced at the purity levels required by customers.

In addition to the welding industry, a diversity of industries depend heavily on cryogenic gases for their technology. For example, liquid oxygen and argon are supplied by the ton for refining steel and heat treating; liquid nitrogen is used for freezing foods.

CRYOGENIC VESSELS

Cryogenic vessels are containers that are used to store products at temperatures lower than −128°C (−200°F).

One of the most important aspects of storing gases in the cryogenic (liquid) state is the saving in space. Gaseous oxygen requires 862 times more storage volume than liquid oxygen. Gaseous nitrogen requires 696 times more storage volume.

Cryogenic vessels must be fabricated of materials that retain good impact values at extremely low temperatures, and must have effective insulation around the inner vessels to protect them from atmospheric heat.

The main problem in cryogenics is to maintain the gases at temperatures ranging from −70 to −270°C (−100 to −452°F). The solution is in the correct selection and fabrication of materials for low temperature applications. Materials generally used are 9% nickel steel, 304 stainless steel, and various aluminum alloys, most notably 5083. All have good weldability and ductility, prime requirements for use in low-temperature service. While these are good selections, there is always a reasonable concern that these high-strength materials may be subject to brittle fracture under certain conditions. A notched specimen must be used in ductility tests. Smooth specimens may show amazing ductility at low temperatures, but a notched specimen may fail in brittle fracture, indicating its notch sensitivity. *See* CHARPY TEST.

Actually, copper was the most widely used material for early low-temperature work. One of the more successful alloys in such service is silicon bronze containing 3% silicon and 1% manganese.

9% Nickel Steel

Nine percent nickel steel is a low-carbon, high-nickel, steel plate material primarily intended for pressure vessel use at low temperatures. When quenched and tempered, or double-normalized and tempered, it has good notch toughness characteristics down to –195°C (–320°F).

Fabrication with 9% nickel steel has been done with a high-nickel, chromium-iron electrode (Inco® Weld A). The composition of this electrode produces joints with strengths higher than the minimum specified for the A353 steel.

A quenched and tempered 9% nickel steel in the as-welded condition exhibits low-temperature notch toughness equal to that of the double-normalized and tempered metal. A basic requirement in welding 9% nickel steel is extreme cleanliness. Before fabrication, components should be pickled or sandblasted.

Immediately prior to fitting the components together to close or restrict access to inner surfaces of a vessel, these surfaces should be cleaned again to ensure removal of all dirt and oil. A muriatic acid wash, followed by a water rinse, is suggested.

For stress relieving after welding, a furnace with a neutral or reducing atmosphere is recommended. Normally, a detrimental scale should not appear under these stress relief conditions. However, as a final precaution, another muriatic acid wash and water rinse after stress relief will remove any remaining scale and loose particles.

Stress relief should be conducted in accordance with American Society for Testing Materials (ASTM) and ASME code specifications. Nine percent nickel steel can meet and exceed these specifications in the as-welded condition.

Stainless Steel

The stainless steels, especially type 304, are the most widely used material for containers subject to temperatures lower than –195°C (–320°F). Although somewhat expensive, austenitic stainless steel has been a favored material for cryogenic containers. A disadvantage of austenitic stainless is that it may transform to brittle martensitic stainless when exposed to extremely low temperatures over a prolonged period. Some of the first vessels fabricated with A363 steel were welded with 310 stainless steel electrodes. Weld joint strength, however, was somewhat below the minimum specified tensile strength. Thus, the designer could not make full use of the strength of this steel. In all other aspects, the 25Cr, 20Ni stainless steel joint was satisfactory.

Fluorine, which is a super-cryogenic deoxidizer used as a rocket propellent, is highly corrosive, and must be stored in Monel® vessels. Fluorine is the most powerful oxidizing agent known, reacting with practically all known organic and inorganic substances.

Aluminum

For cryogenic service in the range of –100 to –195°C (–150 to –320°F), two weldable aluminum alloys, 5083 and 5086, are frequently used for cryogenic vessels. These are both high-strength alloys of aluminum, magnesium and manganese, but they have the excellent weld ductility characteristic of other alloys in the 5XXX series.

One of the most popular of these aluminum-magnesium-manganese alloys, 5083, offers a combination of properties required for cryogenic service: good weldability and weld ductility, resistance to corrosion and stress concentration, and in addition, light weight.

Since high-strength materials may be subject to brittle fracture under certain conditions, ductility at low temperatures is a major concern. An extensive battery of tests, however, has proved that at temperatures as low as –195°C (–320°F), 5083-H113 aluminum alloy plate and welds made with 5183 alloy filler can be used without the occurrence of ductile-brittle transition.

The 5083-H113 aluminum alloy plate was used for the study because its temper is much stronger than the annealed 5083-0, and since the latter is a softer, more ductile-tempered plate, it would be at least equivalent to the H113 in brittle fracture resistance.

In the unnotched tensile impact tests, the increased strain rate did not produce a ductile-brittle transition in either the 5083 plate or its welds. In the notched tensile impact tests, a ductile-brittle transition was not produced in either the 5083 plate or its heat-affected zone, or in the 5183 weld deposit. Plate properties were virtually insensitive to testing temperature.

In the Charpy keyhole impact tests (most likely to produce a ductile-brittle transition in fracture-susceptible material) the results were the same as in the tensile impact tests.

Vessel Construction

The basic construction of this type of vessel consists of two or more concentric tanks, one inside the other. The most common type of large volume storage or transport container consists of an inner vessel and an outer vessel, with the vacuum space between filled with insulating powder such as pearlite, silica aerogel, phenolic spheres, or diatomaceous earth. The area between the vessels is evacuated to a high vacuum.

The outer shell is constructed to withstand rough treatment and to act as protection for the inner vessel. The inner shell is supported within the outer shell by rods, cables, or chains strong and flexible enough to withstand lateral or vertical jars and sudden forces of acceleration. Connection between the shells should have a minimum contact area consistent with adequate strength to minimize heat flow from the shell to the liquid in the inner vessel.

CUP

A nonstandard term when used for GAS NOZZLE.

CUP FRACTURE

The shape of a fracture of tensile test specimens when the exterior portion is extended and the internal relatively depressed, so that it looks like a cup. When only a portion of the exterior is extended, the terms *half-cup* and *quarter cup* are used.

CUPPING

A defect in wire which causes it to break with a cup fracture accompanied by very little reduction in area.

CUPRO-NICKEL

A high-nickel content copper alloy.

CURIE POINT

Although the change from gamma to alpha iron involves an atomic rearrangement, there is another change at about 770°C (1415°F) known as the *Curie point*, below which alpha iron becomes ferromagnetic. This is probably caused by an electron rearrangement or shift in the atoms themselves, although the exact reason has not been established.

CURRENT

The flow of electricity through a circuit.

CURRENT DENSITY

Current density is an indication of the amperes per cm^2 ($in.^2$) of cross sectional area of an electrode. To calculate the current density for an electrode, divide the amperes being used by the cross sectional area of the electrode.

CUTTER

See STANDARD WELDING TERMS. *See* THERMAL CUTTER.

CUTTING

See STANDARD WELDING TERMS. *See* THERMAL CUTTING.

CUTTING ATTACHMENT

A device for converting an oxyfuel gas welding torch into an oxygen cutting torch. See STANDARD WELDING TERMS.

CUTTING, Bevel

See THERMAL CUTTING, OXYFUEL GAS CUTTING, Plate Edge Preparation.

CUTTING BLOWPIPE

A nonstandard term for OXYFUEL GAS CUTTING TORCH.

CUTTING ELECTRODE

A nonfiller metal electrode used in arc cutting. See STANDARD WELDING TERMS. *See also* METAL ELECTRODE.

CUTTING HEAD

The part of a cutting machine in which a cutting torch or tip is incorporated. See STANDARD WELDING TERMS.

CUTTING NOZZLE

A nonstandard term for CUTTING TIP.

CUTTING OPERATOR

See STANDARD WELDING TERMS. *See* THERMAL CUTTING OPERATOR.

CUTTING PROCESSES

See AIR CARBON ARC CUTTING, GAS TUNGSTEN ARC CUTTING, PLASMA ARC CUTTING, OXYFUEL GAS CUTTING, *and* FLAME CUTTING.

CUTTING TIP

The part of an oxygen cutting torch from which the gases issue. See STANDARD WELDING TERMS. *See* Figure C-11.

CUTTING TORCH

See STANDARD WELDING TERMS. *See* AIR CARBON ARC CUTTING TORCH, GAS TUNGSTEN ARC CUTTING

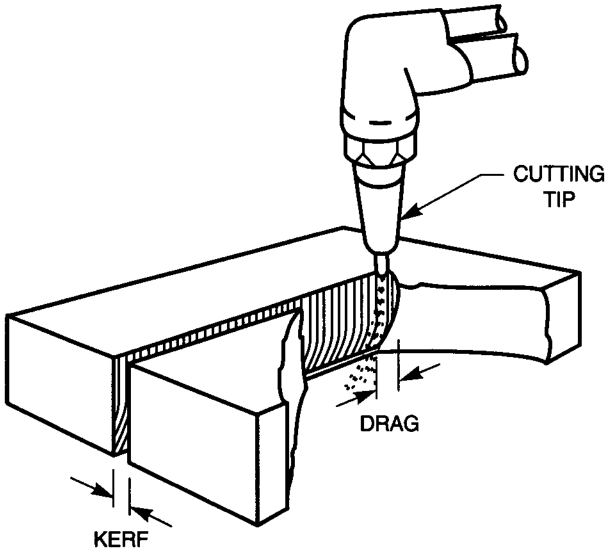


Figure C-11—Oxygen Cutting

TORCH, PLASMA ARC CUTTING TORCH, *and* OXYFUEL GAS CUTTING TORCH.

CUTTING, Underwater

See OXYFUEL GAS CUTTING, Underwater Cutting; *and* PLASMA ARC CUTTING.

CYCLE

The duration of alternating current represented by the current increase from an initial value to a maximum in one direction then to a maximum in the reverse direction and its return to the original initial value. See STANDARD WELDING TERMS.

CYLINDER

See STANDARD WELDING TERMS. *See* GAS CYLINDER.

CYLINDER MANIFOLD

A multiple header for interconnection of gas sources with distribution points. See STANDARD WELDING TERMS.

Individual cylinders cannot supply high rates of gas flow, particularly for continuous operation over long periods of time. Manifolding of cylinders is one answer to this problem. A reasonably large volume of gas is provided by this means, and it can be discharged at a moderately rapid rate. Manifolds are available as portable or stationary units.

Portable. Portable manifolds are useful where moderate volumes of gas are required for jobs of a nonrepetitive nature, either in the shop or in the field. Two portable systems are commonly used. Both permit the manifolded cylinders to be located near the point of use. In one type of portable manifold, Ts are connected to the individual cylinder valves, and leads (pigtails) successively join the Ts together. The gas from each cylinder passes through the T, into the main gas stream, and finally, to a regulator that serves the entire group of cylinders.

In the second type of portable manifold, the cylinders are connected by individual cylinder leads (pigtails) to a common coupler block that is connected to a pressure reducing regulator.

Stationary. Stationary manifolds, Figure C-12, are installed in shops or plants where larger volumes of gas are required. This type of manifold feeds a pipeline system distributing the gas to various stations throughout the plant. This arrangement allows many operators to work from a common pipeline system without interruption. Alternatively, it may supply large automatic torch brazing or oxygen cutting operations.

This type of manifold consists of an adequately supported high-pressure header to which a number of cylinders are connected by means of pigtails. One or more permanently mounted regulators reduce the pressure and regulate the flow of gas from the manifold into the plant piping system.

An important protective device for the fuel gas pipeline system is the hydraulic seal, or hydraulic flashback arrester, which keeps flashback originating at a station from passing further into the system. It consists of a small pressure vessel partly filled with water through which the gas supply flows. The gas continues through the space above the water level and through the vessel head to the station regulator. A flashback of high pressure backup will set off the relief valve to the vessel head, which will vent the pressure to the outside atmosphere. A check valve prevents the water from backing up into the line.

Regulations and Safe Practices for Manifolds and Pipelines. The rules and regulations set forth in the current issue of NFP A51, *Standard for the Installation and Operation of Oxyfuel Gas Systems for Welding and Cutting,* as recommended by the National Fire Protection Association, govern the installation of oxygen and acetylene manifolds and pipelines. In all cases, manifolds should be obtained from reliable suppliers and

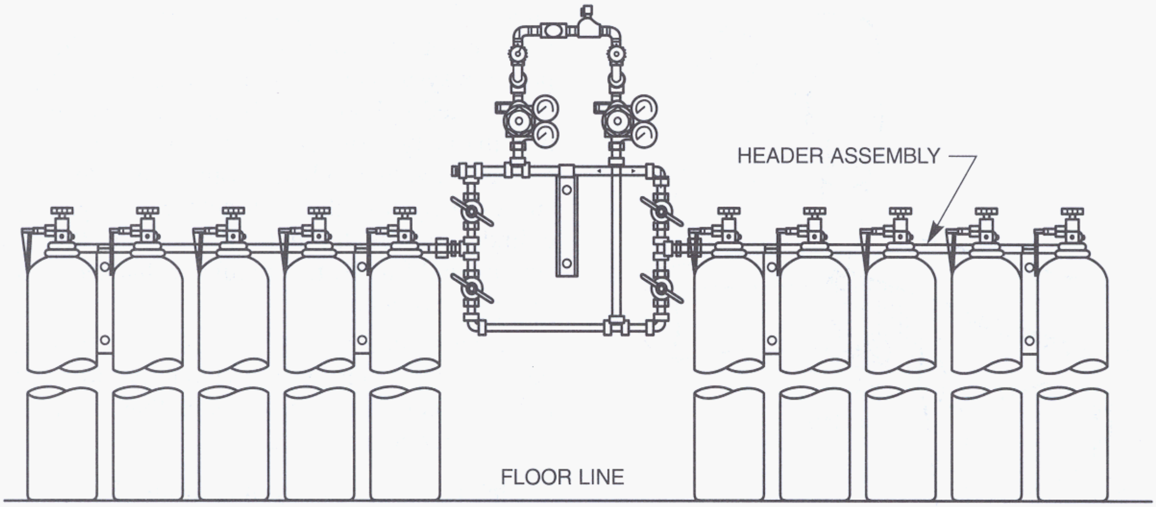


Figure C-12—Typical Arrangement for a Stationary Gas Manifold

installed by personnel familiar with proper construction and installation of manifolds and pipelines.

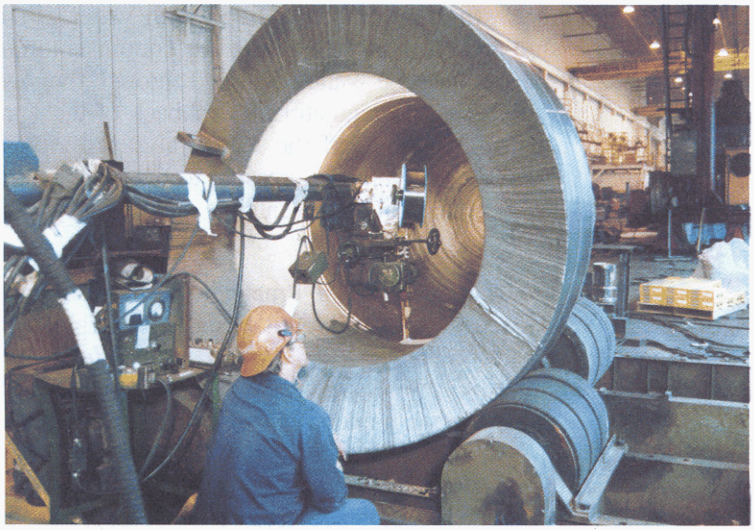
CYLINDERS, RULES FOR SAFE HANDLING

Consult the material safety data sheet for each gas product, available from the gas manufacturer. Refer to ANSI/AWS Z49.1 *Safety in Welding, Cutting, and Allied Processes. See* SAFE PRACTICES.

CYLINDER TRUCK

A wheeled cart designed to transport gas cylinders securely fastened in an upright position.

The most important quality in a cylinder truck is strength. It should be sufficiently strong to support the load while being moved; it should also be stable and well-balanced to minimize chances of cylinders being knocked over.



A worker supervises the two-pass submerged arc Monel® strip cladding of a carbon steel forging to be installed in the bottom of a horizontal pressure vessel

Photo courtesy of Beaird Industries

D

DC or D-C

Abbreviation for direct current. DC is hyphenated when used as an adjective, but not when used as a noun.

D-C ARC Welding

An arc welding process using a power source that supplies a direct current to the welding arc.

DCEN or DC (–)

Abbreviation for *direct current electrode negative*. *See* DIRECT CURRENT ELECTRODE NEGATIVE.

DCEP or DC (+)

Abbreviation for *direct current electrode positive*. *See* DIRECT CURRENT ELECTRODE POSITIVE.

DECARBURIZATION

The removal of carbon (usually referring to the surface of solid steel) by the action of media which reacts with the carbon to cause its oxidation.

DEEP DRAWING

As it refers to sheet metal, drawing is a process of forming flat sheet metal into hollow shapes by means of a punch that causes the metal to flow into a die cavity. If the depth of the formed part (die cavity) is one or more times the sheet thickness, the process is called *deep drawing*.

Examples of deep drawing are found in shell case forming, the forming of deep pans, and some automobile body panels and other parts. Alloys used for this purpose are required to have high ductility. The stock must be fine-grained, since a coarse-grained material will exhibit a very rough surface after forming, due to localized yielding, and the ductility of such material is generally too low to permit such extensive drawing without cracking.

DEEP WELDING

Deep welding is a term applied to a shielded metal arc welding (SMAW) technique which utilizes higher welding speeds than conventional methods, uses the benefits of greater arc penetration to obtain the required weld strength, and thereby decreases the cost of the welding operation. When applied to fillet welding, it is often called *deep-fillet welding*.

Basic Idea

For years, sound welds have been made by conventional methods in the accepted belief that deeper penetration was produced by slower arc speeds. In fact, however, faster speeds, within limits, result in greater penetration, while slower speeds tend to build up more of the weld metal on the surface. A fillet weld with greater penetration resulting from faster travel speed appears smaller, but its strength actually is as great or greater than the weld made at slow speed, which sacrifices penetration for buildup. Since increased penetration reduces the amount of deposited metal needed, the speed of welding can be increased without impairing the strength.

Travel Speed—Penetration

The key factor in applying arc force is making the arc travel fast enough to utilize the penetrating power of the arc. An analogy would be to squirt a stream of water through the nozzle of a hose to dig into the ground. The digging action of the stream of water is effective only when the stream is directed at the digging point in the dirt, not when directed into the pool of water that soon accumulates. To maintain the digging action, the of stream of water must be kept moving rapidly enough to stay ahead of the pool, because when it is directed into the pool, its force is expended in merely displacing and churning the water in the pool, not in digging into the ground.

The same principle can be applied in welding. When the arc is moved slowly, the pool of molten metal buffers the arc, and its force is expended in the molten pool instead of penetrating into the parent metal at the root of the joint. This molten metal merely flows along the joint under the weld without fusing to the parent metal below the depth of arc penetration. When the arc is moved forward rapidly enough, the arc force digs into the base metal and the result is good penetration.

When conventional arc speeds are used, there is usually a small puddle of molten metal under the arc, dissipating the arc force and preventing full penetration. The limiting speed is usually the highest speed at which the surface appearance remains satisfactory. *See* Figure D-1 for a comparison of arc penetration at conventional and high travel speeds. Note that deposited weld metal is minimized.

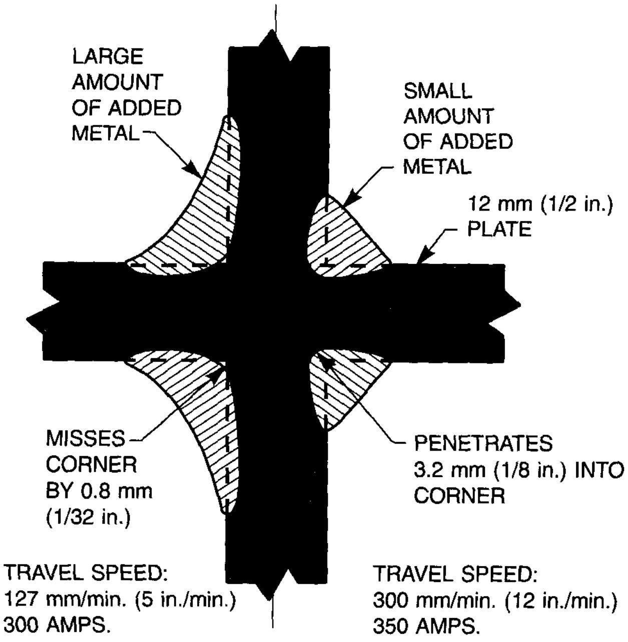


Figure D-1—Comparison of Arc Penetration at Conventional and High Travel Speeds

Effect of Current

An increase in current increases the arc force, which increases penetration, just as an increase in the analogous volume of water through the same size hose nozzle increases the digging power of the stream of water. To use higher currents, larger size electrodes may be needed. In general, the first indication of excess current is a poor surface appearance of the weld.

Effect of Arc Length

In a further comparison of the arc to the stream of water from a hose, to dig deeply into the dirt the nozzle must be kept as close to the ground as possible in order to avoid letting the stream of water spread out into an ineffective spray. In welding, when a long arc is held, heat is dissipated into the air, the stream of molten metal from the electrode to the work is scattered in the form of spatter, and the arc force is spread over a large area. The result is a wide, shallow bead instead of a narrow bead with deep penetration.

The advantages of deep-welding are: (1) less deposited metal, (2) increased rate of deposit, and (3) lower costs and simplified process.

Less Deposited Metal. By getting deeper penetration, the welded joint is comprised of more fused base metal and less deposited metal than in conventional welding. Since the deposited metal is relatively costly and the fused base metal can be utilized at practically no additional cost (other than labor to make the weld), the deep-welded joint is made at a proportionately reduced cost.

Greater penetration also allows changing joint preparation from a V-butt in 3/8-inch plate to a plain square-edge butt joint, reducing the amount of filler metal deposited by about 50%. This, in turn, reduces labor by almost 80%. Figure D-2 shows the use of arc penetration to reduce plate edge preparation.

Travel Speed. On welds where penetration is the major consideration, such as square-edge butt welds

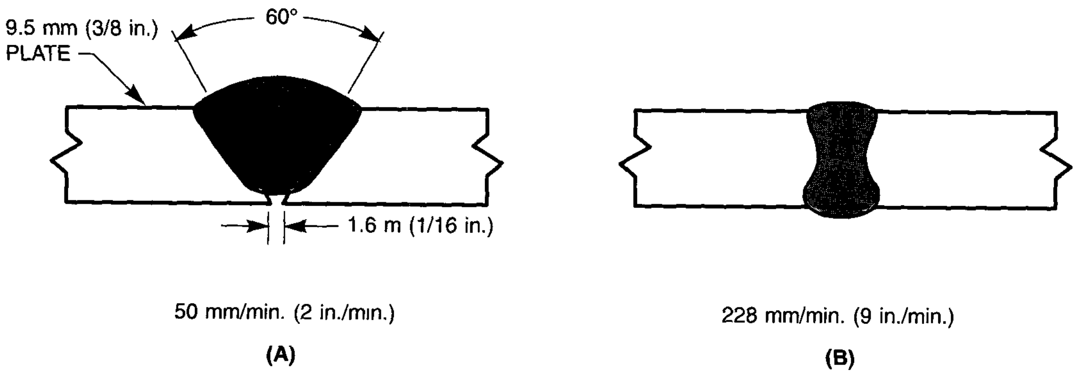


Figure D-2—Use of Arc Penetration to Reduce Plate Edge Preparation

and fillet welds made by deep-welding procedures, the travel speed is not proportional to the current, since the limiting factor for travel speed is the rate at which the slag will follow and cover the weld. Thus, the travel speed with this type of joint is determined by the slag-covering characteristics of the coated electrode, rather than by the melt-off rate.

DEFECT

A discontinuity or discontinuities that by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. The term designates rejectability. See STANDARD WELDING TERMS. *See also* DISCONTINUITY *and* FLAW.

Defects in welds are points, areas or volumes of a weld that are unsound, indicating that there is either a geometric or metallurgical discontinuity in the structure. Such defects may involve regions where metal is absent and there is no solid present (e.g., pores, voids, cracks), regions where there are low-density (compared to the weld metal) non-metallic inclusions (e.g., entrapped slag), regions where there are high-density (compared to the weld metal) inclusions (e.g., tungsten inclusions), or various geometric discontinuities (e.g., lack of penetration, missed seam, mismatch, or undercut).

Defects in welds can arise from one or more of the following sources:

(1) Improper joint design, preparation, alignment, or fit-up

(2) Inherent base or filler metal characteristics

(3) Process characteristics

(4) Environmental factors

Regardless of origin, defects almost always act as points of stress concentration, often reduce the cross-sectional load-bearing area, and sometimes degrade the properties of the metal, especially ductility and toughness.

Joint-Induced Defects

Improper or inappropriate joint design, preparation, alignment, or fit-up can lead to the following types of defects:

(1) Lack of complete penetration of the joint groove or seam because of improper design or inappropriate process or parameter selection

(2) Mismatch or surface offset due to misalignment of joint elements

(3) Severe distortion caused by unbalanced masses or excessive heat input

(4) Porosity resulting from entrapped air or volatile contaminants

(5) Shrinkage, voids or cracks resulting from poor fit-up or excessive restraint

(6) Underfill caused by poor fit

(7) Excessive dilution resulting from improper design or process selection.

Fusion-Zone Defects

Potential defects that can occur in the fusion zone of a weld include:

(1) Porosity caused by dissolved gases being released on solidification

(2) Entrapped slag within or between passes from the coatings of electrodes, the cores of flux-cored wires, or other sources, in processes employing slag

(3) Solidification hot cracks resulting from low-melting constituents at grain boundaries being pulled open by shrinkage stresses

(4) Severe macro-segregation resulting from gross unmixed dissimilar base metals or unmatched fillers and base metals

(5) Cold cracks caused by hydrogen embrittlement

(6) High-density inclusions resulting from contamination by non-consumable tungsten electrodes used in gas tungsten arc welding.

Partially-Melted Zone Defects

The three major defects in the partially-melted zone in fusion welds are solidification hot cracks, back-filled hot cracks, and hydrogen cold cracks.

Heat-Affected Zone Defects

Defects in the heat-affected zone of fusion welds include:

(1) Hydrogen cold cracks

(2) Liquation, reheat, or strain-age cracks

(3) Stress-corrosion cracks, weld decay cracks, or knife-line attack cracks (e.g., in sensitized stainless steels).

(4) Lamellar tears in base metals containing extensive non-metallic inclusions in the form of stringers

DELAYED CRACKING

A nonstandard term when used for cold cracking caused by hydrogen embrittlement. *See* COLD CRACK.

DELONG DIAGRAM

Named after W. T. DeLong. The DeLong Diagram is a method of calculating the Ferrite Number (FN) of a stainless steel weld deposit from its chemical composition. The DeLong Diagram is a modified Schaeffler Diagram predicting the Ferrite Number up to a maximum of 18. Ferrite is important in a weld because it is known to be beneficial in reducing cracking or fissuring in weld metal. *See* SCHAEFFLER DIAGRAM, WRC 1992 (FN) Diagram, *and* ANSI/AWS A5.22, Specification for Stianless Steel Electrodes for Flux Cored Arc Welding and Stainless Steel Rods for Gas Tungsten Arc Welding.

DELTA IRON

A term applied to iron which assumes the body-centered cubic structure between 1535 and 1400°C (2796 and 2552°F). When the temperature of the iron is reduced to 1400°C (2552°F), a transformation occurs and the iron below that temperature assumes a face-centered cubic structure and is called gamma iron. *See* METALLURGY.

DEMAGNETIZATION

The process of removing the magnetic fields of force from a magnetized substance. Demagnetization can be accomplished by (1) heating to a red heat, (2) by violent jarring, or (3) by holding the magnetized substance in the magnetic field of a solenoid operated on alternating current, and then gradually removing it.

DENDRITIC GROWTH

Growth of a crystalline solid (e.g., metal) from a melt along certain preferred crystallographic orientations or easy growth directions, resulting in a tree-like appearance in the grain. Dendrites typically contain primary and secondary branches or arms, and may even contain tertiary branches, all of which are aligned with easy growth directions. In welds made in alloys, dendritic growth can exhibit any or all of several substructures including: equiaxed dendritic, columnar dendritic, and cellular dendritic. *See* METALLURGY *and* WELD METAL.

DENSENESS

Compactness or soundness; the absence of porosity in a material or weld. *See* SPECIFIC GRAVITY.

DENSITY

The ratio of the mass of a homogeneous portion of matter to its volume. The density of solids is compared to water at 16.7°C (62°F), and gases are compared to air at 15.6°C (60°F) at a pressure of 762 mm (30 in.) of mercury (101 kPa [14.7 psi]).

DEOXIDIZED COPPER

Usually a 99 to 99.9% pure copper with a fractional percentage of one or more deoxidizing agents such as phosphorus, silicon, manganese, cadmium, zinc or aluminum. All of these agents act to reduce the cuprous oxide and thus entirely purge the metal of oxygen. Deoxidized copper is preferred when the metal is to be welded because weaknesses due to the cuprous oxide are avoided. *See* COPPER ALLOY WELDING.

DEOXIDIZING AGENT

Deoxidizing agents are elements such as aluminum, silicon, or titanium, which, when added to filler metals, eliminate oxygen and ensure sound welds free from oxide inclusions and porosity, or blowholes.

DEPOSIT

A nonstandard term when used for THERMAL SPRAY DEPOSIT.

DEPOSITED METAL, Surfacing

Surfacing metal that has been added during surfacing. See STANDARD WELDING TERMS.

DEPOSITED METAL, Welding, Brazing and Soldering

Filler metal that has been added during welding, brazing or soldering. See STANDARD WELDING TERMS.

Deposited metal refers to metal which has been added by any of these fusion processes or a non-fusion welding process (using friction) to apply a surface overlay during surfacing.

DEPOSITED METAL ZONE

In a fusion weld, the portion or area of the weld metal zone external to the original surface or edge planes of the base metal, and consisting substantially of deposited weld metal. For metal deposited by a non-fusion process, the deposited metal zone is the portion comprised of the metal added by friction.

DEPOSITION EFFICIENCY

See STANDARD WELDING TERMS. *See* ARC WELDING DEPOSITION EFFICIENCY *and* THERMAL SPRAYING DEPOSITION EFFICIENCY.

Deposition efficiency is the ratio of the weight of deposited metal to the net weight of electrodes or wire consumed, exclusive of any loss from stubs, or cut off.

An effective method for calculating the deposition efficiency for a given process is to use that process to deposit a measurable electrode weight on a clean plate of known weight, remove the slag and spatter, and reweigh. (If wire is a factor, the method is the same as above; wire weight is determined by weighing the reel of wire and subtracting the weight of the reel). The ratio of *weight added to the plate* to the *weight of the electrode used* is the deposition efficiency. Typical deposition efficiencies for various processes are shown in Table D-1. *See also* ARC WELDING DEPOSITION EFFICIENCY.

Table D-1
Typical Deposition Efficiencies for Various Welding Processes

Process	Deposition Efficiency
Shielded Metal Arc Welding	60 to 70%
Flux Cored Arc Welding (Self-Shielded)	70 to 80%
Flux Cored Arc Welding (Gas Shielded)	80 to 90%
Gas Metal Arc Welding (CO_2 Shielded)	85 to 90%
Gas Metal Arc Welding (Argon/CO_2 Shielded)	90 to 96%
Submerged Arc Welding	100%

DEPOSITION RATE

The weight of material deposited in a unit of time. See STANDARD WELDING TERMS.

Deposition rate is a direct measure of the amount of weld metal deposited in kg/h (lb/h) or kg/min (lb/min) under a given set of conditions.

The deposition rate of a specific electrode varies according to the type of power source. In a test using E6012 electrodes, the deposition rate with a d-c motor-generator welding machine was about 9% greater than the transformer-rectifier type, and 15% greater than one powered with an a-c transformer. The deposition rate of an electrode is always less than the melting rate because of losses by spatter and fumes.

The melting rate of an electrode, sometimes called the "burn-off rate," is the rate at which the electrode of a specific type and size is melted by a specific welding current. It is usually expressed in cm/min (in./min.). The melting rate increases rapidly as the current is increased, especially for small diameter electrodes.

DEPOSITION OR DEPOSIT SEQUENCE

A nonstandard term when used for WELD PASS SEQUENCE.

DEPTH OF BEVEL

The perpendicular distance from the base metal surface to the root edge or the beginning of the root face. See STANDARD WELDING TERMS. *See* Appendix 6.

DEPTH OF FUSION

The distance that fusion extends into the base metal or previous bead from the surface melted during welding. See STANDARD WELDING TERMS. *See also* JOINT PENETRATION. Figure D-3 illustrates depths of fusion for various types of welds.

DESCALING

A process of removing scale (i.e., mill oxide) from steel surfaces with a multi-flame torch. The term also refers to removal of mill or process-induced oxide by means of any of various mechanical or chemical processes (e.g., etching).

DETONATION FLAME SPRAYING

A thermal spraying process variation in which the controlled explosion of a mixture of fuel gas, oxygen, and powdered surfacing material is utilized to melt and propel the surfacing material to the substrate. See STANDARD WELDING TERMS.

DESTRUCTIVE TEST

Qualitative or quantitative tests which involve the destruction of a complete welded unit, or selected representative specimens that have been cut from the unit to be tested. Among the destructive tests are tensile, bend, nick break, impact, fatigue, specific gravity, hardness, drift and crush.

DIAL, DIAL GAUGE, or DIAL INDICATOR

The graduated face of a gauge, instrument or meter.

DIAPHRAGM

The flexible partition in a gas regulator under the regulator spring.

DIE

In resistance flash welding, a device on a fixture which holds the moving part. In manufacturing, a perforated block through which metal or plastic is drawn or extruded.

A die is a tool or device which imparts a desired shape, form or finish to a material, or which is used to impress an object or material. Also, a die is the larger of a pair of cutting or shaping tools, which, when moved toward one another, produce a certain form or impression by pressure or by a forceful blow. *See* RESISTANCE WELDING *and* FORGE WELDING.

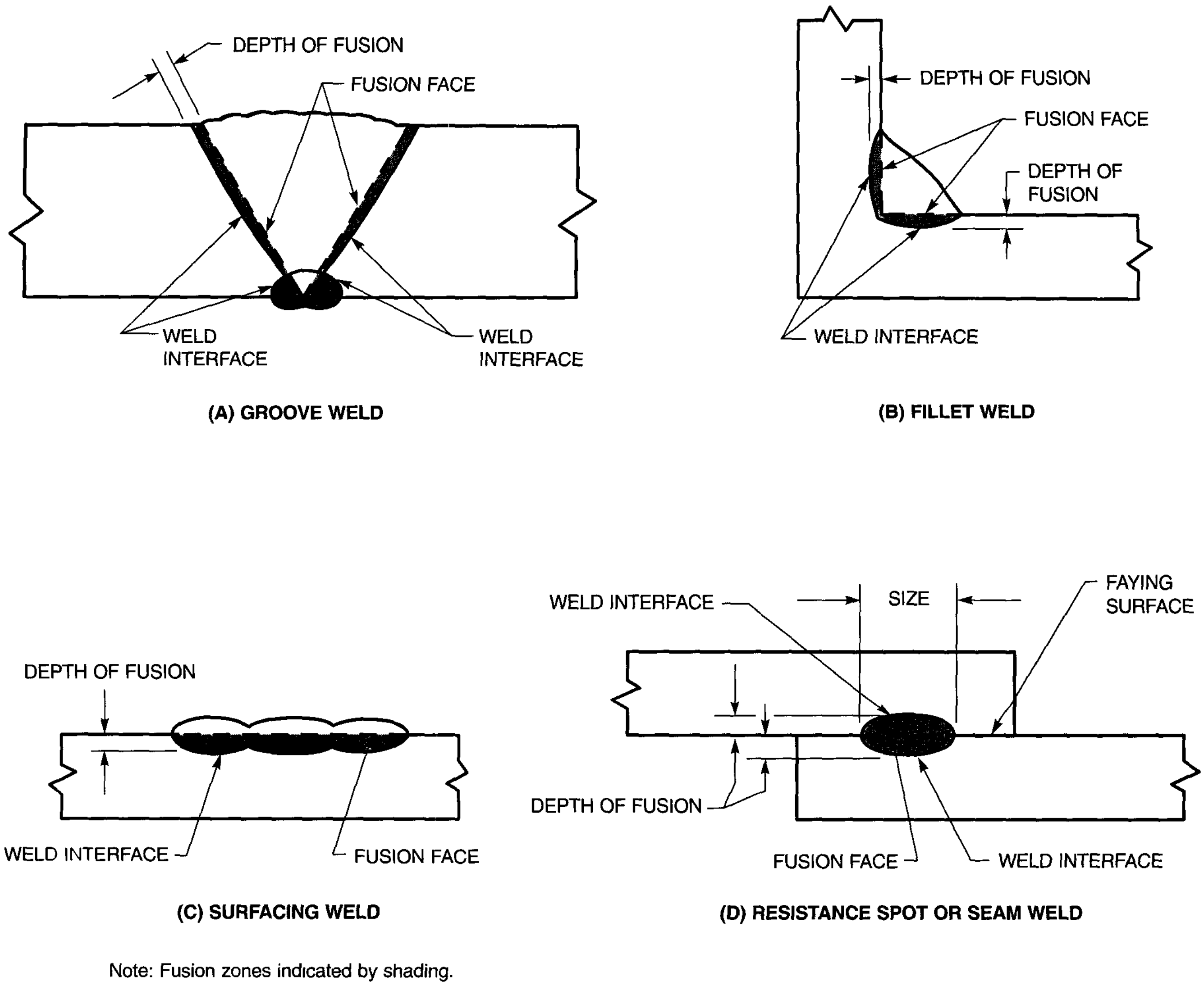


Figure D-3—Depths of Fusion for Various Types of Welds

DIE CASTING

A casting made in a permanent metal mold by injecting molten metal under high pressure into the mold.

DIE WELDING

A nonstandard term when used for COLD WELDING and FORGE WELDING. *See* COLD WELDING.

DIELECTRIC

A nonconductor of electric current.

DIE REPAIR

See TOOL AND DIE WELDING, Shielded Metal Arc.

DIFFUSION AID

A solid filler metal applied to the faying surfaces to assist in diffusion welding. See STANDARD WELDING TERMS.

DIFFUSION BONDING

A nonstandard term for DIFFUSION BRAZING and DIFFUSION WELDING.

DIFFUSION BRAZING (DFB)

A brazing process that produces coalescence of metals by heating them to brazing temperature and by using a filler metal or an ***in situ*** *liquid phase. The filler metal may be distributed by capillary attraction or may be placed or formed at the faying surfaces. The filler metal is diffused with the base metal to the extent that the joint properties are changed to approach those of the base metal. Pressure may or may not be applied. See* STANDARD WELDING TERMS.

DIFFUSION WELDING (DFW)

A solid-state welding process that produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the workpieces. A solid filler metal may be inserted between the faying surfaces to take up gaps or facilitate the diffusion process. See STANDARD WELDING TERMS.

This is a process in which two absolutely clean, perfectly matched, metal (or ceramic or intermetallic) surfaces are placed in contact and heated, but not to the melting point. As a result of the heating, the diffusion of atoms in each direction across the interface will interlock the two atomic structures so that they become one, eliminating the interface.

Temperature is a very important factor in diffusion welding. Pressure may be of secondary importance, as long as intimate contact is maintained throughout the solid state diffusion process.

One of the difficulties in diffusion welding is that the surfaces to be joined are seldom, if ever, perfectly clean or perfectly matched. All metal and many intermetallic surfaces, no matter how carefully finished, have surface irregularities and become covered with an oxide film or other tarnish layers when exposed to air. Ceramic surfaces are normally free of hindering tarnish layers. Other surface materials may also be present, such as oil, grinding compounds or cleaning chemicals. A weakened or defective bond is sometimes the result.

Applications

A wide variety of similar and dissimilar metal combinations may be successfully joined by diffusion welding and brazing. Most applications involve titanium, nickel, and aluminum alloys, as well as several dissimilar metal combinations. The mechanical properties of the joint depend on the characteristics of the base metals. For example, the relatively low creep strength and the solubility of oxygen at elevated temperatures contribute to the excellent properties of titanium alloy diffusion weldments.

Several industries use the diffusion welding process to advantage, particularly the aerospace industry. The engine mount of the space shuttle vehicle was designed to have 28 diffusion welded titanium parts, ranging from large frames to interconnecting box tubes. This structure is capable of withstanding three million pounds of thrust. Tubes 203 mm (8 in.) square were fabricated with diffusion welding in lengths up to 457 cm (180 in.). The gas turbine industry has used diffusion welding to produce a Ti-6%Al-4%V component for an advanced high-thrust engine. This application marked the first production use of diffusion welding in a rotating engine component.

Diffusion Welding Principles

Metal surfaces have several general characteristics: (1) roughness, (2) an oxidized or chemically reacted and adherent layer, (3) other randomly distributed solid or liquid (oil, grease, and dirt), and (4) adsorbed gas or moisture, or both.

Two necessary conditions must be met for a satisfactory diffusion weld:

(1) Mechanical intimacy of faying surfaces

(2) The disruption and dispersion of interfering surface contaminants to permit metallic bonding.

A diffusion weld is formed in three stages. In the first stage, deformation of the contacting surface roughness occurs primarily by yielding and by creep deformation mechanisms which produce intimate contact over a large fraction of the interfacial area. At the end of this stage, the joint is essentially a grain boundary at the areas of contact with voids between these areas. During the second stage, diffusion becomes more important than deformation, and many of the voids disappear as grain boundary diffusion of atoms continues. Simultaneously, the interfacial grain boundary migrates to an equilibrium configuration away from the original weld interface, leaving many of the remaining voids within the grains. In the third stage, the remaining voids are eliminated by volume diffusion of atoms to the void surface (equivalent to diffusion of vacancies away from the void). The stages overlap, and mechanisms that may dominate one stage also operate to some extent during the other stages.

This description is consistent with several experimentally observed trends:

(1) Temperature is the most influential variable, since it, together with pressure, determines the extent of contact area during stage one, and it alone deter-

mines the rate of diffusion that governs void elimination during the second and third stages of welding.

(2) Pressure is necessary only during the first stage of welding to produce a large area of contact at the welding temperature. Removal of pressure after this stage does not significantly affect joint formation. However, removal of pressure before completion of the first stage is detrimental to the process.

(3) Rough initial surface finishes generally adversely affect welding by impeding the first stage and leaving large voids that must be eliminated during the later stages of welding.

(4) The time required to form a joint depends on the temperature and pressure used; time is not an independent variable.

This description of diffusion welding is not applicable to diffusion brazing or hot pressure welding processes where intimate contact is achieved through the use of molten filler metal and bulk deformation, respectively.

Advantages and Limitations

Diffusion welding and brazing have a number of advantages over the more commonly used welding and brazing processes, as well as a number of distinct limitations on their applications. Following are advantages of diffusion welding and brazing:

(1) Joints can be produced with properties and microstructure very similar to those of the base metal. This is particularly important for lightweight fabrications.

(2) Components can be joined with minimum distortion and without subsequent machining or forming.

(3) Dissimilar alloys can be joined that are not weldable by fusion processes or by processes requiring axial symmetry, such as friction welding.

(4) A number of joints in an assembly can be made simultaneously

(5) Members with limited access can be joined.

(6) Large joint members of base metals that would require extensive preheat for fusion welding can be more readily joined. An example is thick copper.

(7) Defects normally associated with fusion welding are not encountered.

Among the disadvantages of diffusion welding and brazing are the following:

(1) The thermal cycle is normally longer than that of conventional welding and brazing processes.

(2) Equipment costs are usually high, and this can limit the maximum size of components that can be produced.

(3) The processes are not adaptable to a high production rate, although a number of assemblies may be joined simultaneously.

(4) Adequate nondestructive inspection techniques for quality assurance are not available, particularly those that assure design properties in the joint.

(5) Suitable filler metals and procedures have not yet been developed for all structural alloys.

(6) The faying surfaces and the fit of joint members generally require greater care in preparation than for conventional hot pressure welding or brazing processes. Surface smoothness may be an important factor in quality control in the case of diffusion brazing.

(7) The need to apply heat and a high compressive force simultaneously in the restrictive environment of a vacuum or protective atmosphere requires specialized equipment.

Gas Pressure Bonding. This process is a type of diffusion welding. In gas pressure bonding, the workpieces to be joined are finished to final size, cleaned to an acceptable surface condition, and assembled inside a container. The container may be an expendable sheet metal box, or it may be made from the parts themselves, by fusion welding around the edges. After the container holding the parts is made pressure-tight, it is evacuated and then placed in an autoclave containing an inert gas at high pressure, usually around 10 000 psi. Under this extreme pressure the matched surfaces are pressed into intimate contact, regardless of the surface contour. After only a few hours the joints are diffusion welded.

In addition to gas pressure, fusion welding can be achieved by pressing the workpieces together between dies after heating by resistance heating. This system works well for small parts, but is not appropriate when the pieces to be joined are large, since it is difficult to keep the dies hot. *See* COLD WELDING, FORGE WELDING, *and* HOT PRESSURE WELDING. Reference: American Welding Society, Welding Handbook, 8th Edition, Vol 2, Welding Processes. Miami Florida: American Welding Society, 1992.

DILUTION

The change in chemical composition of a welding filler metal caused by the admixture of the base metal or previous weld metal in the weld bead. It is measured by the percentage of base metal or previous weld metal in the weld bead. See STANDARD WELDING TERMS. *See* Figure D-4, which shows a cross-section of a weld deposit.

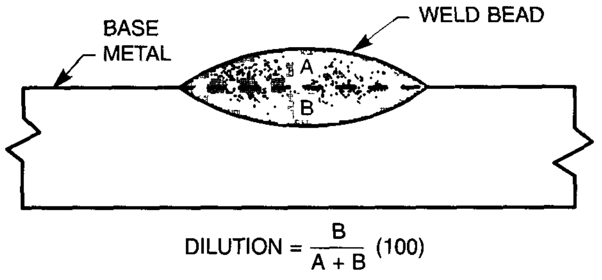


Figure D-4—A Method of Calculating Weld Dilution

The percentage dilution can be determined by measuring areas labeled A and B. Percentage dilution is then calculated as:

$$\frac{B}{A+B} \cdot 100$$

Dilution is usually considered as a percentage of the base metal which has entered into the weld metal.

When two pieces of base metal are welded together, the final composition of the weld deposit consists of a mixture of base metal and filler metal. The portion of the base metal that has been melted in with the filler material and has diluted it may be expressed in percent dilution. This is determined by the following formula:

$$Dilution = \frac{Weight\ of\ base\ metal\ in\ weld}{Total\ weight\ of\ weld} \cdot 100$$

Typical values of dilution for various processes are shown in Table D-2.

Table D-2
Average Values of Dilution for Various Processes

Process	Dilution
Shielded Metal Arc	25 to 40%
Submerged Arc	25 to 50%
Gas Metal Arc	25 to 50%
Gas Tungsten Arc	25 to 50%

Many factors affect dilution. The greatest dilution occurs when no filler metal is added. In this instance, all of the weld deposit is self-generated by the base metal. Similarly, a single-pass weld will have a higher percentage of dilution than a multi-pass weld. There is always considerable dilution in the root pass. The greater the amount of weaving, the greater the dilution.

Dilution as low as 2% has been achieved with the plasma arc hot wire cladding operation utilizing two hot wires connected in series. The application was welding copper rotating bands on artillery shells.

DIP BRAZING (DB)

A brazing process that uses heat from a molten salt or metal bath. When a molten salt is used, the bath may act as a flux. When a molten metal is used, the bath provides the filler metal. See STANDARD WELDING TERMS. *See also* METAL-BATH DIP BRAZING *and* SALT-BATH DIP BRAZING.

In dip brazing, joining is produced by heating the workpieces in a molten chemical or metal bath and by using a non-ferrous filler metal, with a melting point above 450°C (840°F), but below that of the base metals. The filler metal is distributed in the joint by capillary action. When a metal bath is used, the bath provides the filler metal.

DIP SOLDERING (DS)

A soldering process using the heat furnished by a molten metal bath that provides the solder filler metal. See STANDARD WELDING TERMS.

DIP TRANSFER, or Dip Transfer Welding

A nonstandard term for SHORT CIRCUITING TRANSFER. *See* SHORT CIRCUIT GAS METAL ARC WELDING, *and* SPRAY TRANSFER.

DIRECT CURRENT (DC)

An electric current flowing in one direction only, and substantially constant (non-pulsating) in value.

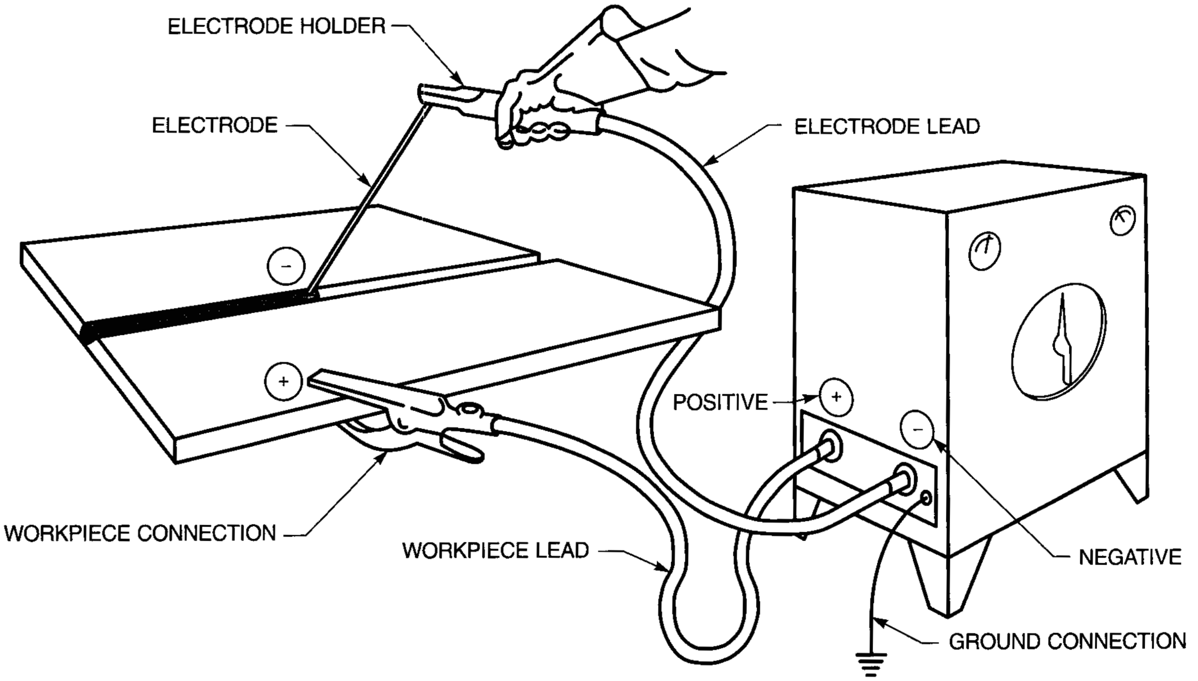
DIRECT CURRENT ARC WELDING

An arc welding process in which the power supply delivers direct current to the arc. *See* ARC WELDING.

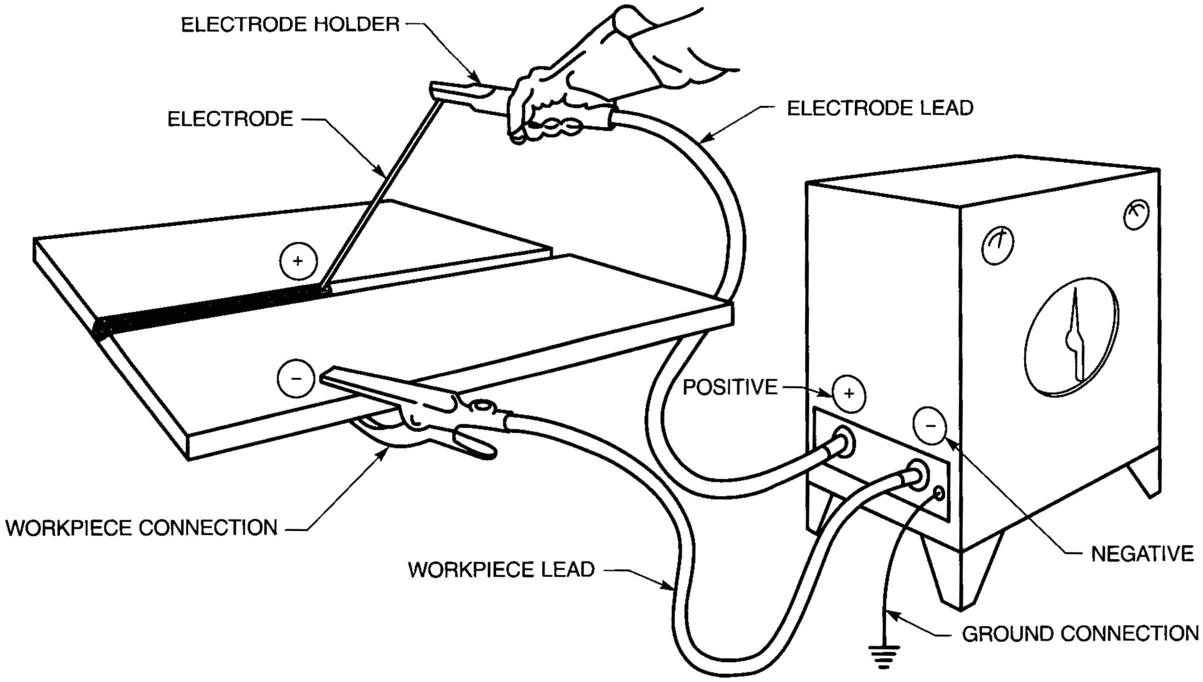
DIRECT CURRENT ELECTRODE NEGATIVE (DCEN)

The arrangement of direct current arc welding leads in which the electrode is the negative pole and workpiece is the positive pole of the welding arc. See STANDARD WELDING TERMS. *See* Figure D-5 (A).

For DCEN, the welding electrode (whether consumable or non-consumable) in an arc welding circuit is caused to be negative relative to the workpiece by the arrangement of the welding leads. Electron flow is to the workpiece, with most (about 70%) of the heat available from the electric arc concentrated at the workpiece.



(A) DIRECT CURRENT ELECTRODE NEGATIVE



(B) DIRECT CURRENT ELECTRODE POSITIVE

Figure D-5—Welding Current Polarity

Straight Polarity. The term *straight polarity* has been used to describe this type of current, but the more accurate and standardized description is *direct current electrode negative.*

DIRECT CURRENT ELECTRODE POSITIVE (DCEP)

The arrangement of direct current arc welding leads in which the electrode is the positive pole and the workpiece is the negative pole of the welding arc. See STANDARD WELDING TERMS. *See* Figure D-5 (B).

Reverse Polarity. The term *reverse polarity* has been used to describe this type of current, but the more accurate and standardized description is *direct current electrode positive.*

DIRECT CURRENT REVERSE POLARITY

A nonstandard term for DIRECT CURRENT ELECTRODE POSITIVE.

DIRECT CURRENT STRAIGHT POLARITY

A nonstandard term for DIRECT CURRENT ELECTRODE NEGATIVE.

DIRECT DRIVE FRICTION WELDING

A variation of friction welding in which the energy required to make the weld is supplied to the welding machine through a direct motor connection for a preset period of the welding cycle. See STANDARD WELDING TERMS. *See* Figure D-6.

One of the workpieces is held in a locked position while the other is rotated by a direct motor connection. When the rotated part is up to speed, pressure is applied to move the rotating part against the stationary part. The resulting friction melts the forging surfaces. Molten metal is ejected from the joint as the pressure is increased. When the rotational force is stopped, forging pressure is increased to complete the weld.

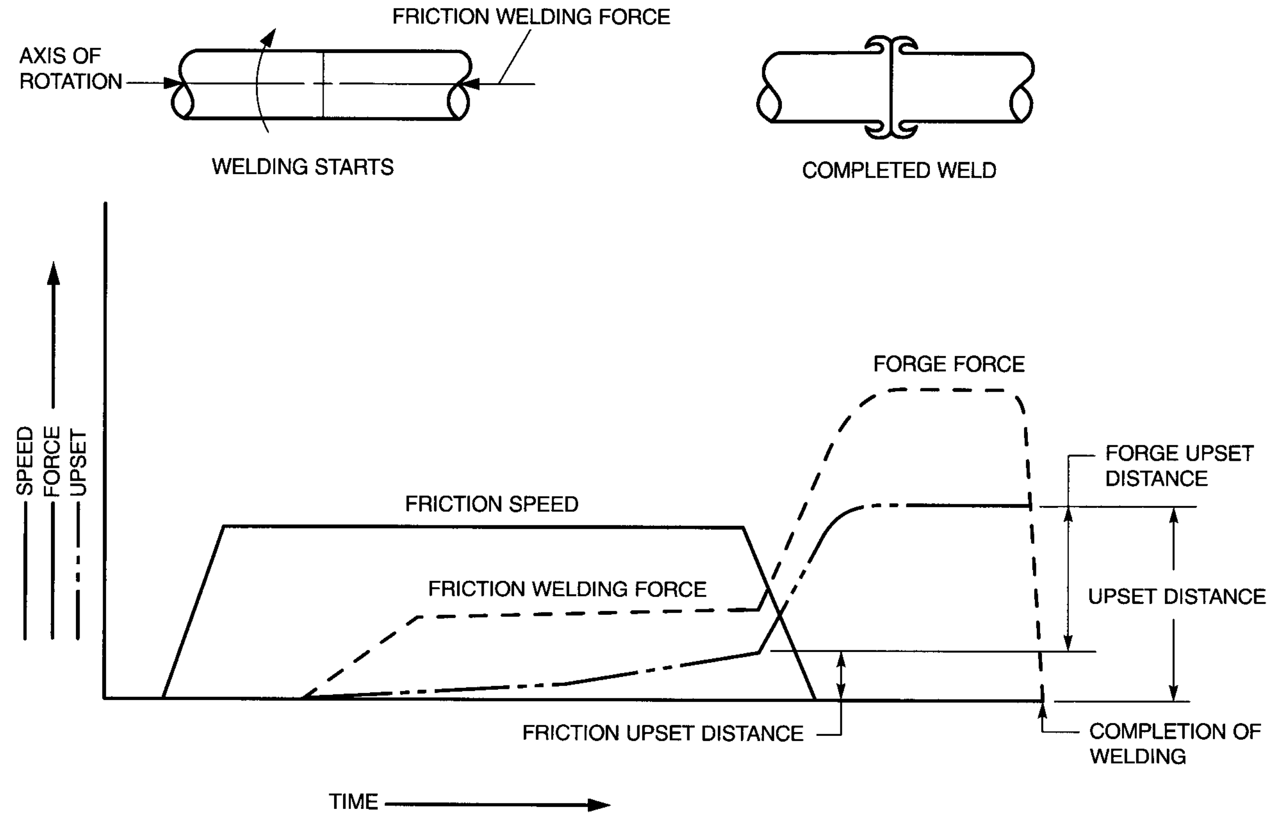


Figure D-6—Generalized Diagram of Direct Drive Friction Welding

DIRECT JOINING

A group of processes for joining ceramics that involves either fusion or non-fusion welding, and involves either no filler (i.e., is autogenous) or employs a filler with the same composition as the base material (i.e., a homogenous filler).

DIRECT WELDING, Resistance Welding

A resistance welding secondary circuit variation in which welding current and electrode force are applied to the workpieces by directly opposed electrodes, wheels, or conductor bars for spot, seam, or projection welding. See STANDARD WELDING TERMS.

DISCONTINUITY

An interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A discontinuity is not necessarily a defect. See STANDARD WELDING TERMS. *See also* DEFECT *and* FLAW.

DISPERSION STRENGTHENED ALLOYS

Alloys which derive their strength from second-phase particles randomly and uniformly distributed throughout a matrix phase. These second phases are not formed as the result of normal metallurgical transformations (e.g., precipitation), but, instead, must be added by mechanical, physical, or special chemical means.

DISSIMILAR METAL JOINTS

Joints between metals or alloys of substantially different compositions, usually in different alloy systems.

DISSOCIATION

Separation of the constituents of a gas, attended by the release of intense heat such as that developed in the combustion of acetylene with oxygen in the torch, which produces the white hot (about 3500°C [6300°F]) cone. Dissociation of acetylene may result from over-pressure and shock.

DISTORTION

The non-uniform expansion and contraction of weld metal and adjacent base metal during the heating and cooling cycle of the welding process.

Weld Metal Shrinkage

At the precise time the weld metal solidifies and fuses with the base metal, it is at its maximum expended state, actually occupying the greatest volume it can occupy as a solid. On cooling, it contracts to the volume it would normally occupy at lower temperatures if it were not restrained from doing so by the adjacent base metal.

Stresses develop within the weld, finally reaching the yield strength of the weld metal. At this point, the weld "stretches," or yields and thins out, thus adjusting to the volume requirements of the joint being welded. But only those stresses that exceed the yield strength of the weld metal are relieved by this accommodation. At the time the weld reaches room temperature, (assuming complete restraint of the base metal so that it cannot move), the weld tends to have locked-in tensile stresses approximately equal to the yield strength. If one or more of the restraints are removed, the locked-in stresses find partial relief by causing the base metal to move, thus causing deformation or distortion.

Base Metal Shrinkage

Shrinkage which produces stresses that lead to distortion in the base metal adjacent to the weld further compounds the problem of shrinkage in the weld. During welding, the base metal near the arc is also heated to the melting point. A few inches away, the temperature of the base metal is substantially lower. This sharp temperature differential causes non-uniform expansion, followed by base metal movement, or metal displacement, if the parts being joined are restrained. As the arc passes further down the joint, thus relocating the source of heat, the base metal begins to cool and shrink along with the weld metal. If the surrounding metal restrains the heat-affected base metal from contracting normally, internal stresses build up; these combine with the stresses developed in the weld metal and increase the tendency to distort.

The volume of this adjacent base metal, which contributes to the distortion, can be controlled by changing the welding procedures. Higher welding speeds reduce the amount of adjacent material that is affected by the heat of the arc, and progressively decrease distortion. Higher welding speeds can be achieved by using powdered-iron manual electrodes, semi-automatic or automatic submerged-arc welding equipment, or automatic gas metal arc welding equipment.

Modes of Distortion

Knowledgeable consideration of the distortion phenomenon and the effects of shrinkage on various types of welded assemblies is invaluable when planning fabrication designs and setting up welding procedures to minimize distortion. *See* Figure D-7.

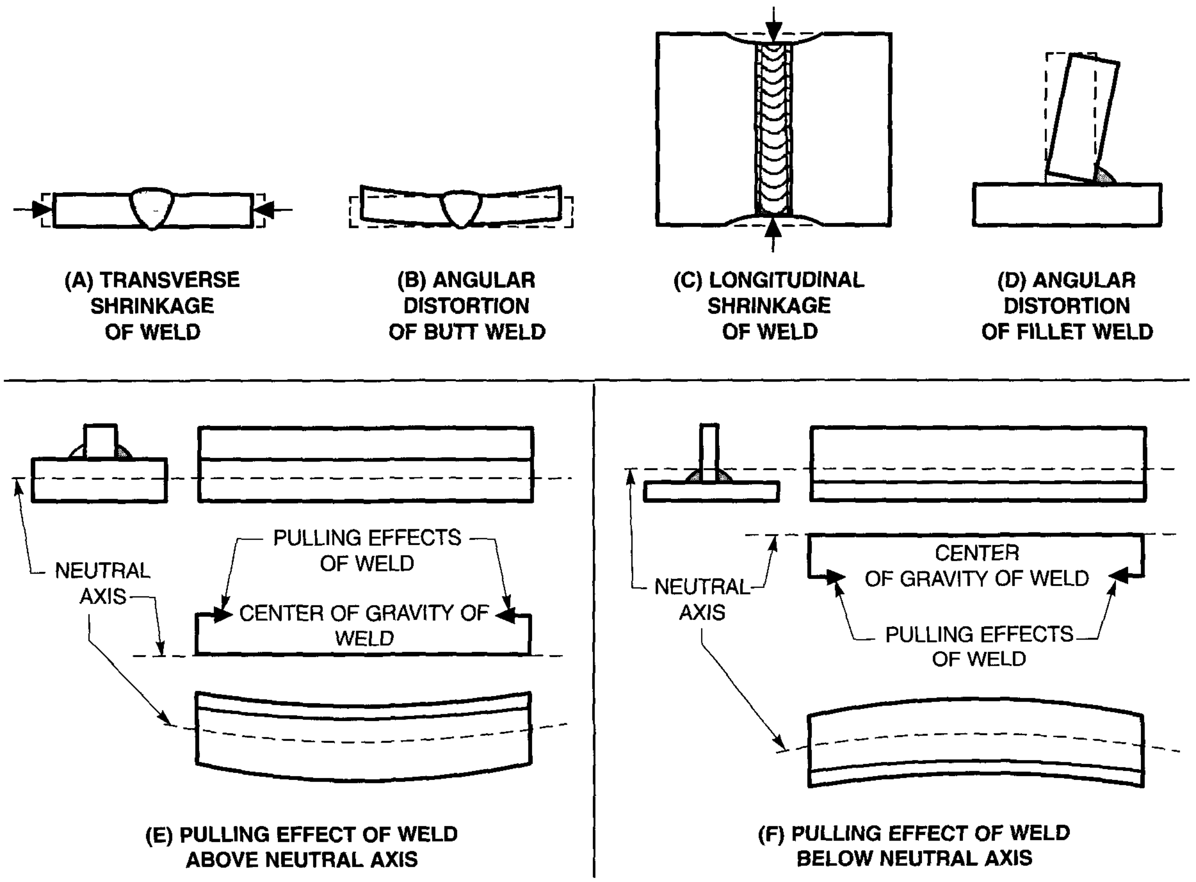


Figure C-7—Types of Distortion

Shrinkage of the weld can cause various types of distortion and dimensional changes. A butt weld between two pieces of plate, by shrinking transversely, changes the width of the assembly as shown in Figure D-7 (A). It also causes angular distortion, as in Figure D-7 (B). Here, the greater amount of weld metal at the top of the weld produces greater shrinkage at the upper surface, causing the ends of the plate to lift. Increasing either the included angle or the weld reinforcement will cause even greater distortion. Longitudinal shrinkage of the same weld would have a tendency to deform the joined plate, as shown in Figure D-7 (C).

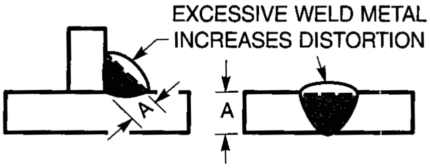
Angular distortion, as in Figure D-7 (D), is a problem with fillet welds. If fillets in a T-assembly are above the neutral axis (center of gravity) of the assembly, the ends of the member tend to be bent upward, as in Figure D-7 (E); if the welds are below the neutral axis, the bending of the member is in the opposite direction, as in Figure D-7 (F).

Control of Shrinkage

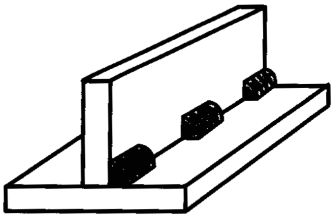
Shrinkage from the effects of the heating and cooling cycles cannot be prevented, but can be controlled. There are various practical procedures and design strategies for minimizing the distortion caused by shrinkage.

(1) Keep the shrinkage forces as low as possible by using only the amount of weld metal required by the joint. The more metal placed in a joint, the greater the shrinkage forces will be. *See* Figure D-8 (A).

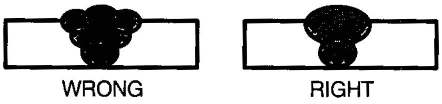
Correctly sizing the weld for the service requirement of the joint helps control distortion. In a conventional fillet weld, only the effective throat is used in determining the strength of the weld. The amount of



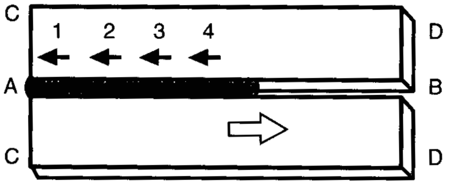
(A) DO NOT OVERWELD...



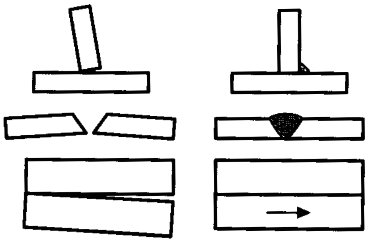
(C) INTERMITTENT WELDING



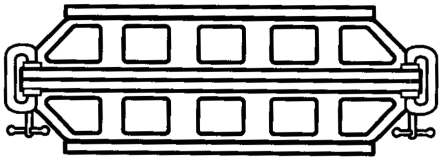
(D) MINIMUM NUMBER OF PASSES



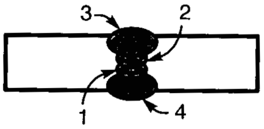
(G) BACKSTEP



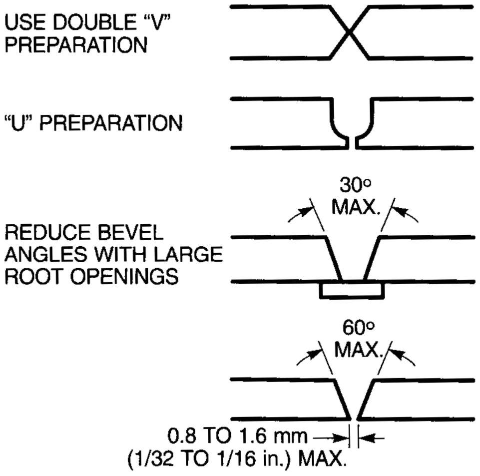
(H) PRESET PARTS



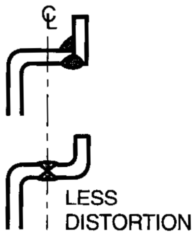
(J) BACK-TO-BACK CLAMPING



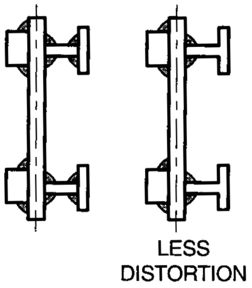
(K) SEQUENCE WELDS



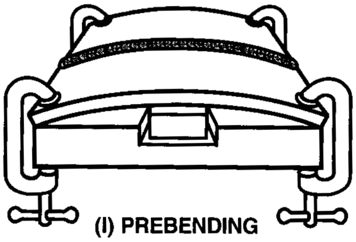
(B) CORRECT EDGE PREPARATION AND GOOD FITUP



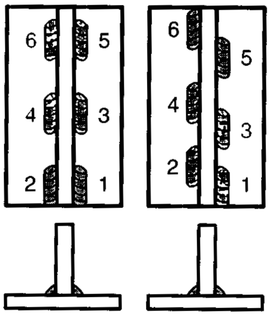
(E) WELD NEAR THE NEUTRAL AXIS



(F) BALANCE WELDS AROUND CENTER OF GRAVITY



(I) PREBENDING



(L) WELD POSITION

Figure C-8—Practical Ways to Minimize Distortion weld metal can be minimized in a fillet by using a flat or slightly convex bead. Excess weld metal in a highly convex bead does not increase the allowable strength in code work, yet it adds to the development of shrinkage forces.

In a butt joint, proper edge preparation, fit-up and reinforcement are important to minimize the amount of weld metal required. When maximum economy is the objective, the plates should be spaced from .8 to 2 mm (1/32 to 1/16 in.) apart. A bevel not exceeding 30° on each side will give proper fusion at the root of the weld, yet require minimum weld metal.

For thicker plates, the bevel may be decreased by increasing the root opening, or a J- or U-groove preparation adopted, to further reduce the amount of weld metal. A double-V joint requires about half of the weld metal of a single-V joint. *See* Figure D-8 (B).

Another way to minimize the amount of weld metal is to use intermittent welds where possible, rather than continuous welds. As an example, when attaching stiffeners to plate, intermittent welds will reduce the volume of weld metal by 75%, yet will provide all the strength needed. *See* Figure D-8 (C).

(2) Use as few weld passes as possible. When transverse distortion is a potential problem, a few passes with large electrodes are preferable to a large number of passes with small electrodes, because the shrinkage resulting from each pass tends to be cumulative. *See* Figure D-8 (D).

(3) Place welds near the neutral axis, as shown in Figure D-8 (E). This reduces distortion by providing a smaller leverage for the shrinkage forces to pull the plates out of alignment.

(4) Balance welds around the center of gravity. This will balance one shrinkage force against another. This design and welding sequence will effectively control distortion. *See* Figure D-8 (F).

(5) Use backstep welding. With this technique, the general progression of welding may be, for example, from left to right, but each bead is deposited from right to left. As shown in Figure D-8 (G), as each bead is placed, the heat from the weld along the edges causes expansion, temporarily separating the plates at B. However, as the heat moves out across the plate to C, the expansion along the outer edges CD brings the plates back together. Expansion of a plate is most pronounced when the first bead is laid. With successive beads, the plates expand less and less because of the locking effect of prior welds. In some cases, backstepping may have less effect, and it cannot be economically used in fully automatic welding.

(6) Make shrinkage work in the desired direction. By locating parts out-of-position before welding, shrinkage can be utilized constructively to pull them back into alignment. *See* Figure D-8 (H).

Pre-bending or pre-springing the parts to be welded, as shown in Figure D-8 (I), is a simple example of using mechanically-induced opposing forces to counteract weld shrinkage. The top of the weld groove, which will contain the bulk of the weld metal, is lengthened when the plates are sprung, since it becomes the convex side of a curve. Thus, the completed weld is slightly longer than it would be if it were made on a flat plate. When the clamps are released after welding, the plates tend to resume their flat shape, and the longitudinal shrinkage stresses of the weld can be relieved by shortening it to a straight line. The two actions coincide, and the welded plates assume the desired flatness.

(7) Balance shrinkage force with opposing forces. Opposing forces may be:

(a) other shrinkage forces

(b) restraining forces imposed by clamps, jigs, and fixtures

(c) restraining forces arising from the arrangement of members in the assembly

(d) the counter force produced by the force of gravity action on the sag in a member.

A common practice for balancing shrinkage forces in identical weldments is to position the workpieces back-to-back and then clamp them tightly together. *See* Figure D-8 (J). The welds are completed on both assemblies and allowed to cool before the clamps are released. Pre-bending can be combined with this method by inserting wedges at suitable positions between the workpieces before clamping.

Locking the workpieces in the desired position in clamps, jigs or fixtures to hold them until welding is finished is probably the most widely used method of controlling distortion in small assemblies of components. The restraining forces provided by clamps cause the build-up of internal stresses in the weldment until the yield point of the weld metal is reached. For typical welds on low-carbon plate, this would probably be approximately 310 MPa (45 000 psi). After welding, one might expect this stress to cause considerable movement or distortion when the workpiece is removed from the jig or clamps. This does not occur, however, since the strain (unit contraction) can be calculated to be a very low value compared to the amount of movement that would have occurred if no restraint were used during welding.

The rigidity of the members and their arrangement in relation to one another may provide the balancing forces needed, particularly in heavy weldments. However, if these natural balancing forces are not present, other means can be used to counteract the distortion. Shrinkage forces in the weld metal can be balanced against one another, or an opposing force can be created by using a fixture.

(8) A well planned welding sequence is often helpful in balancing shrinkage forces against each other. The intent should be to place weld metal at different points on the structure so that as it shrinks in one place, it will counteract the shrinkage forces of welds already made. An example of this is welding alternately on both sides of the neutral axis in making a butt weld, as shown in Figure D-8 (K). Another is making intermittent fillet welds, shown in Figure D-8 (L).

(9) One way to help control shrinkage forces occurring during or after welding is by peening, but peening is not a definitive practice. Peening is a mechanical method of applying force to the weld to make it thinner, thereby making it longer and relieving residual stresses.

A root bead should never be peened because of the danger of either concealing a crack or causing one. Generally, peening is not permitted on the final pass because of the possibility of covering a crack and interfering with inspection, and also because of a possible work-hardening effect, so the utility of this technique is limited.

In special cases, stress relief by controlled heating of the weldment to an elevated temperature, followed by controlled cooling is another way to remove shrinkage forces. Sometimes two identical weldments are placed back-to-back, clamped together, welded and then stress-relieved while held in this straight condition. The residual stresses that would tend to distort the weldment are thus removed.

(10) Reduce welding time. Since complex cycles of heating and cooling are in progress during welding, and time is required for heat transmission, the time factor affects distortion. In general, it is advantageous to finish the weld quickly before too great a volume of surrounding metal expands because of the heat. The amount of shrinkage and distortion is affected by the welding process used, the type and size of electrode, welding current, and travel speed. Using mechanized welding equipment reduces the time of welding and the amount of metal affected by heat, and consequently tends to reduce distortion.

To deposit a weld in thick plate with a process operating at 175 amps, 25 volts and 7.6 cm (3 in.) per minute, 34 400 joules of energy per linear centimeter are required. The same size weld produced with a process operating at 310 amps, 30 volts, and 20.3 cm (8 in.) per minute requires only 27 500 joules per linear centimeter of weld. The difference represents "excessive" heat available for transmission farther into surrounding metal, increasing its temperature, and producing added expansion and displacement of metal.

DOPED SOLDER

A *solder containing a small amount of an element added to ensure retention of one or more characteristics of the base materials on which it is used. See* STANDARD WELDING TERMS.

DOUBLE ARCING

A condition in which the welding or cutting arc of a plasma arc torch does not pass through the constricting orifice but transfers to the inside surface of the nozzle. A secondary arc is simultaneouslyestablished between the outside surface of the nozzle and the workpiece. See STANDARD WELDING TERMS.

DOUBLE-BEVEL EDGE SHAPE

A type of edge shape having two prepared surfaces adjacent to opposite sides of the material. See STANDARD WELDING TERMS. *See* Appendix 6, Section 3.

DOUBLE-BEVEL-GROOVE WELD

A type of groove weld. See Appendix 6, Section 5.

DOUBLE-FLARE-BEVEL-GROOVE WELD

A weld in grooves formed by a member with a curved surface in contact with a planar member. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-FLARE-V-GROOVE WELD

A weld in grooves formed by two members with curved surfaces. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-GROOVE WELD, Fusion Welding

A groove weld that is made from both sides. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-J EDGE SHAPE

A type of J-edge shape having two prepared surfaces adjacent to opposite sides of the material. See STANDARD WELDING TERMS. *See* Appendix 6, Section 3.

DOUBLE-J-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-SPLICED BUTT JOINT

See STANDARD WELDING TERMS. *See* SPLICED JOINT.

DOUBLE-SQUARE-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-U-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-V-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOUBLE-WELDED JOINT, Fusion Welding

A joint that is welded from both sides. See STANDARD WELDING TERMS. *See* Appendix 6, Section 5.

DOVETAILING, Thermal Spraying

A method of surface roughening involving angular undercutting to interlock the thermal spray deposit. See STANDARD WELDING TERMS.

DOWNHAND

A nonstandard term for FLAT WELDING POSITION.

DOWNHAND WELDING

Flat position welding, in which the weld is made in a workpiece in a horizontal plane. *See* FLAT WELDING POSITION *and* WELDING POSITION.

DOWNHILL, *adv.*

Welding with a downward progression. See STANDARD WELDING TERMS.

DOWNSLOPE TIME

See STANDARD WELDING TERMS. *See* AUTOMATIC ARC WELDING DOWNSLOPE TIME *and* RESISTANCE WELDING DOWNSLOPE TIME.

DRAG, Thermal Cutting

The offset distance between the actual and straight line exit points of the gas stream or cutting beam measured on the exit surface of the base metal. See STANDARD WELDING TERMS. *See* Figure C-11.

DRAG ANGLE

The travel angle when the electrode (in arc welding) is pointing in the direction opposite to the progression of welding. This angle can also be used to partially define the position of guns, torches, rods, and beams in welding processes. See STANDARD WELDING TERMS. *See also* BACKHAND WELDING, PUSH ANGLE, TRAVEL ANGLE, *and* WORK ANGLE.

DRAG WELDING

A technique of welding with a consumable coated or stick electrode in which the coating of the electrode is placed in contact with the metal surface, joint, or fillet and dragged along as the arc causes melting of the core wire and base metal.

DRAWING

See ANNEALING *and* TEMPERING.

DRILLING, Oxyfuel

See OXYGEN LANCE CUTTING *and* FLAME CUTTING.

DROOPER

A term applied to a conventional welding machine in which the volt-ampere output curve has a steep angle between the open circuit voltage and the short circuit current, called the apex of the volt-ampere curve.

The term *drooper* also refers to the decrease of voltage at points along a circuit because of resistance.

DROP-THROUGH

An undesirable sagging or surface irregularity, usually encountered when brazing or welding near the solidus of the base metal, caused by overheating with rapid diffusion or alloying between the filler metal and the base metal. See STANDARD WELDING TERMS.

DROP-WEIGHT TEST

This test is used extensively to investigate the fracture characteristics of ferritic steels 15.9 mm (5/8 in.) and thicker.

A crack-starter bead of hard surfacing material is deposited on the specimen to be tested, then a notch is cut into the bead. After cooling to a specified temperature, the specimen is placed on an anvil, with the crack-starter bead down. A weight is dropped on the specimen from a height selected to give the necessary impact energy. The impact energy is determined by the approximate yield strength of the weld metal being tested.

When the weight strikes the specimen, it either bends until it hits a deflection stop, or cracks in two pieces, with little or no bending.

The drop-weight test is also used to determine the nil-ductility transition temperature of the weld metal. This test is conducted by impacting a series of specimens, each tested at a different temperature. The maximum temperature at which a specimen breaks is the nil-ductility transition. This temperature must be determined within 5°C (10°F). Details of the Drop Weight Test are published in ASTM Standard E208.

DRUM

A filler metal package consisting of a continuous length of welding wire wound or coiled in a cylindrical container. See STANDARD WELDING TERMS.

DUCTILITY

The property of a material that allows it to undergo some reasonable degree of irreversible permanent plastic deformation without fracturing. Ductility is the property of metals and alloys that allows them to be drawn or stretched. In general, metals and alloys with face-centered cubic structures exhibit the greatest ductility, followed by body-centered cubic structures, and then hexagonal close-packed structures. The order of ductility of certain materials is shown in Table D-3.

Table D-3
Order of Ductility

(1) Gold
(2) Silver
(3) Platinum
(4) Iron
(5) Nickel
(6) Copper
(7) Aluminum
(8) Tungsten
(9) Zinc
(10) Tin
(11) Lead

DUCTILE-BRITTLE TRANSITION

The behavior of certain metals and alloys, most notably those with body-centered cubic structures, in which they exhibit a pronounced decrease in ability to absorb energy without fracturing below a certain temperature (i.e., the ductile-to-brittle transition temperature) or above a certain strain rate. The ductile-to-brittle transition temperature is especially important in considering the material's ability to absorb impact, as measured by the Charpy (or related) tests.

DUPLEX CABLE

A cable consisting of two wires insulated from one another, with a common insulation covering both.

DURALUMIN

An old term applied to aluminum alloys, especially in Germany.

DUPLEX STAINLESS STEEL

The term *duplex stainless steel* describes steel with microstructure containing austenite and ferrite in which the lesser phase is at least 30% by volume. First generation duplex stainless steels (typically 26% Cr, 4.5% Ni, 1.5% Mo) were about 75 to 80% ferrite.

Unlike the common-grade austenitic stainless steels, duplex stainless steels are highly resistant to chloride-ion stress corrosion cracking (SCC); they have excellent resistance to pitting and crevice corrosion, and have approximately twice the strength of the common austenitics.

In general, poor weldability was a characteristic of the first generation duplex stainless steels. Corrosion resistance and toughness of the base metal heat-affected zone (HAZ) were poor due to the effects of the welding operation. However, HAZ problems were greatly decreased with the advent of the argon-oxygen decarbonization process used in steel making which made it possible to precisely alloy with nitrogen. Nitrogen, which is a strong austenite former, permitted lower nickel contents and improved tensile properties and resistance to pitting and corrosion. These alloys are typically higher in chromium than the common-grade austenitics. Utilization of molybdenum as high as 4.5% accounts for resistance to pitting and crevice corrosion.

The duplex stainless alloys are characteristically stronger than either of their two phases considered separately. The coefficient of expansion and heat transfer characteristics are, as would be expected, intermediate between the ferrite and austenitic stainless steels. Many duplex stainless steels, as with most of the other stainless steels, are proprietary alloys.

The second generation duplex materials, especially alloy 2205, have found increasing uses in the brewery business, chemical process industry and various chemical shipping containers including tankers and barges. This use includes heat exchangers, pressure vessels, tanks, columns, pumps, valves, shafts and pulp digesters where the increased resistance to chloride ion SCC pitting and crevice corrosion, and increased strength give advantages over the molybdenum-bearing austenitics.

Because of the large quantities of ferrite in the microstructure, the duplex stainless steels are subject to embrittlement when exposed to the 704 to 927°C (1300 to 1700°F) temperature range due to the formation of chi and sigma phases. For minimization of this form of metallurgical reaction, high levels of nitrogen are beneficial and high levels of molybdenum are detrimental.

Weldability. Acceptable techniques have been developed for SMAW, SAW, GTAW, GMAW and PAW of duplex stainless steels. The complexity of welding these alloys is related to the increased concern for hydrogen-related embrittlement due to large percentages of ferrite, the ability to reform austenite on the welding thermal cycle, and concern for formation of embrittling intermetallics.

Machinability. Special tool angles, low speed and heavy feed are required to machine duplex stainless steels. Due to the combination of high strength and toughness, machinability is considerably poorer for these steels than the common-grade materials.

DUST

See WELDING FUMES.

DUST-COATED ELECTRODE

This term refers to an obsolete electrode which was lightly coated with an arc-stabilizing chemical. This coating might simply have been the lime retained from the lubricant used in the drawing operation, or a light rust coating which formed on the electrode after it was drawn.

These electrodes were more commonly used when arc welding electrodes were initially introduced. The coating of a dust-coated electrode did not affect the character of deposited weld metal, but served to produce more uniform arc characteristics than those obtained with bare wire. The dust coating did not affect the prevention of oxidation, and no slag was formed on the weld bead. *See* ELECTRODE MANUFACTURE, Historical Background.

DUTY CYCLE

The percentage of time during an arbitrary test period that a power source or its accessories can be operated at rated output without overheating. See STANDARD WELDING TERMS.

DWELL TIME, Thermal Spraying

The length of time that the surfacing material is exposed to the heat zone of the thermal spraying gun. See STANDARD WELDING TERMS.

DYNAMIC ELECTRODE FORCE

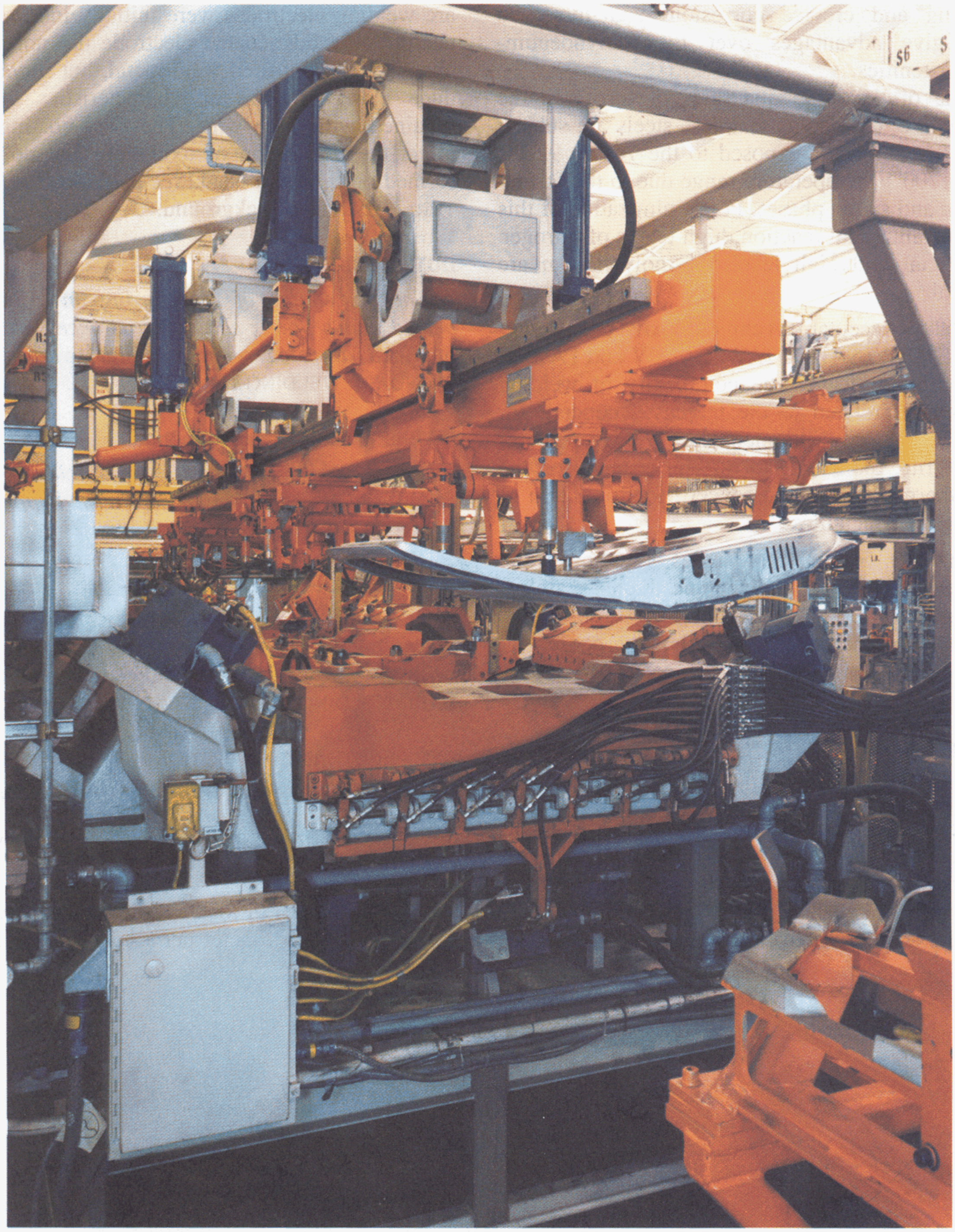
The force exerted by electrodes on the workpieces during the actual welding cycle in making spot, seam, or projection welds by resistance welding. See STANDARD WELDING TERMS.

DYE PENETRANT INSPECTION

See NONDESTRUCTIVE EXAMINATION, *and* LIQUID PENETRANT TESTING.

DYNE

A unit of power or force required to cause the acceleration of one centimeter per second in a mass of one gram.



An automobile door panel is welded with automated resistance spot welding

E

E

Symbol for volts.

E.M.F.

Abbreviation for electromotive force.

EARTH GROUND

The side of an electric circuit grounded to the earth by means of a copper rod driven into the ground.

EDDY CURRENT

A current running contrary to the main current. The eddy current in armatures, pole pieces, and magnetic cores is induced by changing electromotive force. It is wasted energy and creates heat.

EDDY-CURRENT LOSS

The loss of energy in an electrical machine which is caused by eddy currents.

EDGE EFFECT, Thermal Spraying

Loosening of the bond between the thermal spray deposit and the substrate at the edge of the thermal spray deposit. See STANDARD WELDING TERMS.

EDGE-FLANGE WELD

A nonstandard term for an edge weld in a flanged butt joint.

EDGE JOINT

A joint between the edges of two or more parallel or nearly parallel members. See STANDARD WELDING TERMS. *See also* Figure E-1 *and* Appendix 5(E).

An edge joint is formed by placing a surface of one base metal part on a surface of another base metal part so that the weld joining the parts is within the outer surface planes of both the parts joined.

EDGE LOSS, Thermal Spraying

Thermal spray deposit lost as overspray beyond the edge of the workpiece. See STANDARD WELDING TERMS.

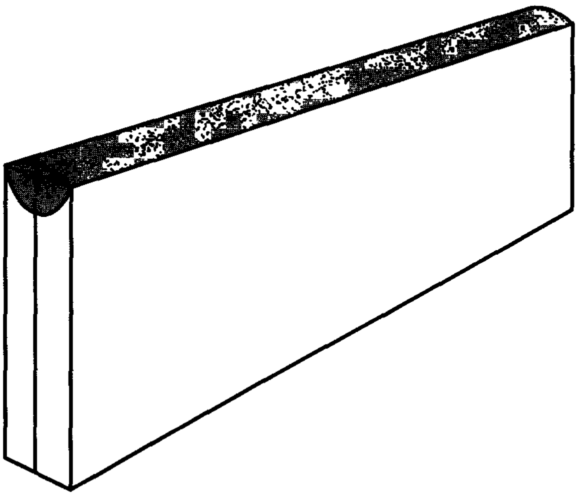


Figure E-1—Typical Edge Weld

EDGE PREPARATION

The preparation of the edges of the joint members, by cutting, cleaning, plating, or other means. See STANDARD WELDING TERMS.

Cleanliness is important in welding. The surfaces of the workpieces and the previously deposited weld metal must be cleaned of dirt, slag, and any other foreign matter that would interfere with welding. To accomplish this, the welder should have a steel wire brush, a hammer, a chisel, and a chipping hammer. These tools are used to remove dirt and rust from the base metal, remove tack welds, and chip slag from the weld bead.

Edge preparation may be done by any of the thermal cutting methods or by machining. The accuracy of edge preparation is important, especially for machine or automatic welding. For example, if a joint designed with a 6.4 mm (1/4 in.) root face were actually produced with a root face that tapered from 7.9 to 3.2 mm (5/16 to 1/8 in.) along the length of the joint, the weld might be unacceptable because of lack of penetration at the start and excessive melt-through at the end. In such a case, the capability of the cutting equipment, as well as the skill of the operator, should be checked and corrected.

Weld Cleaning

Preweld and postweld cleaning are part of the welding operation. Preweld cleaning occurs by default in some types of acetylene welding, where the pre-heating operation of the torch automatically cleans the weld site. In other instances welding and brazing fluxes aid in the cleaning. Gas welding operations rarely require postweld cleaning unless they include a corrosive type of flux, in which case the operation includes flux removal to prevent weld or base metal corrosion.

Cleaning processes are usually chemical or mechanical. The condition of the workpieces, the nature of any contamination, the degree of cleanliness required, and the type, shape, size, and thickness of the workpieces to be cleaned determine the choice between mechanical or chemical cleaning.

Chemical Cleaners

A chemical bath provides uniform cleaning. This uniformity is necessary, for example, to produce consistent welds in resistance welding operations. Certain chemical cleaners require accurate timing, and the operator's ability to control the exposure time of the material in the bath is critical to achieving a high degree of uniformity. The cleaning solution will be ineffective if the exposure time of the workpiece is insufficient. If left in the bath too long, the chemical may react with the base metal and cause a high-resistance film or other undesirable chemical reaction. Chemical cleaning processes also present a safety hazard and require precautionary measures to prevent injury to workers.

Chemical cleaning solutions are usually one of four types: alkaline, solvent, petroleum spirits, and emulsifiable.

Alkaline Cleaners. The alkaline cleaner is probably the most popular because it will emulsify greases and oils, and because of its low cost. Since alkaline cleaners are sprayable at high pressure, the mechanical action of the spray assists in removing solid particles and dirt. Most alkaline cleaners are not caustics and therefore are less hazardous to the worker. Alkaline cleaners are effective in almost all metal cleaning applications, although they may cause corrosion in various nonferrous alloys, especially aluminum, brass, and zinc.

Solvent Cleaners. These cleaners are commonly used in resistance welding operations. In this application, the workpieces are soaked in a tank of solvent so that the cleaning penetrates rolled edges, pockets, and seams. Water-based solvents are not easily rinsed from edges, pockets and seams. Solvent cleaners are ideal for cleaning nonferrous metal particles in applications where water and steam might allow corrosion or contamination.

Petroleum Spirit Cleaners. These cleaning agents primarily remove processing contaminants, and do not provide the chemically cleaned surface required by some finishing operations, such as plating. Petroleum spirit cleaners are highly flammable and present a fire hazard.

Emulsified Cleaners. Emulsified cleaners do not damage or attack the metal surface. This type of cleaner is effective as a spray or in a bath. Exposure time is usually short, sometimes as little as 30 seconds. After a brief drainage period, a water spray rinse removes contaminants and cleaning solution. An alternative to solvent and alkaline cleaners, emulsified cleaners are not temperature dependent, although a hot water rinse assures more satisfactory results and rapid self-drying.

Mechanical Cleaning

Mechanical cleaning requires skilled operators who must remove undesirable surface coatings and particles without roughening the surface of the material or causing other undesirable surface conditions. Mechanical cleaning is effective for both resistance and arc welding applications. A wire brush or abrasive wheel is the most common mechanical cleaner.

The major advantage of mechanical cleaning is that it requires cleaning at the weld site only; chemical cleaning involves the entire surface of the workpiece.

EDGE SHAPE

The shape of the edge of the joint member. See STANDARD WELDING TERMS. *See* Appendix 6, Section 3.

The shape of the edge will vary with plate thickness. See Figure E-2 for typical edge shapes based on plate thickness.

EDGE WELD

A weld in an edge joint, a flanged butt joint or a flanged corner joint in which the full thickness of the members is fused. See STANDARD WELDING TERMS. *See* Figure E-1.

EDGE WELD SIZE

The weld metal thickness measured from the weld root. See STANDARD WELDING TERMS. *See* Figure E-3.

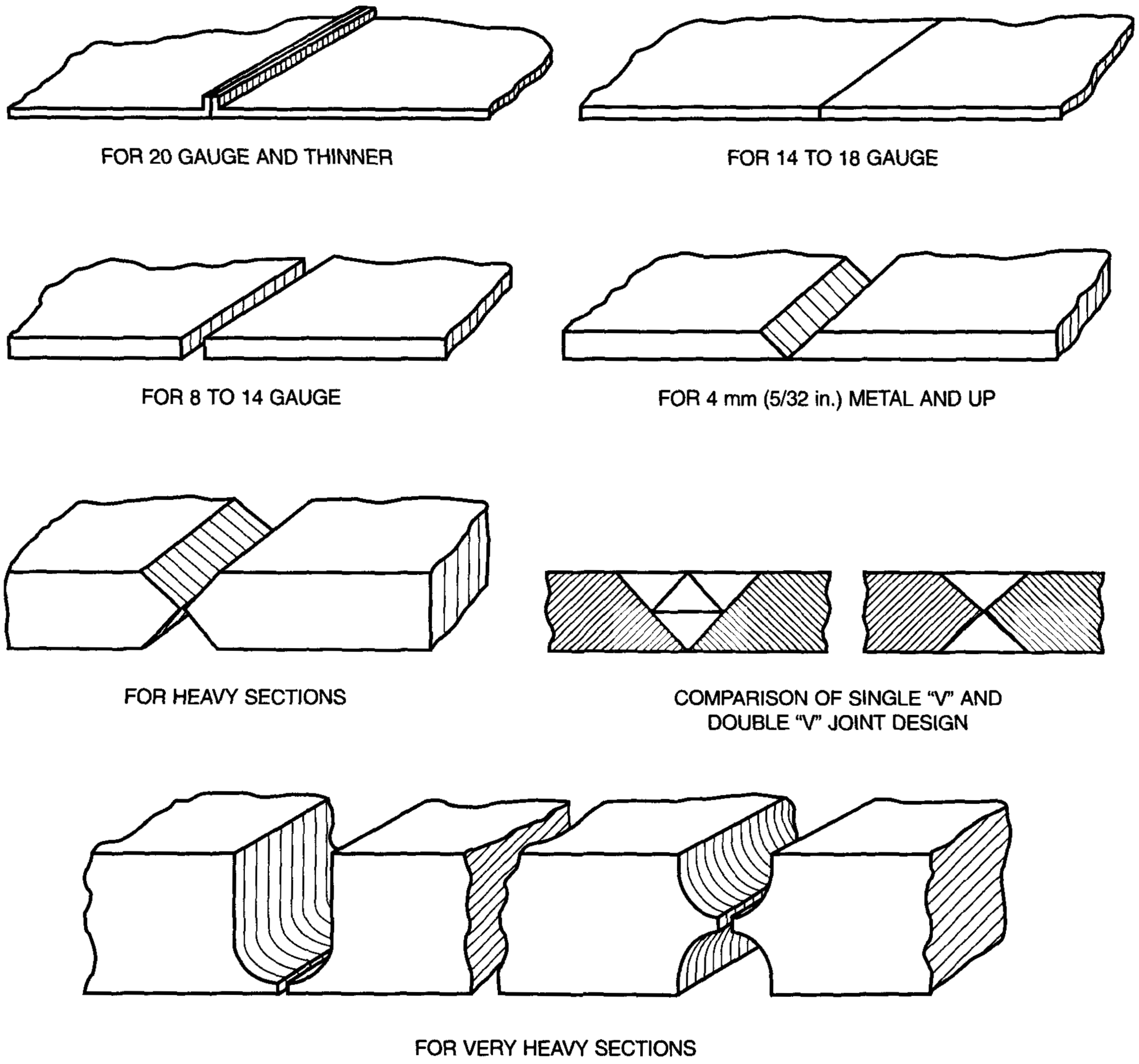


Figure E-2—Typical Weld Joints for Various Thicknesses of Base Metal

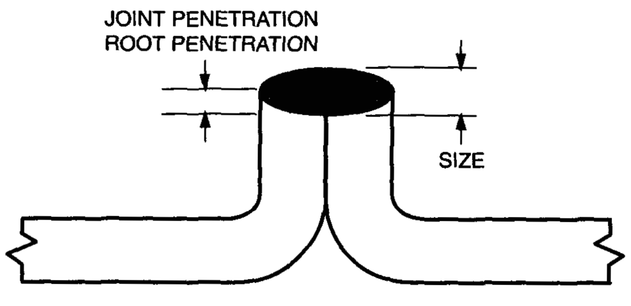


Figure E-3—Edge Weld Size

EFFECTIVE LENGTH OF WELD

The length of the correctly proportioned cross section of a weld. In a curved weld, it is measured along the weld axis.

EFFECTIVE THROAT

The minimum distance minus any convexity between the weld root and the face of a fillet weld. See STANDARD WELDING TERMS. *See* Appendix 11, (A).

EFFICIENCY

The ratio of the amount of useful energy, power or work delivered by a machine to the amount of energy, power or work required to operate it, or effective operation measured by a comparison of production with cost.

ELASTIC LIMIT

The maximum load (or stress) a metal will sustain before it deforms permanently or plastically. *See* ELONGATION.

ELASTICITY

The resilience of a material; the property of resisting deformation by stretching. Elasticity is the characteristic of a material to return to its original shape quickly after the deforming force is removed.

ELECTRIC ANNEALING

See ANNEALING, Electric.

ELECTRIC ARC SPRAYING

A nonstandard term for ARC SPRAYING.

ELECTRIC BONDING

A nonstandard term for surfacing by thermal spraying.

ELECTRIC BRAZING

A nonstandard term for ARC BRAZING and RESISTANCE BRAZING. A group of brazing processes in which heat is obtained from electric current. *See also* INDUCTION BRAZING.

ELECTRIC CIRCUIT

The complete path of the flow of electric current, usually including the source of electric energy. The intensity or pressure of the electric current is expressed as *volts*. The rate of flow or current in the circuit is expressed as *amperes*.

In a direct-current (d-c) circuit (sometimes called a continuous current circuit), the product of the volts and the amperes in the circuit represents the amount of electrical power (watts) produced. The product of the volts and the amperes in the circuit, together with the time of flow, is expressed as *watt hours* of energy expended in the circuit. One thousand watts are expressed as a *kilowatt*. Electrical energy is measured in *kilowatt hours*.

As an example of this calculation, if the voltage across a portion of an electrical circuit is 50 volts and the current flowing in the circuit is 600 amperes, the amount of power being consumed in the circuit is 30 kilowatts, or 30 000 watts. If the circuit is maintained for one hour, 30 kW-hr of energy will be expended.

ELECTRIC CONDUCTIVITY

The electrical conducting characteristics of a material; the reciprocal of electrical restivity. Table E-1 shows a comparison of the electrical conductivity of various metals, considering copper as 100.

Table E-1
Electrical Conductivity of Various Metals

Silver	108	Iron	17
Copper	100	Steel	17
Aluminum	56	Nickel	15
Magnesium	38	Tin	15
Zinc	29	Lead	9

ELECTRIC CURRENT

The path of movement or rate of movement of electricity; flow of electricity.

ELECTRIC INDUCTION HEATING

Heating a material by means of an electric current that is caused to flow through the material by electromagnetic induction.

ELECTRIC INDUCTION PREHEATING

A method of preheating workpieces for welding using an electric current to generate heat by electromagnetic induction. *See* INDUCTION HEATING *and* PREHEATING BY INDUCTION.

ELECTRIC RESISTANCE

The measure of free electrons in a material; the property of a substance which causes it to oppose the flow of electricity through it. Electrical resistance may be either the resistance of a conducting body or the resistance of various contacting surfaces. Body resistance is proportional to the restivity of the material and the length of the current path, and inversely proportional to the area of the current path. Contact resistance depends on the surface condition of the materials involved.

ELECTRIC RESISTANCE WELDING

See RESISTANCE WELDING.

ELECTRIC TEMPERING

Reheating steel by electricity to impart hardness, elasticity or weldability; to anneal by electric heating.

Electric tempering is a useful application for the electric butt welding machine. Small pieces can be tempered by clamping them between the jaws of a butt welder and heating them quickly by turning on the current, then quenching them in water or oil.

ELECTRIC WELDING

The joining of metals by concentrating heat from an electric circuit at the point to be welded. The sources of heat are the electric arc established to the workpiece, or losses from internal resistance. *See* ARC WELDING *and* RESISTANCE WELDING.

ELECTRICAL RESISTANCE PYROMETER

See PYROMETER.

ELECTRICAL UNITS

The nomenclature, volt (E), ampere (I) and ohm (R) with which electric energy is defined and measured.

Volt (E). The electrical pressure (electromotive force) which causes electricity to flow through a conductor is measured in volts. A volt is the unit of electrical pressure required to cause a current of one ampere to flow through a conductor having a resistance of one ohm. Voltage is also referred to as *potential difference*.

Ampere (I). The unit of electric current which will flow through a conductor with a resistance of one ohm under a pressure of one volt is one ampere. The ampere expresses the amount of current which flows through a conductor.

Ohm (R). The unit of resistance of a circuit through which a potential difference of one volt produces a current of one ampere. The ohm is usually defined as the resistance of a given conductor of a certain material, size and form.

The relationship between volts, amperes, and ohms is expressed in Ohm's law as follows: I equals E/R, or E equals I × R, or R equals E/I.

When I equals the current in amperes, E equals the electromotive force or pressure in volts, and R equals the resistance in ohms.

ELECTRODE

A component of the electrical circuit that terminates at the arc, molten conductive slag, or base metal. See STANDARD WELDING TERMS. *See also* ELECTRODE MANUFACTURE, CUTTING ELECTRODE, TUNGSTEN ELECTRODE, STAINLESS STEEL *and* WELDING ELECTRODE.

Metal Arc Electrode. Filler metal in the form of a wire or rod, either bare or covered, through which current is conducted between the electrode holder and the arc.

Carbon Arc Electrode. A carbon or graphite rod through which current is conducted between the electrode holder and the arc.

Atomic Hydrogen Electrode. One of two tungsten rods between the points of which the arc is maintained. *See* ATOMIC HYDROGEN WELDING.

Resistance Welding Electrode. The part or parts of a resistance welding machine through which the welding current and the pressure are applied directly to the work. *See* RESISTANCE WELDING.

ELECTRODE, BARE

An uncoated electrode.

ELECTRODE CAP

A replaceable electrode tip used for resistance spot welding. See STANDARD WELDING TERMS.

ELECTRODE CARRIER

A container for carrying arc welding electrodes.

ELECTRODE CLASSIFICATION

The American Welding Society (AWS) has published the A5 series of specifications for consumables used in the arc and electroslag welding processes. *See* Appendix 17 for a complete listing.

Historical Background

Standards for arc welding electrodes did not exist until 1940, although by that time manufactures were recommending similar types of electrodes for various welding applications. In 1940, the AWS, in conjunction with the American Society for Testing and Materials (ASTM), developed tentative specifications for iron and steel arc welding electrodes used to weld mild steels.

AWS Classification System

The AWS has since developed specifications for filler metals to cover arc welding of carbon, alloy, stainless and corrosion-resistant steels; copper and copper-base alloys, and aluminum alloys. Through these specifications and classifications, an electrode can be selected which will produce a weld metal with specific mechanical properties. The electrode identification system is shown in Figure E-4.

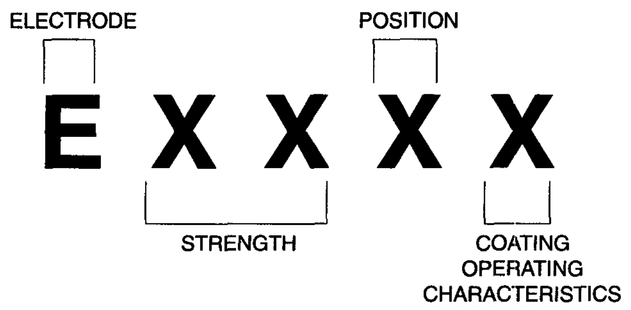


Figure E-4—SMAW Electrode Identification System

This system also classifies electrodes for minimum tensile strength, various positions of welding, and for type of welding current (alternating or direct current). *See* Table E-2.

The AWS classification system uses a four or five-digit number to identify the properties of the electrode, prefixed by the letter E. The letter E indicates that the filler material is an electrical conductor. The first two digits indicate minimum tensile strength in thousands of pounds per square inch (stress relieved); if it is a five digit number, the first three digits indicate minimum tensile strength. The second to last digit designates welding position. The last two digits taken together designate the type of current with which the electrode can be used and the type of covering on the electrode. Additional designators may be used to indicate special electrode classifications. These classifications are extremely important to help the welder to select the right electrode for each specification of the weld; for example, selecting a particular type of filler metal capable of depositing a high-strength, ductile weld.

Coated Electrodes

Prior to the development of coated electrodes, atmospheric gases in the high-temperature welding zone formed oxides and nitrides with the weld metal. In general, oxides are low in tensile strength and ductility, and tend to reduce the normal physical properties of the base metal. Coating materials were added to the electrode to provide an automatic cleansing and deoxidizing action on the molten weld puddle. As the coating burns in the arc, it releases a gaseous atmosphere that protects the molten end of the electrode, as well as the molten weld pool. This atmosphere excludes harmful oxygen and nitrogen from the molten weld area while the burning residue of coating forms a slag to cover the deposited weld metal. The slag also serves to exclude oxygen and nitrogen from the weld until it is cooled to a point where oxides and nitrides will no longer form; it slows the cooling of the deposit metal to produce welds with better ductility.

Through metal additives to the coating, electrodes can be used to add alloying agents to the weld metal or restore lost elements, and sometimes to enhance deposition rates. In addition, the slag from the coating not only protects the weld bead, but even helps shape it.

Iron Powder in Coatings

Some electrodes are made for use with direct current (dc) and some for alternating current (ac). Some d-c electrodes are for DCEN (electrode holder connected to the negative pole) and some are for DCEP (electrode holder attached to the positive pole). Still other d-c electrodes perform satisfactorily with either polarity.

Iron powders are added to the coating of many basic electrodes. In the intense arc heat, the iron powder is converted to steel, and this contributes additional metal to the weld deposit. When iron powder has been added to the electrode coating in relatively large amounts (up to 50% by weight), weld appearance and the speed of welding is appreciably increased. These electrode coatings have an insulating effect, help control the puddle for out-of-position welding, and also affect the arc length and welding voltage.

Obviously, to serve all these functions, the composition of an electrode must be a careful blend of specific ingredients so that performance characteristics are correctly balanced. There are other requirements of the electrode coating. It should have a melting point somewhat lower than that of the core wire or the base metal. The resulting slag must have a lower density in order to be expelled quickly and thoroughly from the rapidly solidifying weld metal. If the electrode is to be used in overhead or vertical welding positions, the slag formed from the melted coating must solidify quickly.

Alloy Steel Electrodes

The greatly expanded use of high alloy steel precipitated development of coated electrodes capable of producing weld deposits with tensile strengths exceeding 690 MPa (100 000 psi). Mechanical properties of this magnitude are achieved by using alloy steel in the core wire of the electrode.

In most electrode compositions, the coating is lime-ferritic, typical of the low-hydrogen design and frequently containing iron powder. These high-tensile electrodes are usually classified as EXX15, EXX16 or

Table E-2
Electrode Classification

AWS Classification	Type of Covering	Welding Position[a]	Type of Current[b]
E6010	High cellulose sodium	F, V, OH, H	dcep
E6011	High cellulose potassium	F, V, OH, H	ac or dcep
E6012	High titania sodium	F, V, OH, H	ac or dcen
E6013	High titania potassium	F, V, OH, H	ac, dcep, or dcen
E6019	Iron oxide titania potassium	F, V, OH, H	ac, dcep, or dcen
E6020	High iron oxide	H-fillets	ac or dcen
		F	ac, dcep, or dcen
E6022[c]	High iron oxide	F, H	ac or dcen
E6027	High iron oxide, iron powder	H-fillets	ac or dcen
		F	ac, dcep, or dcen
E7014	Iron powder, titania	F, V, OH, H	ac, dcep, or dcen
E7015	Low hydrogen sodium	F, V, OH, H	dcep
E7016	Low hydrogen potassium	F, V, OH, H	ac or dcep
E7018	Low hydrogen potassium, iron powder	F, V, OH, H	ac or dcep
E7018M	Low hydrogen iron powder	F, V, OH, H	dcep
E7024	Iron powder, titania	H-fillets, F	ac, dcep, or dcen
E7027	High iron oxide, iron powder	H-fillets	ac or dcen
		F	ac, dcep, or dcen
E7028	Low hydrogen potassium, iron powder	H-fillets, F	ac or dcep
E7048	Low hydrogen potassium, iron powder	F, OH, H, V-down	ac or dcep

Notes:

a. The abbreviations indicate the welding positions as follows:

F = Flat
H = Horizontal
H-fillets = Horizontal fillets
V-down = Vertical with downward progression
V = Vertical
OH = Overhead
{ For electrodes 3/16 in. (4.8 mm) and under, except 5/32 in. (4.0 mm) and under for classifications E7014, E7015, E7016, E7018, and E7018M.

b. The term "dcep" refers to direct current electrode positive (dc, reverse polarity). The term "dcen" refers to direct current electrode negative (dc, straight polarity).

c. Electrodes of the E6022 classification are intended for single-pass welds only.

EXX18. The operational characteristics parallel those of the typical E60XX low-hydrogen electrode.

In alloy steel electrodes, the basic four- or five-digit number designation for an electrode is usually followed by a letter symbol, such as A1, B2, B3. These AWS suffixes have been added to indicate specific additions of alloying elements as indicated in Table E-3.

Table E-3
AWS Designation of Major Alloying Elements in Shielded Metal Arc Electrodes

Suffix to Electrode Number	Alloying Element				
	Cr	Mn	Mo	Ni	Va
A1			0.40–0.65		
B1	0.40–0.65		0.45–0.65		
B2	1.00–1.50		0.45–0.65		
B3	2.00–2.50		0.90–1.20		
B4	1.75–2.25		0.40–0.65		
B5	0.40–0.60		1.00–1.25		0.05
C1				2.00–2.75	
C2				3.00–3.75	
C3	0.15		0.35	0.80–1.10	0.05
D1		1.25–1.75	0.25–0.45		
D2		1.65–2.00	0.25–0.45		
D3		1.00–1.75	0.40–0.65		
G	0.30	1.00	0.20	0.50	0.10
NM	0.05	0.80–1.25	0.40–0.65	0.80–1.10	0.02

Note: Single values are maximum percentages.

General Coating Types

Coated or shielded metal-arc electrodes achieve performance characteristics through design or formulation of the coating. The coatings of electrodes for welding mild and low-alloy steels may be designed to include as many ingredients and performance characteristics as necessary from among the following:

(1) Cellulose to provide a gaseous shield on disintegration

(2) Metal carbonates to adjust slag basicity and provide a reducing atmosphere

(3) Titanium dioxide to improve slag fluidity and freezing, and to aid in ionization

(4) Ferromanganese and ferrosilicon to help with deoxidation of molten weld metal and supplement the Mn or Si content in the deposit

(5) Clays and gums to aid in coating extrusion

(6) Calcium fluoride to provide shielding, adjust slag basicity, and provide fluidity and solubility to metal oxides

(7) Mineral silicates to provide slag and give strength to the coating

(8) Alloying metals (i.e., Ni, Mo, Cr and others) to provide alloy content to the deposit

(9) Iron or manganese oxide to adjust slag fluidity, and, for small amounts of iron oxide, help stabilize the arc

(10) Iron powder to enhance deposition rate

By using different combinations and amounts of these and other ingredients, a tremendous diversity of coatings can be produced. Following are descriptions of electrodes used for mild and low-alloy steels.

E6010 Electrodes. Electrodes in this classification have a cellulose/sodium coating and are designed to produce the best possible mechanical properties consistent with good usability characteristics in all welding positions, using DCEP.

They are best suited for vertical and overhead welding and some sheet metal applications. The spray-type arc produced by the E6010 electrode has a digging characteristic to produce deep penetration. This calls for electrode manipulation by the welder to minimize spatter and the tendency to undercut.

Fillet welds made with 6010 electrodes are relatively flat in profile and have a rather coarse, unevenly spaced ripple. These electrodes are highly recommended when quality of deposit is of prime importance, particularly on multi-pass applications in vertical and overhead positions, and when radiographic requirements must be met. Most applications for the E6010 electrode are on mild steel; however, they may be used to advantage on galvanized plate and some low-alloy steels.

E6011 Electrode. These electrodes are sometimes considered the a-c counterpart of the E6010. Performance characteristics of the two are similar; however, the E6011 electrode performs equally well with either a-c or d-c power sources. These electrodes produce a forceful digging arc resulting in deep penetration.

While the coating is slightly heavier on the E6011, the resulting slag and weld profiles are similar to those of the E6010. The coatings are high in cellulose and are designated as the high cellulose potassium type. In addition to the other ingredients usually found in the E6010 electrode coating, small quantities of calcium and potassium are usually present.

As in the case of the E6010 electrodes, sizes larger than 4.8 mm (3/16 in.) diameter are not usually used for all welding positions. The current ranges usually recommended are identical to those for the E6010, but similarly, high currents result in high spatter losses. Usually the ductility, tensile strength and yield strength of the deposited weld metal from an E6011 is higher than that of an E6010.

E6012 Electrodes. The E6012 electrodes are designed for all purpose welding in all positions, using either DCEN or an a-c power source. They are specifically recommended for horizontal and most downhill welding applications. They are especially recommended for single pass, high-speed, high-current horizontal fillet welds. Characteristics of the E6012 are ease of handling, medium penetration, no spatter, and good fillet weld profile. These electrodes can withstand high current and can bridge gaps caused by poor-fit-up conditions.

The 6012 electrodes are referred to as titania or rutile type, since the coating is high in titania, usually exceeding 35% by weight. In addition to titania, the coatings usually contain various silicious material such as feldspar and clay, small amounts of cellulose, and ferromanganese, with sodium silicate as the binder. Small amounts of calcium may be used to produce satisfactory arc characteristics on DCEN, and a small amount of iron powder is added to improve arc characteristics. The slag coverage is complete and is easily removed.

When E6012 electrodes are used with a d-c power source, DCEN is preferred.

E6013 Electrodes. Although E6013 electrodes are very similar to the E6012s, there are some notable differences. They are designed for welding in all positions, ac or dc. They produce a minimum spatter and have a minimum tendency to undercut. The beads have a fine ripple and are superior in appearance.

Slag removal is somewhat better and the arc can be established and maintained more readily, particularly with the small (1.6, 2.0, and 2.4 mm [1/16, 5/64, 3/32 in.]) electrodes, thus permitting satisfactory operation at a lower open-circuit voltage. These characteristics make the E6013 ideally suited to welding thin metals; the arc is soft and penetration very light. Mechanical and radiographic properties are slightly better than E6012.

These electrodes were originally designed specifically for sheet metal work.

While the E6012 electrode produces convex fillet weld contour characteristics, the E6013s produce a flat fillet weld similar to that of the E6020 electrode classification. The E6013 electrodes are also used for making groove welds because of the concave bead shape and easily removed slag. In addition, the weld metal contains fewer slag and oxide inclusions than E6012 weld metal, and quality verified by radiography is better.

The E6013 coating is very similar to that of the E6012, containing rutile, silicious materials, cellulose, ferromanganese and silicate binders. An important difference, however, is that easily ionized materials are incorporated in the coating, permitting establishment and maintenance of an arc with ac at lower welding currents and low open-circuit voltages. Some manufacturers have also introduced small quantities of iron powder into the E6013 coating.

E7014 Electrodes. This designation supersedes the E6014 designation. As the first two numbers of E7014 electrodes indicate, this is a 70,000 psi minimum tensile strength electrode. Although similar to E6013 electrodes, the coating of E7014 electrodes is considerably thicker, since it contains substantial amounts of iron powder (30% of coating weight). The amount of coating and the percentage of iron powder in it is usually less than that found in the E7020 electrodes.

The presence of iron powder in E7014 permits higher welding currents and means higher deposition rates and welding speeds. While the electrode is classified for all-position welding, the thicker coating is not ideally suited for out-of-position production welding on thin-gauge materials. Performance characteristics make it particularly suited for production welding of irregularly shaped products, where some out-of-position welding is required.

Mechanical properties of the E7014 weld metal are superior to those of E6012 or E6013. Slag removal is very easy, sometimes almost self-cleaning. General penetration and the rapid solidification characteristics make it well suited for handling poor fit-up conditions.

E7015 Electrodes. This electrode is commonly referred to as a low-hydrogen electrode. It was the first DCEP, all-position electrode designed for welding high-sulphur and high-carbon steels, materials which tend to develop porosity and sometimes crack under the weld bead.

Underbead cracks usually occur just below the weld metal in the base metal, and are caused by hydrogen absorption from arc atmospheres. Elimination of hydrogen with its subsequent underbead cracking improves welding conditions, and permits welding of "difficult-to-weld" steels with less preheat than required for electrodes which are not classified as low-hydrogen electrodes. Although underbead cracks do not occur in mild steel, they may occur when an electrode that is not low-hydrogen is used on high tensile steels.

The E7015 coating is high in limestone, sodium, and other ingredients with low-hydrogen content, which prevents the introduction of hydrogen in the weld. The arc is moderately penetrating; the slag is heavy, friable and easily removed, and the deposited weld metal lies in a flat bead, or may even be slightly concave.

The E7015s, through 4 mm (5/32 in.) diameter, can be used in all positions. The larger diameters are useful for fillet welds and horizontal and flat positions. Welding currents are somewhat higher than recommended for E6010s of comparable diameter. Also recommended: as short an arc as possible for all welding positions will produce best results. A short arc reduces the tendency for underbead cracking.

The E7015 electrode was originally developed for welding hardenable steels, in addition to alloy, high-carbon and high-sulfur steels. They are useful in welding malleable irons, spring steel, and the mild steel sides of clad plates. These electrodes are commonly used for making small welds on heavy weldments, since they are less susceptible to cracking than non-low-hydrogen electrodes. They are also extensively used for welding steels which are subsequently enameled, and on all steels which contain selenium.

The successful performance of this electrode led to development of the E7016 and E7018 electrodes, which also have a coating with very low moisture content.

E7016 Electrodes. These electrodes have all the characteristics of the E7015. The core wire and coatings are very similar except that the coatings of the E7016 contain certain amounts of potassium silicate and other potassium salts, which makes this electrode suitable for use with ac as well as DCEP. All the characteristics attributed to the E7015 also apply to the E7016 electrodes.

E7018 Electrodes. Similar to the E7016 electrodes, E7018 electrodes are all-position, low-hydrogen, and have a coating of 25% to 40% iron powder. They operate with either a-c or DCEP. The E7018 electrodes have all the desirable low-hydrogen characteristics of producing sound welds on troublesome steels, such as the high-sulfur, high-carbon, and low-alloy grades.

As is common with all low-hydrogen electrodes, a short arc should be maintained at all times. Fillet welds made in a horizontal or flat position are slightly convex in profile, with a smooth, finely rippled surface. Electrodes are characterized by a smooth, quiet arc, low penetration, very low spatter, and they can be used at high lineal speeds.

The minerals in the low-hydrogen electrode coatings are limited to inorganic compounds such as calcium fluoride, calcium carbonate, magnesium-aluminum-silicate, ferroalloys and such binding agents as sodium and potassium silicate. These electrodes are referred to as lime-ferritic electrodes because of the lime-type coatings (since this lime is a decomposed product of such compounds as calcium carbonate).

Since the coating of E7018 electrodes is heavier than most, vertical and overhead welding are usually limited to the smaller diameter electrodes. Currents used are somewhat higher than for the E6010 electrodes of corresponding size.

E6020 Electrodes. These electrodes are designed to produce high quality, horizontal fillet welds at high welding speeds, using either ac or DCEN. In the flat position, the E6020 can be used with ac or DCEN or DCEP.

The E6020 electrodes are characterized by a forceful spray-type arc and heavy slag, which completely covers the deposit and is easily removed. Penetration is medium at normal welding speeds, but high current and high travel speeds result in deep penetration. Deposits are usually flat or may be slightly concave in profile, and have a smooth, even ripple. Radiographic qualities are excellent, but the electrode produces medium spatter and has a tendency to undercut.

The E6020 electrodes are essentially mineral-coated electrodes, with high percentages of iron oxide, with manganese compounds and silicates, and sufficient deoxidizers to give the deposit the desired composition. The slag coverage is so extensive and the slag-metal reaction of such a nature that the electrodes generally do not depend on gaseous protection.

The coatings of E6020 electrodes usually produce iron oxide, manganese oxide, and silica slag. Other materials such as aluminum, magnesium or sodium may be present in the coating to modify this slag. Ferromanganese is used as the main deoxidizer; sodium silicate is used as a binder. The quantity of basic oxide, acid silica and silicates and deoxidizers must be carefully controlled to assure satisfactory operation and to produce good weld metal. The heavy slag produced will be well honeycombed on the underside, while completely covering the deposit. It can be readily removed.

E7024 Electrodes. These electrodes, ideally suited for production fillet welding, are designed for horizontal fillet or flat positions using either an a-c or d-c power source.

The E7024, although generally used on mild steel, also produces satisfactory welds on many low-alloy, medium and high carbon steels. The welds are slightly convex in profile, with a smooth surface and an extremely fine ripple. The electrodes are characterized by a smooth, quiet arc, very low spatter, low penetration, and can be used at high lineal speeds.

The coating contains 50% iron powder, which helps produce deposition rates and welding speeds considerably higher than those of the E6012, E6013 or E7014 types which have similar performance characteristics. Except for the high percentage of iron powder, the coating ingredients of the E7024 are similar to those used in the E6012 and E6013 electrodes.

E6027 Electrodes. With a 50% iron powder design, these electrodes have arc characteristics which closely duplicate the E6020. They are designed to produce satisfactory fillet or groove welds in the flat position with ac or dc, either polarity, and will produce flat or slightly concave horizontal fillet welds with either ac or DCEN.

The E6027 has a spray-type metal transfer and deposits metal at a high lineal speed. Penetration is medium and spatter loss is very low. The slag, though very heavy and honeycombed on the underside, crumbles for easy removal. The E6027 is particularly suited for multi-pass, deep groove welding.

Welds produced with the E6027 have a flat to slightly concave profile with a smooth, fine, even ripple, and with good metal wash up the joint sides. The weld metal might be somewhat inferior in soundness to that produced with E6020.

High current can be used; a considerable portion of the electrical energy passing through the electrode is needed to melt the coating and the iron powder contained in it. These electrodes are well suited to welding fairly heavy sections.

In many respects, the E6027 electrodes produce high quality weld metal with physical properties closely duplicating those of E6010.

E7028 Electrodes. The E7028 electrodes are the last of the mild steel series. They have a low-hydrogen coating containing 50% iron powder. These electrodes are very much like the E7018 electrodes, but have several different characteristics.

The E7018s are all-position electrodes; but E7028s are suitable for horizontal fillet and flat position welding only. The coating of the E7028 electrode is much thicker than that of the E7018 because of its higher iron powder content, so it has a much higher deposition rate on horizontal fillet and flat welding than E7018 electrodes of comparable size. (The coating of E7028 represents about 50% of its weight).

The means of metal transfer of these two electrodes is also different. The E7028 has a spray transfer; the E7018 has a globular transfer. Both these electrodes are capable of producing the physical properties and weld quality typical of low-hydrogen electrodes.

ELECTRODE EFFICIENCY

The ratio of the weight of the metal deposited from an electrode to the weight of the electrode consumed, times 100.

ELECTRODE EXTENSION, Flux Cored Arc Welding, Electrogas Welding, Gas Metal Arc Welding, and Submerged Arc Welding

The length of electrode extending beyond the end of the contact tube. See STANDARD WELDING TERMS. *See* Appendix 10.

The length of electrode extending beyond the electrode holder (for carbon arc cutting), or the end of the contact tube (for flux-cored, electrogas, gas-metal arc, or submerged arc welding).

ELECTRODE EXTENSION, Gas Tungsten Arc Welding

The length of tungsten electrode extending beyond the end of the collet. See STANDARD WELDING TERMS. *See* Appendix 10.

ELECTRODE FORCE

The force applied to the electrodes in making spot, seam, or projection welds by resistance welding. See STANDARD WELDING TERMS. *See also* DYNAMIC ELECTRODE FORCE, STATIC ELECTRODE FORCE, *and* THEORETICAL ELECTRODE FORCE.

Dynamic. In spot, seam and projection welding, the force (pounds) between the electrodes during the actual welding cycle.

Theoretical. In spot, seam and projection welding, the force, neglecting friction and inertia, available at the electrodes of a resistance welding machine, by virtue of the initial force application and the theoretical mechanical advantage of the system.

Static. In spot, seam and projection welding, the force between the electrodes under welding conditions, but with no current flowing and no movement in the welding machine.

ELECTRODE GAP

A nonstandard term for ARC LENGTH.

ELECTRODE HOLDER

A device used for mechanically holding and conducting current to an electrode during welding or cutting. See STANDARD WELDING TERMS. *See* Figure D-5.

An electrode holder is a clamping device which allows the welder to hold and control the electrode. It also serves as a device for conducting the welding current from the welding cable to the electrode. An insulated handle on the holder separates the welder's hand from the welding circuit. The current is transferred to the electrode through the jaws of the holder. To assure minimum contact resistance and to avoid overheating of the holder, the jaws must be kept in good condition. Overheating of the holder not only makes it uncomfortable for the welder, but also it can cause excessive voltage drop in the welding circuit. Either can impair the welder's performance and reduce the quality of the weld.

The holder must grip the electrode securely and hold it in position with good electrical contact. Installation of the electrode and removal of the expended electrode stub must be quick and easy. The holder needs to be light in weight and easy to handle, yet it must be sturdy enough to withstand rough use. Most holders have insulating material around the jaws to prevent grounding of the jaws to the work.

Electrode holders are produced in sizes to accommodate a range of standard electrode diameters. Each size of holder is designed to carry the current required for the largest diameter electrode that it will hold. The smallest size holder that can be used without overheating is the best one for the job. It will be the lightest, and it will provide the best operator comfort.

The electrode holder must be kept clean to ensure maximum operating life. Clean jaws and contact points maintain good electrical connection and consequently less heating and burning of the holder. The insulation must be kept tight and in good repair. If the jaws are closed by a spring, the electrode holder should be inspected to see that the spring is in good order at all times. Under extreme heat, springs sometimes lose temper and must be replaced. A weak spring slows up welding and reduces the quality of the weld.

ELECTRODE INDENTATION, Resistance Welding

The depression formed on the surface of workpieces by electrodes. See STANDARD WELDING TERMS.

ELECTRODE LEAD

The electrical conductor between the source of arc welding current and the electrode holder. See STANDARD WELDING TERMS. *See* Figure D-5.

ELECTRODE MANUFACTURE

Electrodes are designed by metallurgists and welding engineers who specify the composition of coated electrodes to achieve various results in weld metal and the finished weld. Manufacturers of electrodes have developed arc welding electrodes to weld ferrous alloys such as cast iron, rolled steel, chrome steel, nickel chrome steel, manganese steel, and non-ferrous alloys such as bronze, brass, copper, or nickel alloys. They have also developed electrodes for welding materials in the pure state, such as aluminum. The ingredients of the electrode coatings can be selected to provide shielding gas, flux, and slag during welding. *See* ELECTRODE.

Historical Background

In the early years of welding, strips of sheet, bare steel rod or wire (sometimes baling wire) were used as consumable electrodes to provide the filler material for metal arc welding. These early electrodes produced an unstable arc which was difficult to initiate, and resulted in welds that were porous and brittle. Better welds seemed to result when the wire and rod were slightly coated with a film of rust, or when the wire or rod had a light lime coating remaining after lime had been used as a lubricant in the drawing process. It was soon determined that the bare electrode must be either sul-coated, which is a special rust-coated finish produced by spraying the wire with water before the last drawing, or lime coated. The light lime coating assisted in keeping the arc steady by producing a vapor which would conduct the current, but it did not significantly improve weld quality. Many materials were used in experiments to find substances that could be added to improve weld results. When the lime coated or sul-coated electrode was wrapped in newspaper, a gaseous shield for the arc was formed which improved the weld, apparently the result of the cellulose in the paper. Among the other materials used experimentally to form cellulosic coatings were sawdust, cotton, wood flour, wheat flour and rice flour.

The carbon content of welding rods for arc welding steel changed the characteristics of the weld. Carbon steel electrodes were manufactured in two grades. A higher carbon content was supplied for arc welding and a lower carbon content for gas welding. Today, electrodes containing from 0.13% to 0.18% carbon are widely used for welding mild steel.

Coatings

In general, there are two types of electrodes for welding ferrous alloys: medium or semicoated, and heavily coated electrodes.

Medium or semicoated electrodes are made by dipping the core wire material in a liquid flux, and withdrawing it to allow the flux coating to dry. A coating of this type usually represents only 1% to 2% of the weight of the electrode.

The heavily coated electrodes are dipped several times to obtain the desired thickness, or they are passed through an extrusion press, the generally accepted practice, where a coating is applied uniformly by extrusion. Specifications require that the extruded coating be concentric with the electrode; a coating which is 3% or more off center is unsatisfactory.

Core Wire Material

The most suitable core material for steel electrodes is a high-grade rimmed steel. Killed or semi-killed steels do not function as well. A typical specification for a widely used type of electrode follows:

Carbon	.13 to .18%
Manganese	.40 to .60%
Silicon	0.06%
Sulphur	0.04%
Phosphorus	0.04%

The tensile strength of the metal, and to some extent, the smoothness and soundness of the deposit are affected by the carbon and manganese content. Minimum sulfur content is important; it should be as far below 0.04% as reasonably possible.

Composition of Coatings

Electrode coatings usually contain substances such as silicon, calcium, barium, and magnesium. Water glass, a solution of sodium silicate, is usually used as a binder, but various gums, glues and lacquers are also used. They are classed as cellulosic and mineral.

Principal stabilizers for both the cellulosic and mineral coatings are titanium dioxide, feldspar and calcium carbonate. Ferromanganese also appears in both types of coatings as a deoxidizer used for porosity control. It also tends to balance the manganese burned out in arc transfer. In some coatings, alloy ingredients such as molybdenum, which has good transfer characteristics, are added.

Cellulosic. This coating contains such ingredients as sodium silicate, ferromanganese, titanium dioxide and alpha and beta cellulose. This type of coating is sometimes referred to as the high ignition loss type, because a considerable portion of the coating burns away to form a gas in the arc.

The cellulosic coating is a high-quality coating used for all-position electrodes; however, it is suitable only for DCEP. Arc action produces a forceful spray weld metal transfer with deep penetration.

Mineral. A mineral electrode coating usually consists of metallic oxides and silicates. This type of coating produces an abundance of slag which provides ample coverage and complete shielding. Electrodes with mineral coatings are usually confined to welding in the horizontal and flat position. These electrodes produce high quality weld metal using either ac or dc.

The mineral ingredients in this coating form gases around the molten and vaporized material from the core iron as they pass through the arc, protecting them from the atmosphere as they form a molten slag covering the weld metal.

Rutile (titanium dioxide) is an important substance in mineral-coated electrodes. The rutile coated electrodes have a coating of moderate thickness so that globular transfer and a rapid rate of solidification occurs. This feature adapts well to joints with a relatively poor fit-up. In addition to an abundance of rutile, these electrode coatings include some ferromanganese, feldspar, and sodium silicate. These general purpose, all-position electrodes operate on ac or DCEN.

ELECTRODE MUSHROOMING

The enlargement of a resistance spot or projection welding electrode tip due to heat or pressure so it resembles a mushroom in shape. See STANDARD WELDING TERMS.

ELECTRODE PICKUP

Contamination of the electrode tips or wheel faces by the base metal or its coating during resistance spot, *seam, or projection welding. See* STANDARD WELDING TERMS.

ELECTRODE SETBACK

The distance the electrode is recessed behind the constricting orifice of the plasma arc torch or thermal spraying gun, measured from the outer face of the constricting nozzle. See STANDARD WELDING TERMS. *See* Appendix 10. *See also* CONTACT TUBE SETBACK.

ELECTRODE SKID

The sliding of a resistance welding electrode along the surface of the workpiece when making spot, seam, or projection welds. See STANDARD WELDING TERMS.

ELECTRODE TIP

The end of a resistance spot or projection welding electrode in contact with the workpiece. See STANDARD WELDING TERMS.

ELECTRODE TIP LIFE

The number of resistance spot welds that can be made with an electrode before redressing of the electrode is required. See STANDARD WELDING TERMS.

ELECTROFORGING DIES

See RESISTANCE WELDING ELECTRODE.

ELECTROGAS WELDING (EGW)

An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool, employing approximately vertical welding progression with backing to confine the molten weld metal. The process is used with or without an externally supplied shielding gas and without the application of pressure. See STANDARD WELDING TERMS.

Historical Background

The first available thick-plate single-pass vertical welding process was electroslag welding. Demand arose immediately for equipment that would apply the process to thinner sections. Almost all vertical joints were being welded with the manual shielded metal arc welding (SMAW) process or by semiautomatic gas metal arc welding (GMAW). In 1961, laboratory studies with an electroslag welding machine adapted to feed auxiliary gas shielding around a flux cored electrode demonstrated that plate as thin as 10 mm (3/8 in.) could be welded in the vertical position in a single pass. The technique is called *electrogas welding* (EGW).

Process

Electrogas welding is a machine welding process. The mechanical aspects of electrogas welding are similar to those of the electroslag process from which it was developed. There are two variations of the process commonly used in the United States. Based on the GMAW process, it can feed a solid electrode into the joint; based on the flux cored arc welding process (FCAW), it can incorporate a flux within a tubular electrode. Both variations use retaining shoes (dams) to confine the molten weld metal, which permit welding in the vertical position. Gas shielding, when needed, is provided through inlet ports in the dams or a gas cup around the electrode, or both. When using a self-shielded FCAW electrode, no gas is added.

A square-groove or single V-groove joint is positioned so that the axis or length of the weld is vertical. Figure E-5 shows typical electrogas welding joint designs. There is no repositioning of the joint once welding has started; welding continues to completion, so that the weld is made in one pass. The nature of the melting and solidification during welding results in a high quality weld deposit. There is little or no angular distortion of the base metal with single-pass welds. The welding action is quiet, with little spatter.

Principles of Operation

The consumable electrode, either solid or flux cored, is fed downward into a cavity formed by the base metals to be welded and the retaining shoes. A sump (starting tab) is used at the beginning of the weld to allow the process to stabilize before the molten weld metal reaches the work. An arc is initiated between the electrode and the sump.

Heat from the arc melts the continuously fed electrode and the groove faces. This is shown schematically in Figure E-6. Melted filler metal and base metal collect in a pool beneath the arc and solidify to form the weld. The electrode may be oscillated horizontally through the joint for uniform distribution of heat and weld metal. As the cavity fills, one or both shoes may move upward. Although the weld travel is vertical, the weld metal is actually deposited in the flat position at the bottom of the cavity.

Applications

Base metals most commonly joined by electrogas welding are plain carbon, structural and pressure vessel steels. Applications of electrogas welding include storage tanks, ship hulls, structural members and pressure vessels. EGW should be considered for any joint

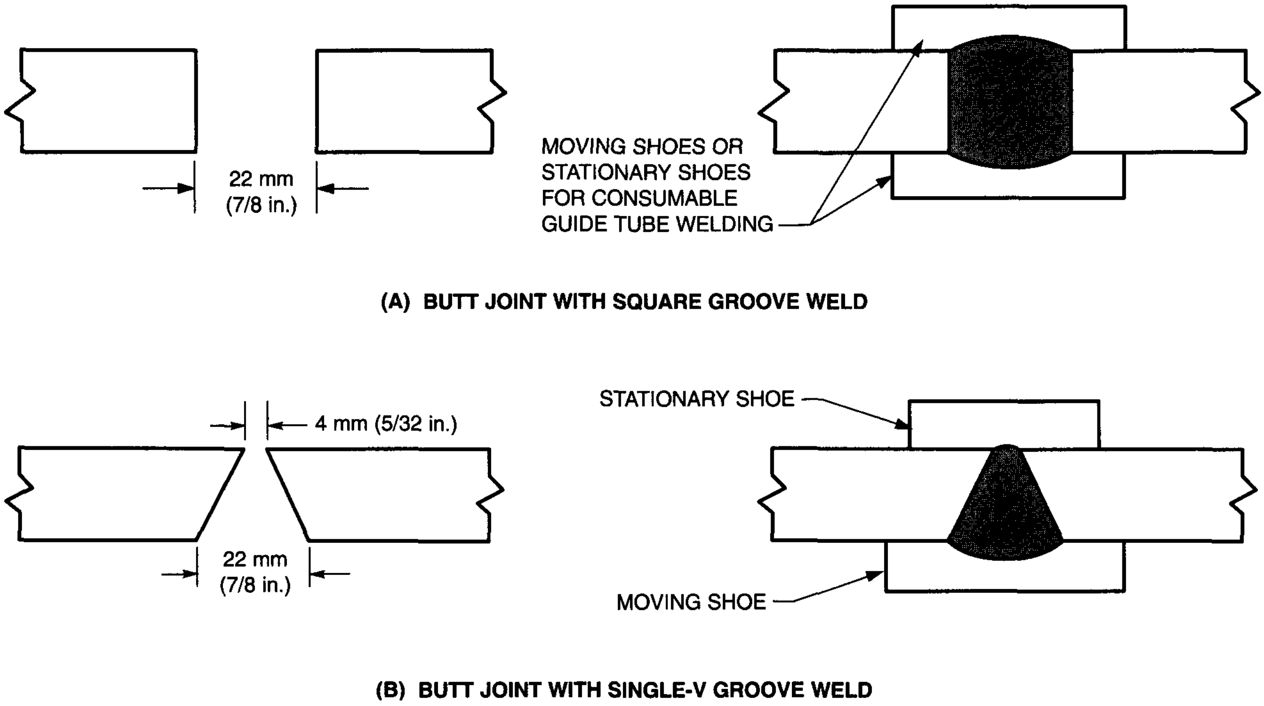


Figure E-5—Typical Electrogas Welding Joint Designs

to be welded in a vertical position in materials ranging in thickness from 10 to 100 mm (3/8 to 4 in.) thick.

Advantages

Some of the advantages associated with EGW have resulted in considerable cost savings, particularly in joining thicker materials, when compared to the more conventional joining methods such as submerged arc welding and flux cored arc welding. Even in some applications involving thinner base materials, EGW may result in cost savings because of its efficiency and simple joint preparation. The following advantages can be achieved with EGW:

(1) Extremely high metal deposition rates; EGW has a deposition rate of 16 to 20 kg (35 to 45 lbs) per hour per electrode.

(2) Preheating is normally not required, even on materials of high hardenability.

(3) High-quality weld deposit; the weld metal stays molten for an appreciable time, allowing gases to escape and slag to float to the top of the weld.

(4) Minimum joint preparation and fit-up requirements; mill edges and flame-cut square edges are normally employed.

(5) High duty cycle; the process is automatic and once started, continues to completion; there is little operator fatigue.

(6) Minimum materials handling; the work needs to be positioned only to place the axis of the weld in the vertical or near vertical position; there is no manipulation of the parts once welding has started.

(7) Elimination of weld spatter, which results in 100% filler metal deposition efficiency.

(8) Minimum distortion; there is no angular distortion in the horizontal plane. Distortion is minimal in the vertical plane, and this is easily compensated for.

Limitations

(1) The EGW process welds only carbon and low alloy steels, and some stainless steels.

(2) The joint must be positioned in the vertical or near-vertical position.

(3) Once welding has started, it must be carried to completion or a defective area is likely to result.

(4) Complex material shapes may be difficult or impossible to weld using EGW.

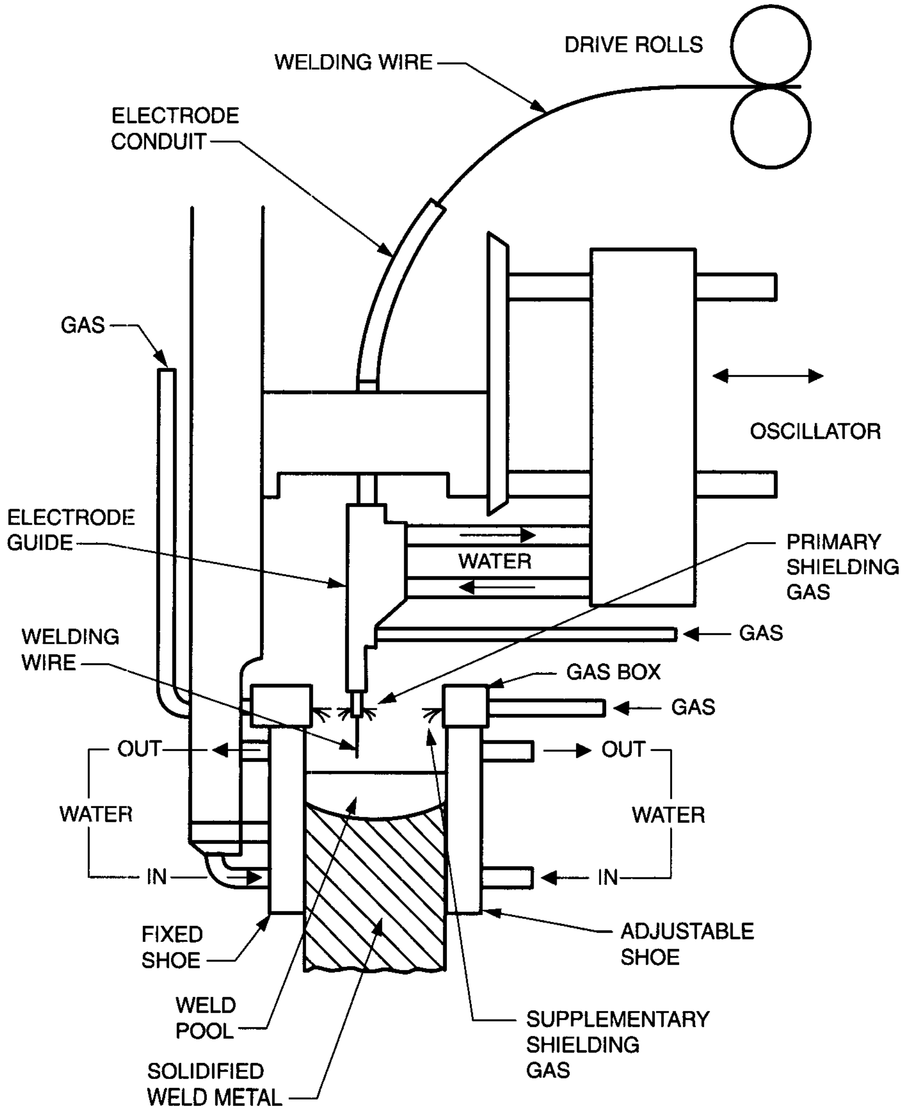


Figure E-6—Electrogas Welding with a Solid Electrode

Electrode Variations

Solid Electrode. In a typical electrogas welding installation, a solid electrode is fed through a welding gun, called a *nonconsumable guide. See* Figure E-6. The electrode may be oscillated horizontally to weld thicker materials. Gas shielding, normally carbon dioxide (CO_2) or an argon-carbon dioxide ($Ar\text{-}CO_2$) mixture, is provided to the weld cavity through gas ports, boxes, or nozzles. Water-cooled copper retaining shoes retain the weld; they move vertically as the machine moves. Vertical movement of the machine must be consistent with the deposition rate, and may be automatic or controlled by the welding operator.

Electrogas welding with solid electrodes can be used to weld base metals ranging in thickness from approximately 10 mm (3/8 in.) to 100 mm (4 in.). Base metal thicknesses most commonly welded are between 13 mm (1/2 in.) and 76 mm (3 in.). Electrode diameters most commonly used are 1.6, 2.0, 2.4, and 3.2 mm (1/16, 5/64, 3/32, and 1/8 in.).

Flux Cored Electrode. The principles of operation and characteristics of the self-shielded flux cored electrode are identical to the solid electrode variation, except that no separate gas shielding is needed. *See* Figure E-7. The flux cored electrode creates a thin layer of slag between the weld metal and copper shoes to provide a smooth weld surface.

Electrogas welding with a flux cored electrode may be done with an external gas shield or a self-shielding electrode. Self-shielded electrodes operate at higher current levels and deposition rates than shielded types.

Diameters of flux cored electrodes commonly vary from 1.6 mm to 3.2 mm (1/16 in. to 1/8 in.). The wire (electrode) feeder must be capable of smooth, continuous feeding of small diameter wires at high speeds and larger diameter wires at slower speeds.

Consumable Guide Process

EGW with a consumable guide is similar to consumable guide electroslag welding. This variation of EGW is primarily used for short weldments in shipbuilding, and in column and beam fabrication. Consumable guide EGW uses relatively simple equipment; the principle difference is that none of the equipment moves vertically during consumable guide welding. Instead, the electrode is fed through a consumable guide tube which extends to about 25 mm (1 in.) from the bottom of the joint. As the weld progresses vertically, the electrode melts back to the guide tube. Initially, the wire electrode penetrates about an inch beyond the end of the guide tube. Then a steady-state relationship develops between melting of the end of guide tube and the electrode wire. This relationship remains until the weld is completed. The consumable guide process is shown schematically in Figure E-7.

The American Welding Society publishes ANSI/AWS A5.26, *Specification for Carbon and Low Alloy Steel Electrodes for Electrogas Welding,* which prescribes requirements for solid and flux cored electrodes for electrogas welding.

Equipment

The basic mechanical equipment for electrogas welding consists of a direct current power supply, a device for feeding the electrode, shoes for retaining molten metal, an electrode guide, a mechanism for oscillating the electrode guide, and equipment needed for supplying shielding gas, when used. In a typical electrogas welding system, the essential components (with the exception of the power supply) are incorporated in an assembly that moves vertically as welding progresses.

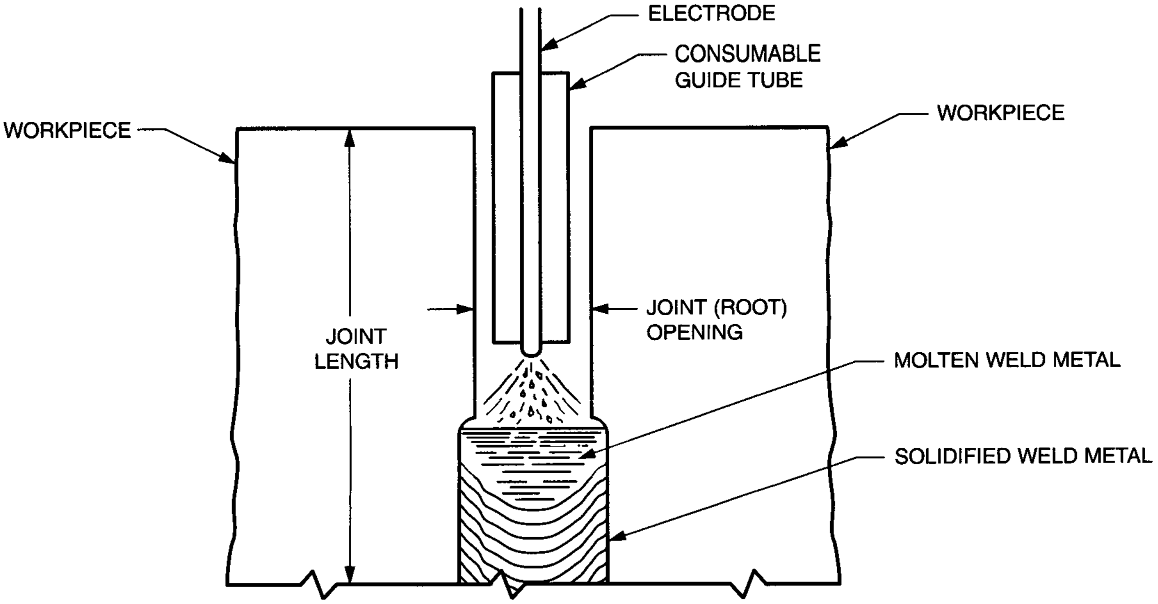


Figure E-7—Schematic View of Consumable Guide Electroslag Welding

Power Supply. Direct current electrode positive (reverse polarity) is normally used for EGW, with the power supply either constant voltage or constant current. The power source should be capable of delivering the required current without interruption during the welding of a seam that may be of considerable length. Power sources used for electrogas welding usually have ratings of 750 to 1000 amperes at 30 to 55 volts and 100% duty cycle. Direct current is usually supplied by transformer-rectifier power sources, although motor-driven and engine-driven generators may be used.

Wire feed for the electrode is of the push type, such as used with automatic GMAW or FCAW. The wire feeder is normally mounted as an integral part of the vertical-moving welding machine. Wire feed speeds may vary up to 230 mm/s (550 in./min). The wirefeed system may include a wire straightener to eliminate the cast and helix in the electrode to minimize electrode wander at the joint.

Electrode Guide. Electrode guides are similar to the welding guns used for semiautomatic GMAW or for FCAW. The guide may have a shielding gas outlet to deliver gas around the protruding electrode.

Electrode Guide Oscillator. The horizontal motion needed when welding base metals 30 mm to 100 mm (1-1/4 in. to 4 in.) thick to move the arc back and forth between the shoes and over the weld pool is accomplished by a system that oscillates the electrode guide and provides adjustable dwell times at either end of the oscillation.

Retaining Shoes. Retaining shoes (also called *dams*), are pressed against each side of the gap between the base metals to be welded to retain (dam) the molten weld metal in the groove. Nonfusing ceramic backups are sometimes used. Sliding shoes may or may not contain gas ports to supply shielding gas directly into the cavity formed by the shoes and the weld groove. When gas ports are not used in the shoes, a "gas box" arrangement may be mounted on the shoes to surround the electrode and welding arc with shielding gas; these are not required when using self-shielding flux cored electrodes.

Controls. With the exception of the vertical travel control, EGW controls are primarily adaptations of the devices used with GMAW and FCAW. Vertical travel controls, either electrical, optical, or manual, maintain a given electrode extension, with the top of the movable shoe a specific distance above the molten weld pool.

Safety

Specific instructions for safe operation of electrogas welding equipment are available in the manufacturer's literature. General safety instructions for all welding and cutting can be found in ANSI/ASC Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society. Mandatory Federal safety regulations are established by the U.S. Labor Department's Occupational Safety and Health Administration, and are available in the latest edition of OSHA Standards, *Code of Federal Regulations, Title 29 Part 1910,* from the Superintendent of Documents, U.S. Printing Office, Washington DC 20402.

Personnel should be protected against exposure to noise generated in welding and cutting operations. *See* Paragraph 1910.95, Occupational Noise Exposure, *Code of Federal Regulations.*

The total radiant energy produced by the EGW process can be higher than that produced by the SMAW process because EGW has a more exposed arc, especially when using an argon shielding gas and when welding on aluminum. Suggested filter glass shades for EGW are shown in Appendix 18.

For general information on metallurgical considerations, mechanical properties, process variables, joint design, fit-up *and* assembly, training of operators, and troubleshooting guide, refer to: American Welding Society, *Welding Handbook*, 8th Edition, Vol. 1; Miami, Florida 1987; and *Welding Handbook*, 8th Edition Vol. 2; Miami, Florida: American Welding Society 1991.

ELECTROLYTE

A nonmetallic conductor of electricity in which current is carried by the movement of ions.

In the cells of an electrolytic oxygen and hydrogen generator, a chemical, (caustic soda or potash) serves as the conductor.

ELECTROLYTIC OXYGEN AND HYDROGEN

See OXYGEN PRODUCTION.

ELECTROMAGNET

A soft iron core wound with a coil through which an electric current is passed. The core is magnetized while the current flows, but is demagnetized when the current stops.

ELECTROMAGNETIC WELDING

See RESISTANCE WELDING, Stored Energy.

ELECTROMOTIVE FORCE (EMF)

The electrical pressure or voltage which forces an electric current through a circuit. The unit of measure of electromotive force is the volt.

ELECTRON BEAM BRAZE WELDING (EBBW)

A braze welding process variation that uses an electron beam as the heat source. See STANDARD WELDING TERMS.

ELECTRON BEAM CUTTING (EBC)

A thermal cutting process that severs metals by melting them with the heat from a concentrated beam, composed primarily of high-velocity electrons, impinging on the workpiece. See STANDARD WELDING TERMS.

ELECTRON BEAM CUTTING OPERATOR

See STANDARD WELDING TERMS. *See* THERMAL CUTTING OPERATOR.

ELECTRON BEAM GUN

A device for producing and accelerating electrons. Typical components include the emitter (also called the filament or cathode) that is heated to produce electrons via thermionic emission, a cup (also called the grid or grid cup), and the anode. See STANDARD WELDING TERMS.

ELECTRON BEAM GUN COLUMN

The electron beam gun plus auxiliary mechanical and electrical components that may include beam alignment, focus, and deflection coils. See STANDARD WELDING TERMS.

ELECTRON BEAM WELDING (EBW)

A welding process that produces coalescence with a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint. The process is used without shielding gas and without the application of pressure. See STANDARD WELDING TERMS. *See also* HIGH VACUUM ELECTRON BEAM WELDING, MEDIUM VACUUM ELECTRON BEAM WELDING, *and* NONVACUUM ELECTRON BEAM WELDING.

When the high-velocity electrons impinge on a joint, their kinetic energy is converted into heat. The density of energy (or heat) is so great that vaporization of the metal (or ceramic) usually occurs, creating a cavity called a keyhole. This keyhole allows exceptionally deep penetration, for a relatively narrow width. The vapor cavity is surrounded by a liquid shell which closes behind the beam (in the direction opposite beam travel) to produce a liquid pool by capillary action. The weld and joint are formed on solidification. A vacuum is required to prevent scattering and dispersion of the beam. This vacuum provides shielding to the molten weld pool and surrounding base metal.

Principles of Operation

The heart of the electron beam welding process is the electron beam gun/column assembly, a simplified representation of which is shown in Figure E-8. Basically, an electron beam welding gun functions in much the same manner as a TV picture tube. The primary difference is that a TV picture tube uses a low-intensity electron beam to continuously scan the surface of a luminescent screen, and thereby produces a picture. An electron beam welding gun uses a high-intensity electron beam to continuously bombard a weld joint, which converts that energy to the level of heat input need to make a fusion weld. In both of these cases, the beam of electrons is created in a similar manner.

The electron beam welding gun typically contains some type of thermionic electron emitter (normally referred to as the gun "cathode" or "filament"), and an anode. Various supplementary devices, such as focus and deflection coils, are also provided to focus and deflect this beam. In EBW, the total beam generating system (gun and electron optics) is called the electron beam gun/column assembly, or simply the electron beam gun column.

There are three basic modes of electron beam welding: high vacuum (EBW-HV), medium vacuum (EBW-MV), and nonvacuum (EBW-NV). The principal difference between these process modes is the ambient pressure at which welding is done.

High vacuum and medium vacuum welding are done inside a vacuum chamber. This imposes an evacuation time penalty to create the "high purity" environment. The medium vacuum welding machine retains most of the advantages of high vacuum welding, with shorter chamber evacuation times, resulting in higher production rates.

Nonvacuum EB welding is used to weld workpieces at atmospheric pressure, but a vacuum is still required to produce the electron beam. Although nonvacuum EB welding incurs no pumpdown time penalty, it is not suitable for all applications because the welds it produces are generally wider and shallower than equal power EB welds produced in a vacuum.

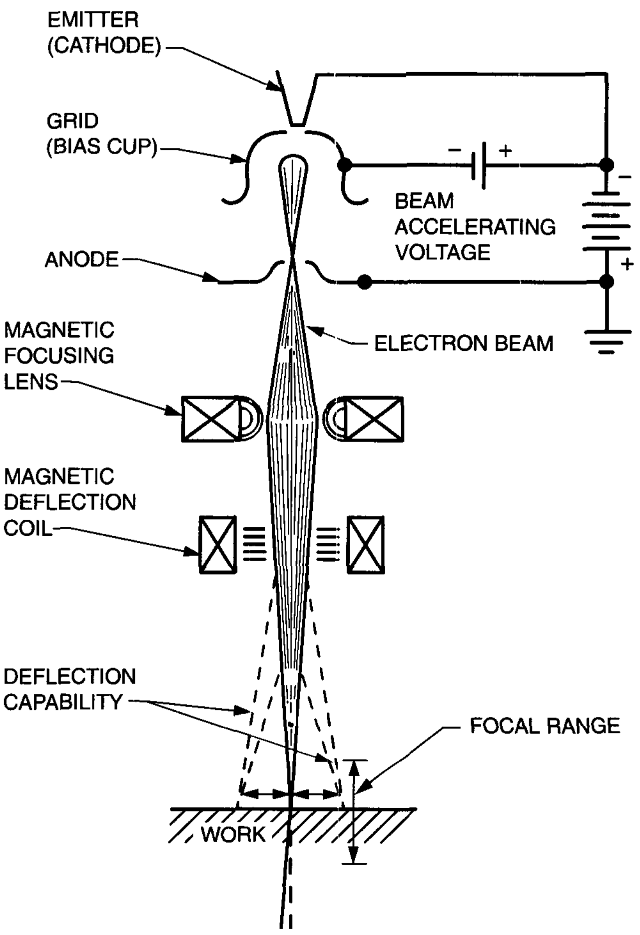


Figure E-8—Simplified Representation of a Triode Electron Beam Gun Column

Applications

In general, metals and alloys that can be fusion welded by other welding processes can also be joined by electron beam welding. The weldability of a particular alloy or combination of alloys will depend on the metallurgical characteristics of that alloy or combination, in addition to the part configurations, joint design, process variation, and selection of welding procedure. Considering these variables, the electron beam process can be used to weld steels, stainless steels, aluminum alloys, titanium and zirconium, the refractory metals, and dissimilar metals.

Electron beam welding is primarily used for two distinctly different types of applications: high precision and high production.

High precision requires a high-purity environment (high vacuum) to avoid contamination by oxygen or nitrogen, or both, and with minimum heat effects and maximum reproducibility. These types of applications are mainly in the nuclear, aircraft, aerospace, and electronic industries. Typical products include nuclear fuel elements, special alloy jet engine components, pressure vessels for rocket propulsion systems, and hermetically sealed vacuum devices.

High production applications take advantage of the low heat input and the high reproducibility and reliability of electron beam welding if a high-purity environment is not required. These relaxed conditions permit welding of components in the semifinished or finished condition, using both medium and nonvacuum equipment. Typical examples are gears, frames, steering columns, and transmission and drive-train parts for automobiles; thin-wall tubing; bandsaw and hacksaw blades, and other bimetal strip products.

The major application of nonvacuum electron beam welding is in high-volume production of parts, the size or composition of which preclude effective welding in a vacuum. The automotive industry employs nonvacuum EB welding for many applications. An example is a torque converter assembly. Manufacturers of welded tubing also use nonvacuum EB welding. Integrated EB welding machine/tube mill units have been built to weld copper or steel tubing continuously at speeds up to 500 mm/s (100 ft/min).

Advantages

Electron beam welding has unique performance capabilities. The high-quality environment, high power densities, and outstanding control solve a wide range of joining problems. The following are advantages of electron beam welding:

(1) EBW is extremely efficient because it directly converts electrical energy into beam output energy.

(2) Electron beam weldments exhibit a high depth-to-width ratio. This feature allows for single-pass welding of thick joints.

(3) The heat input per unit length for a given depth of penetration can be much lower than with arc welding; the resulting narrow weld zone has low distortion, and fewer deleterious thermal effects.

(4) A high-purity environment (vacuum) for welding minimizes contamination of the metal by oxygen and nitrogen.

(5) The ability to project the beam over a distance of several feet in vacuum often allows welds to be made in otherwise inaccessible locations.

(6) Rapid travel speeds are possible because of the high melting rates associated with this concentrated heat source. This reduces welding time and increases productivity and energy efficiency.

(7) Reasonably square butt joints in both thick and relatively thin plates can be welded in one pass without the addition of filler metal.

(8) Hermetic closures can be welded with the high or medium vacuum modes of operation while retaining a vacuum inside the component.

(9) The beam of electrons can be magnetically deflected to produce various shaped welds, to improve weld quality, or increase penetration.

(10) The focused beam of electrons has a relatively long depth of focus, which will accommodate a broad range of work distances.

(11) Full penetration, single-pass welds can be produced with nearly parallel sides, and exhibiting nearly symmetrical shrinkage.

(12) Dissimilar metals and metals with high thermal conductivity, such as copper, can be welded.

Limitations

Some of the limitations of electron beam welding are:

(1) Capital costs are substantially higher than those of arc welding equipment. However, depending on the volume of parts to be produced, the final per-piece cost attainable with EBW can be highly competitive.

(2) Preparation for welds with high depth-to-width ratio requires precision machining of the joint edges, exacting joint alignment, and good fit-up. In addition, the joint gap must be minimized to take advantage of the small size of the electron beam. However, these precise part preparation requirements are not mandatory if high depth-to-width ratio welds are not needed.

(3) The rapid solidification rates achieved can cause cracking in highly constrained, low ferrite stainless steel.

(4) For high and medium vacuum welding, work chamber size must be large enough to accommodate the assembly operation. The time needed to evacuate the chamber will influence production costs.

(5) Partial penetration welds with high depth-to-width ratios are susceptible to root voids and porosity.

(6) Because the electron beam is deflected by magnetic fields, nonmagnetic or properly degaussed metals should be used for tooling and fixturing close to the beam path.

(7) With the nonvacuum mode of electron beam welding, the restriction on work distance from the bottom of the electron beam gun column to the work will limit the product design in areas directly adjacent to the weld joint.

(8) With all modes of EBW, radiation shielding must be maintained to ensure that there is no exposure of personnel to the x-radiation generated by EB welding.

(9) Adequate ventilation is required with nonvacuum EBW, to ensure proper removal of ozone and other noxious gases formed during this mode of EB welding.

Equipment

High vacuum, medium vacuum, and nonvacuum EBW equipment employs an electron beam gun/column assembly, one or more vacuum pumping systems, and a power supply. High and medium vacuum equipment operates with the work in an evacuated welding chamber. Although nonvacuum work does not need to be placed in a chamber, a vacuum environment is necessary for the electron beam gun column. All three basic modes can be performed using so-called high-voltage equipment, i.e., equipment using gun columns with beam accelerating voltages greater than 60 kV. Nonvacuum electron beam welding performed directly in air requires beam accelerating voltages greater than 150 kV. High vacuum and medium vacuum welding can also be performed with so-called low-voltage equipment (i.e., equipment with gun columns that employ beam accelerating voltages of 60 kV and lower). Because high-voltage gun columns are generally fairly large, they are usually mounted on the exterior of the welding chamber, and are either fixed in position or provided with a limited amount of tilting or translational motion, or both. Low-voltage gun columns are usually small. Some units are "fixed" externally. Others are internally mounted "mobile" units capable of being moved about, with up to five axes of combined translational motion.

Electron Beam Guns. An electron beam gun generates, accelerates, and collimates the electrons into a directed beam. The gun components can logically be divided into two categories: (1) elements that generate free electrons (the emitter portion), and (2) a rod- or disc-type filament indirectly heated by an auxiliary source, such as electron bombardment or induction heating. The specific emitter design chosen will affect the characteristics of the final beam spot produced on the work.

Power Supplies. The electron gun power source used for an electron beam welding machine is an assembly of at least one main power supply and one or more auxiliary power supplies. It produces high-voltage power for the gun and auxiliary power for the emitter and beam control.

Vacuum Pumping Systems. Vacuum pumping systems are required to evacuate the electron beam gun chamber, the work chamber for high and medium vacuum modes, and the orifice assembly used on the beam exit portion of the gun/column assemblies for medium vacuum and nonvacuum welding. Two basic types of vacuum pumps are used: one is a mechanical piston or vane-type, and the other is an oil-diffusion-type pump used to reduce the pressure.

Work Chambers. Work chambers of low-voltage systems are usually made of carbon steel plate. The thickness of the plate is designed to provide adequate x-ray protection and the structural strength necessary to withstand atmospheric pressure. Lead shielding may be required in certain areas to ensure total radiation tightness of the system.

Safety

Since electron beam welding machines employ a high-energy beam of electrons, the process requires users to observe several safety precautions not normally necessary with other types of fusion welding equipment. The four primary potential dangers associated with electron beam equipment are electric shock, x-radiation, fumes and gases, and damaging visible radiation. In addition to the potential dangers associated with welding specific materials, such as beryllium, there may also be a potential danger associated with collateral materials (solvents, greases and others) used in operating the equipment. Precautionary measures should be taken to assure that all required safety procedures are strictly observed. ANSI/AWS F2.1, *Recommended Safe Practices for Electron Beam Welding and Cutting,* and ANSI/ASC Z49.1, *Safety in Welding and Cutting* (latest editions) give the general safety precautions that must be taken.

For information on fundamentals of electron beam welding, process variations, equipment, weld characteristics, welding procedures, fixturing, filler metal additions, selection of welding variables, weldability of metals, weld quality, safety precautions, and bibliography, see American Welding Society, *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

ELECTRONIC CONTROLS, Resistance Welding

The principal functions of resistance welding controls are (1) to provide signals to control machine actions, (2) to start and stop the current to the welding transformer, and (3) to control the magnitude of the current. There are three general groups of controls: timing and sequencing controls, welding contactors, and auxiliary controls.

Electronic control of resistance welding machines has enabled manufacturers to use this process in precision production, and made possible its extension to welding a wide variety of metals and alloys, such as stainless steel, brass, bronze and aluminum.

For information on electronic controls for resistance welding, and such auxiliary electronic equipment as heat controls, upslope and downslope current controls, quench and temper controls, forge delay controls, electronic current and voltage regulators, electrical power load distribution, and monitoring and adaptive controls, see *Resistance Welding Controls,* American Welding Society, *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

ELECTRONIC HEAT CONTROL

A device used in resistance welding for adjusting the heating value (rms value) of current, and controlling the firing or ignition of the electronic circuit. The control uses vacuum tubes (in older systems) or solid-state devices (e.g., SCRs). The flow of current is initiated each half-cycle at an adjustable time (or firing angle) with respect to the zero point on the voltage wave. *See* ELECTRONIC CONTROLS, Resistance Welding.

ELECTRONIC TUBE

A vacuum tube containing a filament heated by low-voltage current and emitting extremely small negatively charged particles of electricity (electrons). In a welding circuit, the electronic tube functions as a single-pole contactor, making and breaking circuits. Small electronic tubes are used as relays and contactors in timing and control circuits; large tubes are used as power contactors.

Electronic tubes have largely been replaced by transistors and other solid-state devices; however, some vacuum tube equipment is still in use.

ELECTROSLAG WELDING (ESW)

A welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag, which moves along the full cross section of the joint as welding progresses. The process *is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpieces. See* STANDARD WELDING TERMS. *See also* ELECTROSLAG WELDING ELECTRODE *and* CONSUMABLE GUIDE ELECTROSLAG WELDING.

The electroslag welding process is most often used to join metals in the vertical or near vertical position, usually in a single pass. However, it has been shown that ESW can be used at angles of 45° or greater from vertical. Some of the advantages associated with ESW have resulted in considerable cost savings, particularly in joining thicker materials. Savings have been achieved where components are joined to make larger units instead of initially producing massive castings or forgings. ESW is often less expensive than more conventional joining methods such as submerged arc welding in thicker section weldments. Even in some applications involving thinner base materials, ESW has resulted in cost savings because of its efficiency and simple joint preparation. The ESW process offers many opportunities for reducing welding costs on specific types of joints.

Applications

Many types of carbon steels can be electroslag welded in production, such as AISI 1020, AISI 1045, ASTM A36, ASTM A441, and ASTM A515. They can generally be welded without post-weld heat treatment.

In addition to carbon steels, other steels are successfully electroslag welded. They include AISI 4130, AISI 8620, ASTM A302, HY80, austenitic stainless steels, ASTM A514, ingot iron, and ASTM A387. Most of these steels require special electrodes and a grain refining post-weld heat treatment to develop required weld or weld heat-affected zone properties.

Advantages

(1) Extremely high metal deposition rates; ESW has a deposition rate of 16 to 20 kg (35 to 45 lbs) per hour per electrode.

(2) Capability to weld very thick materials in one pass; there is one equipment setup and no interpass cleaning, since there is only one pass.

(3) Preheating is normally not required, even on materials of high hardenability.

(4) High-quality weld deposit; the weld metal stays molten for an appreciable time, allowing gases to escape and slag to float to the top of the weld.

(5) Minimum joint preparation and fit-up requirements; mill edges and flame-cut square edges can usually be used.

(6) High duty cycle; the process is automatic and once started, continues to completion; there is little operator fatigue.

(7) Minimum materials handling; the work needs to be positioned only to place the axis of the weld in vertical or near vertical position; there is no manipulation of the parts once welding has started.

(8) Elimination of weld spatter, which results in 100% filler metal deposition efficiency.

(9) Low flux consumption; approximately 1 pound of flux is used for each 20 pounds of weld metal.

(10) Minimum distortion; there is no angular distortion in the horizontal plane. Distortion is minimum in the vertical plane, but this is easily compensated for.

(11) Minimum welding time; ESW is the fastest welding process for thick metal.

Limitations

(1) The ESW process welds only carbon and low alloy steels, and some stainless steels.

(2) Joining must be positioned in the vertical or near vertical position.

(3) Once welding has started, it must be carried to completion or a defective re-start area is likely to result.

(4) ESW cannot be used on materials thinner than about 19 mm (3/4 in).

(5) Complex material shapes may be difficult or impossible to weld using ESW.

Principles of Operation

To set up for an electroslag weld, a square groove joint is positioned so that the axis or length of the weld is vertical or nearly vertical. The process is initiated by starting an electric arc between the electrode and the joint bottom. Granulated welding flux is then added and melted by the heat of the arc. As soon as a sufficiently thick layer of molten slag (flux) is formed, all arc action stops, and the welding current passes from the electrode through the slag by electrical conduction. Welding is started in a sump or on a starting tab to allow the process to stabilize before the welding action reaches the work. Figure E-9 is a schematic representation of an electroslag welding operation.

Heat generated by the resistance of the molten slag to passage of the welding current is sufficient to fuse the welding electrode and the edges of the workpiece. The interior temperature of the bath is in the vicinity of 1925°C (3500°F). The surface temperature is

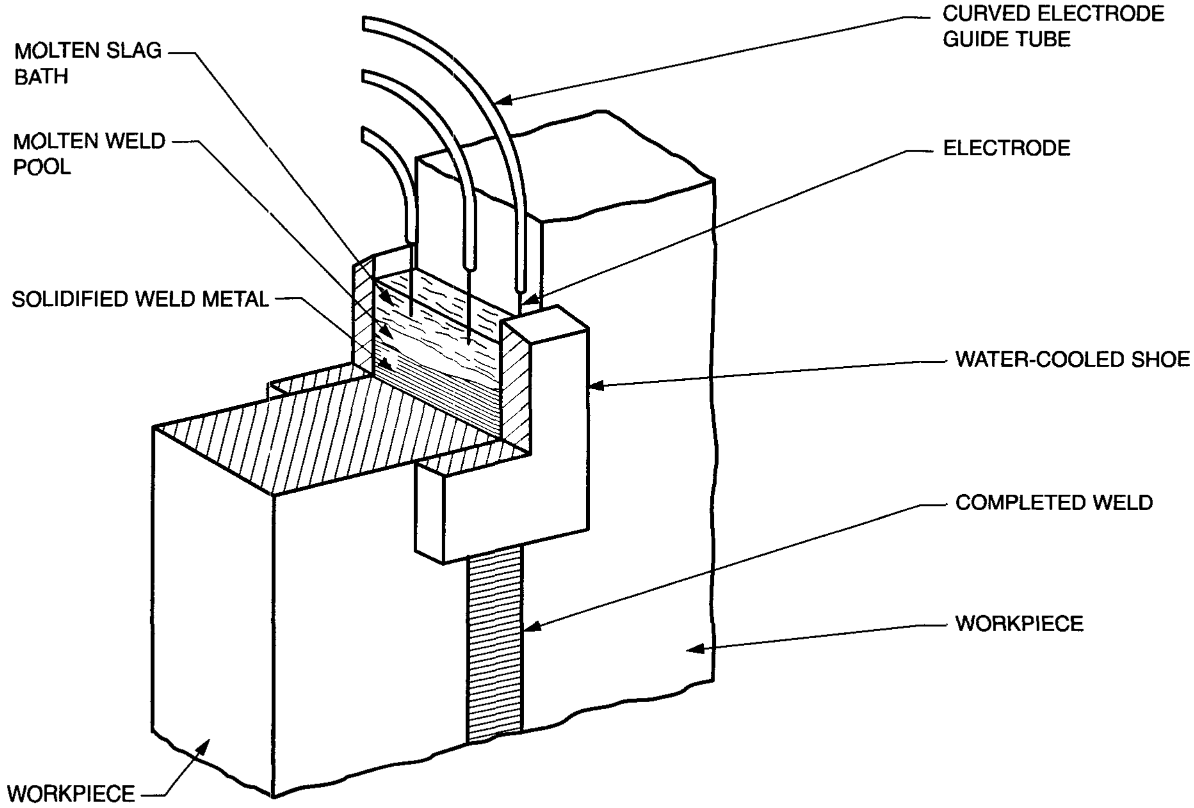


Figure E-9—Schematic Representation of Electroslag Welding (Three-Wire)

approximately 1650°C (3000°F). The melted electrode and base metals collect in a pool beneath the molten slag bath and slowly solidify to form the weld. There is progressive solidification from the bottom upward, and there is always molten metal above the solidifying weld metal.

Run-off tabs are required to allow the molten slag and some weld metal to extend beyond the top of the joint. Both starting and run-off tabs are usually removed flush with the ends of the joint.

Equipment

The equipment used for electroslag (and electrogas) welding is very similar to that required for submerged arc welding (SAW) or flux cored arc welding (FCAW). The same power sources can be used for either process, with one exception: both a-c and d-c power supplies are used with the electroslag process, while in the electrogas process, a-c power supplies are not used. Standard power sources used for either process should have a minimum open circuit voltage of 60 V and be capable of delivering 600 A continuously (100% duty cycle). The power supplies should be equipped with remote controls. The number of power supplies required depends on the number of welding electrodes being used to fill the joint. One power supply is required for each welding electrode. Special constant-voltage d-c power supplies designed for electroslag and electrogas welding are available. Typical power supplies are transformer-rectifiers having 74 V open circuit and a current rating of 750 A at 50 V output, 100% duty cycle. The primary input is 60 Hz, three phase, 230/460 V.

Safety

As in any type of welding, reasonable care must be exercised in the set-up, welding, and post-welding procedures for ESW. Various potential hazards exist, some minor and others serious, but all can be eliminated. Failure to use safety protection equipment or follow safe practices can result in physical danger to personnel, as well as damages to production parts, equipment, and facilities.

For detailed safety information, refer to the manufacturer's instructions and the latest editions of the following publications: ANSI Z49.1, *Safety in Welding and Cutting*, and ANSI Z87.1 *Practice for Occupational and Educational Eye and Face Protection.* Reference: American Welding Society, *Welding Handbook*, Vol. 1, 8th Edition. Miami, Florida: American Welding Society, 1987.

For mandatory Federal Safety Regulations established by the U.S. Labor Department's Occupational Safety and Health Administration, refer to the latest edition of OSHA Standards, *Code of Federal Regulations*, Title 29, Part 1910, available from the Superintendent of Documents, U.S. Printing Office, Washington, DC 20402.

Other considerations involve equipment, safety, consumables, applications, quality control, qualifications, training, troubleshooting, and definitions associated with the process. Reference: American Welding Society, *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

ELECTROSLAG WELDING ELECTRODE

A filler metal component of the welding circuit through which current is conducted from the electrode guiding member to the molten slag. See STANDARD WELDING TERMS.

ELECTROSTATIC

Pertaining to electricity, a phenomenon produced by attractions or repulsions of electric charges, but not dependent on the motion of the charges.

ELECTROSTATIC WELDING

See RESISTANCE WELDING, Stored Energy.

ELEMENTS

See CHEMICAL ELEMENTS.

ELONGATED POROSITY

A form of porosity having a length greater than its width that lies approximately parallel to the weld axis. See STANDARD WELDING TERMS.

ELONGATION

The amount of permanent extension in the vicinity of a fracture in the tension test; usually expressed in percentage of original gauge length, such as 20% in 50 mm (2 in.).

EMERY WHEEL

See GRINDING MATERIALS.

EMISSIVE ELECTRODE

A filler metal electrode consisting of a core of a bare electrode or a composite electrode to which a very light coating has been applied to produce a stable arc. See STANDARD WELDING TERMS.

ENDOTHERMIC

Characterized or formed by the absorption of heat during chemical reactions or transformations. Acetylene gas, for example, is an endothermic substance; heat is absorbed during the production of acetylene and later liberated during combustion.

END-QUENCH TEST

See JOMINY TEST.

END RETURN

A nonstandard term for BOXING.

ENTRY LEVEL WELDER

AWS document EG2.0, *Guide for the Training and Qualification of Welding Personnel: Entry Level Welder*, provides a complete curriculum for training welders to Entry Level (Level I) requirements. Contact American Welding Society, (800) 443-9353.

EQUIAXED

This term is applied to the grains of a metal or alloy after solidification and to grains of metals or alloys which have been strained and allowed by a process of annealing to assume a condition approaching crystalline equilibrium.

EQUIAXED GRAIN

An unstrained grain which has approximately equal dimensions in all directions. This term is practically restricted to unstrained metals.

EROSION, Brazing

A condition caused by dissolution of the base metal by molten filler metal resulting in a reduction in the thickness of the base metal. See STANDARD WELDING TERMS.

ETCHING

A process of preparing metallic specimens and welds for macroscopic or microscopic examination.

In examining for exceedingly small discontinuities or for metallurgical structure at high magnifications, specimens are polished, etched and examined by microscope to reveal the microstructure of the base metal, heat-affected zone, fusion zone, and weld metal. Procedures for selection, cutting, mounting and polishing metallographic specimens are given in ASTM E3 *Standard Methods of Preparation of Metallographic Specimens.* Recommended chemical solutions for etching various metals and alloys and safety precautions in handling etching chemicals are given in ASTM E407, *Standard Method for Micro Etching Metals and Alloys.*

Preparing Specimen for Examination

A weld can be etched by filing a top-to-bottom section of the weld with a coarse file, followed by finer files. File marks should crisscross the previous file marks. After filing, the surface should be polished with emery paper, starting with No. 1 and ending with No. 000 to achieve a high polish. The polished surface must be kept free of fingerprints, grease or dirt. After polishing, an acid solution (nitric acid and water for iron, steel, copper, brass and bronze; hydrochloric acid and water for aluminum) is applied with a brush to the clean surface. Etching reagents for various metals are shown in Table E-4.

Table E-4
Etching Reagents for Metallographic Examination

Type of Specimen	Reagent
Iron and steel	1 part nitric acid to 2 parts water
Copper, brass, and bronze	1 part nitric acid to 3 parts water
Aluminum	1 part hydrochloric acid to 9 parts water

This solution immediately attacks the oxide, exposing any adhesion, blowholes, lack of metal, or other irregularities. The maximum time for the solution to act is fifteen minutes. The etched surface is then washed with water and dried with alcohol.

The test should be preserved by wrapping it in a layer of transparent polyurethane, or a similar protective covering, for subsequent microscopic inspection.

ETCHING REAGENT

A substance, usually acid or alkali, used to reveal the structure of a metal or alloy by causing a difference in the appearance of constituent parts or grains. The substance is usually a solution of reagent in water, but etching may, in some cases, be brought about by a differential oxidation produced by "heat tinting."

EUTECTIC ALLOY

The composition in an alloy system at which two descending liquidus curves in a binary system, or three descending liquidus surfaces in a ternary system, intersect at a point. Such an alloy has a lower melting point than neighboring compositions. More than one eutectic composition may occur in a given alloy system.

EUTECTOID

The metal or alloy with the lowest melting point possible in its classification.

EUTECTOID STEEL

A steel of the eutectoid composition. This composition in pure iron-carbon alloys is 0.90% carbon, but variations from this are found in commercial steels, and particularly in alloy steels in which the euctectoid composition is usually lower. *See* METALLURGY.

EXCITER

A small battery or generator furnishing current to the field winding of a large generator.

EXHAUST BOOTH

A mechanically ventilated, semi-enclosed area in which an air flow across the work area is used to remove fumes, gases, and solid particles. See STANDARD WELDING TERMS.

EXOTHERMIC

Relates to the liberation of heat during chemical reactions or transformations. An example is the thermite welding process, where the chemical combination of iron oxide and aluminum gives off heat and melts the steel weld metal.

EXOTHERMIC BRAZE WELDING (EXBW)

A braze welding process variation that uses an exothermic chemical reaction between a metal oxide and a metal or inorganic nonmetal as the heat source, with a reaction product as the filler metal. See STANDARD WELDING TERMS.

EXOTHERMIC BRAZING (EXB)

A brazing process using an exothermic chemical reaction between a metal oxide and a metal or inorganic nonmetal as the heat source, with filler metal preplaced in the joint. See STANDARD WELDING TERMS.

In this process, a commercial filler metal is heated by a solid-state exothermic chemical reaction, which releases heat as the free energy of the reactants.

Exothermic brazing uses simplified tooling and equipment. The reaction heat brings adjoining metal interfaces to a temperature at which preplaced brazing filler metal melts and wets the base metal interface surfaces. Several commercially available brazing filler metals have suitable flow temperatures. The process is limited only by the thickness of the base metal and the effect of brazing heat, or any previous heat treatment, on the metal properties.

Reference: American Welding Society. *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

EXPANDED TEMPLATE

A durable pattern designed to be expanded or contracted so that similar objects of different sizes can be outlined.

EXPANSION, Thermal

The increase in the dimensions of metals caused by heat. *See* COEFFICIENT OF LINEAR EXPANSION.

When metals are heated they expand in every direction. The expansion in length is *linear expansion;* the increase in volume is *cubical expansion.* Conversely, a decrease in temperature causes the metal to contract, decreasing the cubical and linear dimensions.

Each metal is susceptible to this change in volume, and each metal expands a specific amount in relation to a specific rise in temperature. In many cases, the only practical concern is the increase in length. The amount of linear expansion can be calculated by measuring the unit length of a specimen rod of the metal when it is raised through one degree of temperature. This amount is the *coefficient of linear expansion.*

The increase in length produced by a rise in temperature is equal to the original length, multiplied by the coefficient of expansion, multiplied by the rise in temperature in °F. The cubical expansion is calculated at three times the linear expansion.

Assuming that the arc is producing a given amount of heat, the amount of expansion at a given point in the structure being welded will depend on the length of time the arc is operating at that point. The contraction will be equal in amount to the expansion, assuming that no internal strain is left. Therefore, it is evident that total expansion or contraction tending to deform the workpieces will be less if 105 kJ/h (100 BTU/h) is applied than if heat is applied at the rate of 1050 kJ/h (1000 BTU/h). The total expansion or contraction depends on the amount of heat applied; in general, the lower the amount of heat applied to a welded seam, the smaller the expansion and contraction effect will be.

A bar of iron expands as it is heated and contracts when cooling; both actions are attended by great force. Expansion in length, width, and thickness is governed by a rise in temperature; contraction is regulated by a fall in temperature. Expansion rates of various metals differ. A copper bar one foot long expands 0.1 in. per 1000°F. A gray iron bar of the same size would expand a little over 0.1 in. when heated to 1500°F, an expansion rate of 0.067 in. per ft per 1000°F rise in temperature. The expansion of aluminum is 0.148 in. per ft for each 1000°F.

Expansion in Welding

One of the greatest challenges in welding is adapting welding conditions to control the expansion and contraction brought about by differences in temperature of different parts of the workpiece. When welding ductile metals like iron and steel, allowances must be made for expansion and contraction, because warping, distortion or buckling will inevitably take place. In non-ductile materials, such as cast iron, aluminum alloys and copper, the strains produced by heat may cause the metal to crack or fracture, because the strength of these materials is lower when near the melting point. Although in many cases distortion or fracture have not taken place, the expansion and contraction effects have produced serious internal strains, which require only a slight additional strain to produce failure by exceeding the strength of the metal. It is for this reason that failure can occur in articles which appear to have been successfully welded.

The metalworker cannot restrain by force the expansion of metals caused by raising the material to a high temperature, and the contraction to approximate original dimensions caused when the heat diminishes and disappears. The forces of expansion and contraction are irresistible, and if attempts are made to control them by force, using clamps, jigs, or other means, distortion, serious internal strains, or failures will result.

EXPANSION GAUGE

A device for indicating the degree of distortion of metal due to expansion caused by heat. If two or more gauges are placed at different points on the metal that is being heated, the various readings on the gauges will show clearly where expansion or distortion is the greatest. A change in the heating arrangement can then be made to prevent unequal distortion and to preserve alignment.

EXPLOSION CUTTING (EXC)

A variant of explosion forming or welding, in which a flexible sheet (shaped) explosive allows cutting of metal by the force of the explosion.

EXPLOSION FORMING

The use of explosives for forming metals. In explosive forming, rapid movement of the metal through its elastic range and into the plastic range produces a permanent set, or shape, within microseconds. This high rate of stress application is the essential difference between explosion metal-forming and conventional methods. Initial stress loads using conventional methods are considerably lower.

Understanding of the changes that occur in metal subjected to explosive forces is largely theoretical. However, it is known that it is the cohesive and repulsive forces acting between atoms in a metal crystal which are disturbed and rearranged during explosion forming.

This deformation, termed a slip, occurs along many planes in the crystal grain of the metal. Total deformation of a specimen is the integration of many small displacements along many slip planes. When the grain boundary is encountered, slip interference (braking) takes place, causing atom adjustment (healing) due to cohesive forces between atoms.

Theoretically, under high stress-strain rates associated with explosion forming, atoms go through a series of slip, brake, and heal events very rapidly. Failure will occur when the healing process or cohesive forces between atoms are unable to cope with the continued process of slipping.

An evaluation of data obtained from explosion forming programs indicates that the capacity of a metal to be formed by explosives is a direct function of one mechanical property: percentage of elongation.

Four factors are critical in determining the success of an explosion forming or welding operation: type, amount, shape, and location of the charge. A charge placed in water, or in some other media (e.g., talc, clay, plastic, or oil) that will transmit the force of the blast, can be 1/10 of the size of a charge used in open air to do the same job.

The explosive is adjusted to provide a force having correct distribution and quantity for a specific forming.

Patents were granted on the explosion forming process to British and German engineers as early as 1900; this process is presently used in the aircraft and aerospace industry.

EXPLOSION WELDING (EXW)

A solid-state welding process that produces a weld by high velocity impact of the workpieces as the result of controlled detonation. See STANDARD WELDING TERMS.

Explosion welding is a solid-state welding process that produces a weld by high-velocity impact of the workpieces as the result of controlled detonation. The explosion accelerates the metal to a speed at which a metallic bond will form between them when they collide. The weld is produced in a fraction of a second without the addition of filler metal. This is essentially a room-temperature process in that gross heating of the workpieces does not occur. The faying surfaces, however, are heated to some extent by the energy of the collision, and welding is accomplished through plastic flow of the metal on those surfaces.

Welding takes place progressively as the explosion and the forces it creates advance from one end of the joint to the other. Deformation of the weldment varies with the type of joint. There may be no noticeable deformation in some weldments, and there is no measurable loss of metal. Welding is usually done in air, although it can be done in other atmospheres or in a vacuum when circumstances dictate. Most explosion welding is done on sections with relatively large surface areas, although there are some applications for sections with small surface areas.

A typical arrangement of the components for explosion welding is shown in Figure E-10.

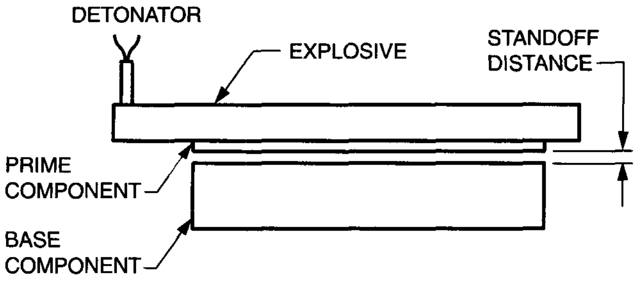


Figure E-10—Typical Component Arrangement for Explosion Welding

Fundamentally, there are three components: base metal, prime or cladding metal, and explosive. The base component remains stationary as the prime component is welded to it. The prime component is usually positioned parallel to the base component; however, for special applications it may be at some small angle with the base component. In the parallel arrangement, the two are separated by a specified spacing, referred to as the *standoff distance*. The explosion locally bends and accelerates the prime component across the standoff distance at a high velocity so that it collides at an angle with and welds to the base component. This angular collision and welding front progresses across the joint as the explosion takes place.

The explosive, almost always in granular form, is distributed uniformly over the top surface of the prime component. The force which the explosion exerts on the prime component depends on the detonation characteristics and the quantity of the explosive. A buffer layer, such as a neoprene material, may be required between the explosive and the prime component to protect the surface of that component from erosion by the detonating explosive. The action that occurs during explosion welding is illustrated in Figure E-11.

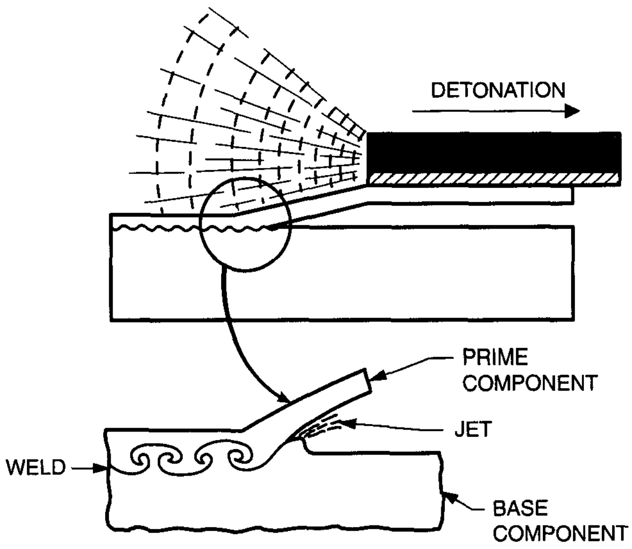


Figure E-11—Action Between Components During Explosion Welding

There are three important interrelated variables of the explosion welding process: collision velocity, collision angle, and prime component velocity. The intense pressure necessary to make a weld is generated at the collision point when any two of these three variables are within certain well defined limits. These limits are determined by the properties of the particular metals to be joined. Pressure forces the surfaces of the two components into intimate contact and causes localized plastic flow in the immediate area of the collision point. At the same time, a jet is formed at the collision point, as shown in Figure E-11. The jet sweeps away the original surface layer on each component, along with any contaminating film that might be present. This exposes clean underlying metal which is required to make a strong metallurgical bond. Residual pressures within the system are maintained long enough after collision to avoid release of the intimate contact of the metal components and to complete the weld.

Capabilities and Limitations

One attribute of the explosion welding process is its ability to join a wide variety of similar and dissimilar metals. The dissimilar metal combinations range from those that are commonly joined by other welding processes, such as carbon steel to stainless steel, to those that are metallurgically incompatible for fusion welding or diffusion bonding processes, such as aluminum or titanium to steel.

The process can be used to join components of a wide range of sizes. Surface areas ranging from less than 6.5 cm^2 (1 $in.^2$) to over 37 m^2 (400 ft^2) can be welded. Since the base component is stationary during welding there is no upper limit on its thickness. The thickness of the prime component may range from .25 to 31.8 mm (0.001 to 1.25 in.) or more depending on the material.

Geometric configurations that can be explosion welded are those which allow a uniform progression of the detonation front and, hence, the collision front. These include flat plates as well as cylindrical and conical structures. Welds may also be made in certain complex configurations, but such work requires thorough understanding and precise control of the process.

Applications

As a general rule, any metal can be explosion welded if it possesses sufficient strength and ductility to withstand the deformation required at the high velocities associated with the process. Metals that will crack when exposed to the collision of the two components cannot be explosion welded. Metals with elongations of at least 5% to 6% (in a 51 mm [2 in.] gauge length), and Charpy V-notch impact strengths of 13.6J (10 ft-lb) or better can be welded with this process. The commercially significant metals and alloys that can be joined by explosion welding are given in Figure E-12. Metallurgical and mechanical properties of the materials must be considered when selecting EXW as a welding process and specifying welding conditions.

	ZIRCONIUM	MAGNESIUM	COBALT ALLOYS	PLATINUM	GOLD	SILVER	COLUMBIUM	TANTALUM	TITANIUM	NICKEL ALLOYS	COPPER ALLOYS	ALUMINUM ALLOYS	STAINLESS STEELS	ALLOY STEELS	CARBON STEELS
CARBON STEELS	●	●			●	●	●	●	●	●	●	●	●	●	●
ALLOY STEELS	●	●	●					●	●	●	●	●	●	●	
STAINLESS STEELS			●		●	●	●	●	●	●	●	●	●		
ALUMINUM ALLOYS		●				●	●	●	●	●	●	●			
COPPER ALLOYS					●	●	●	●	●	●	●				
NICKEL ALLOYS		●		●	●			●	●	●					
TITANIUM	●	●				●	●	●	●						
TANTALUM					●		●	●							
COLUMBIUM				●			●								
SILVER						●									
GOLD															
PLATINUM				●											
COBALT ALLOYS															
MAGNESIUM		●													
ZIRCONIUM	●														

Figure E-12—Commercially Significant Metals and Alloys that can be Joined by Explosion Welding

Cladding. The cladding of plate constitutes the major commercial application of explosion welding. It is customary to supply explosion clad plate in the as-welded condition because the hardening which occurs immediately adjacent to the interface does not significantly affect the bulk engineering properties of the plate. Despite this, some service requirements may demand postweld heat treatment. Clad plates are usually distorted somewhat during explosion welding and must be straightened to meet standard flatness specifications. Pressure vessel heads and other components can be made from explosion clad plates by conventional hot or cold forming techniques.

Explosion welding can be used to clad the inside and outside surfaces of cylinders. Transition joints between two incompatible metals can be made with EXW techniques. In electrical systems, aluminum, copper, and steel are the most commonly used materials, and joints between them are often necessary to take advantage of the special properties of each. Transition joints cut from thick explosion welded plates of aluminum and copper, or aluminum and steel, provide efficient conductors of electricity. This concept is routinely used in the fabrication of anodes for the primary aluminum industry.

Tubular transition joints in various configurations can be machined from thick clad plate. While the majority of explosion welded tubular transition joints are aluminum to steel, other metal combinations for this type of joint include titanium to stainless steel, zirconium to stainless steel, zirconium to nickel base alloys, and copper to aluminum.

Explosion welding can be used to make tube-to-tube sheet joints in heat exchanger fabrication. Most applications of these joints involve tube diameters in the range of 13 to 38.1 mm (0.5 in. to 1.5 in.). Metal combinations include steel to steel, stainless steel to stainless steel, copper alloy to copper alloy, nickel alloy to nickel alloy clad steel, and both aluminum and titanium to steel.

Electric utilities and petro-chemical companies use explosion welding to plug leaking tubes in heat exchangers; however only qualified, trained technicians should implement it. An explosive handling permit is required.

Explosion welding is also used to join lengths of large diameter gas and oil transmission pipelines. It is also used for buildup and repair of worn components, particularly repair of inside and outside surfaces of cylindrical components.

Safety

Explosives and explosive devices are a part of explosion welding. Such materials and devices are inherently dangerous. Safe methods for handling them do exist. However, if the materials are misused, they can kill or injure anyone in the area and destroy or damage property.

Explosive materials should be handled and used by competent people who are experienced in that field. Handling and safety procedures must comply with all applicable federal, state, and local regulations. Federal jurisdiction over the sale, transport, storage, and use of explosives is through the U.S. Bureau of Alcohol, Tobacco, and Firearms; the Hazardous Materials Regulation Board of the U.S. Department of Transportation, the Occupational Safety and Health Agency; and the Environmental Protection Agency. Many states and local governments require a blasting license or permit, and some cities have special explosive requirements.

Reference: American Welding Society, *Welding Handbook*, Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

EXPULSION

The forceful ejection of molten metal from a resistance spot, seam, or projection weld usually at the faying surface. See STANDARD WELDING TERMS. *See also* SURFACE EXPULSION.

EXPULSION POINT

The level of welding current (for a specific set of welding conditions in spot, seam, or projection welding) above which there is significant expulsion. See STANDARD WELDING TERMS.

EXTENSION

The distance a workpiece or electrode projects from a welding die, clamp, chuck, or holder. See STANDARD WELDING TERMS.

EXTENSOMETER

A device for measuring the elongation of materials under stress to accurately determine the yield point or the stress-strain curve of a welded test specimen.

EXTRUSION

A specific shape formed by forcing metal through a die; also used as a means of coating electrodes. Extrusion is used extensively in the manufacture of various lead, aluminum, magnesium, and brass shapes.

The metal to be extruded is heated to a plastic temperature, then placed in a closed chamber fitted with a die of the desired shape at one end and a piston at the other. It is then forced by hydraulic pressure through the die to produce the specific shape. Perfectly round or intricately shaped forms can be extruded.

Lead can be satisfactorily extruded as pipe or cable sheaths at 204°C (400°F); brass must be heated to about 816°C (1500°F). In general, the lower the melting point of the metal, the easier it will extrude at a given temperature. It should be noted that extrusion is a process of solid flow and not of a plastic mass, such as molten solder. *See* ELECTRODE MANUFACTURE.

EYE PROTECTION

Ultraviolet and infrared rays, as well as certain welding fumes, can have a harmful effect on the eyes and skin unless the welding operator is adequately protected from them. From an early age people learn that looking directly at the sun's rays is harmful to the eyes. The radiation from welding heat sources is injurious to the eyes for the same reason. The invisible rays which can harm the eyes are the same from both sources.

In welding and cutting operations, the radiation from the arc or from intensely heated solids or gases may be (1) invisible ultraviolet rays, (2) visible light rays, and (3) invisible infrared rays.

Strong ultraviolet rays are capable of causing severe inflammation similar to sunburn on the eyes and surrounding membranes. Extremely intense visible light rays may cause eye strain and possibly temporary blindness. Infrared rays are not absorbed, but penetrate the eye. They may cause cumulative effects which might lead to cataracts, retina injuries, as well as to opacity of the cornea and the aqueous chamber.

The intensity of the ultraviolet and the infrared radiation is determined by the temperature of the welding source, consequently the intensity is greater from an arc than from a gas flame. Surroundings also affect the intensity, depending on how much of the radiation is absorbed or reflected.

Despite the many potential hazards that exist in the welding environment which might be harmful to the eyes, strictly following recommended safety precautions will prevent visual deterioration or other ocular damage.

The American Welding Society has developed specifications for protective lenses recommended for various welding and cutting operations, shown in Appendix 18.

In addition to welding personnel, other workers in the area may be indirectly or temporarily exposed to harmful radiant energy and must also be protected. These persons can be protected by surrounding the welding operation with screens or booths. A booth provides the best protection from the arc rays. When building a booth for arc welding, the interior walls and surfaces should be covered with paint which will absorb the dangerous arc rays.

Automatic arc welding operations are frequently enclosed in a cabinet equipped with a colored glass protective window, through which the operator may watch the progress of the welding. This enclosure makes it unnecessary for the welder to wear a helmet, and adequately protects all workers in the vicinity from the rays of the arc.

Flashed Eyes

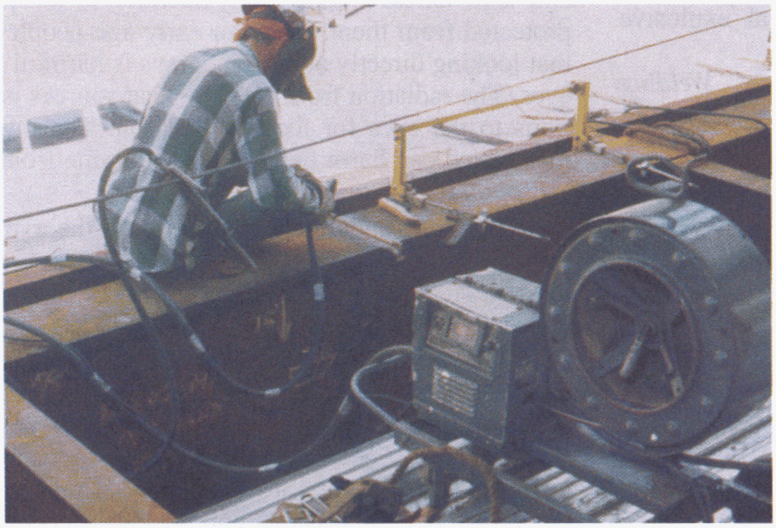
Despite all precautions, flashed eyes are sometimes experienced, more often among persons working in the vicinity than those engaged in the actual welding.

The symptoms of flashed eyes are a pronounced irritation under the eyelids, a feeling as if there were "sand in the eye." These symptoms usually develop several hours after exposure, which means that they frequently develop after the worker has left for the day, sometimes occurring late at night in places where a doctor is not readily available. To prevent incidents of flashed eyes, it is extremely important that co-workers and all visitors are either completely screened from the welding operation, or provided with the correct protective goggles.

Standards for welding helmets, hand shields, face shields, goggles, and spectacles are given in ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection.* New York: American National Standards Institute (latest edition).

EYE SHIELD

A plastic mask with a transparent section to protect the eyes of workers in grinding, coating or resistance welding operations. The transparent portion of the eye shield may be either clear or colored.



Self-shielded flux cored arc welding (FCAW) on a steel structure

F

FACE

A nonstandard term for WELD FACE.

FACE BEND TEST

A test in which the weld face is on the convex surface of a specified bend radius. See STANDARD WELDING TERMS.

FACE CRACK

See STANDARD WELDING TERMS.

A crack that appears on the face of a weld or on the crown bead(s), which runs either parallel with (i.e., longitudinal) or perpendicular (i.e., transverse) to the direction of welding. *See* Appendix 9.

FACE FEED

The application of filler metal to the joint, usually by hand, during brazing and soldering. See STANDARD WELDING TERMS.

FACE OF WELD

The exposed surface of a weld on the side from which the welding is done, regardless of the process used. See STANDARD WELDING TERMS. *See also* WELD FACE.

FACE REINFORCEMENT

Weld reinforcement on the side of the joint from which welding was done. See STANDARD WELDING TERMS. *See* Figure B-6. *See also* ROOT REINFORCEMENT.

FACE SHIELD

A device positioned in front of the eyes and over all or a portion of the face to protect the eyes and face from arc light, weld spatter or expulsion, slag popping, or chipping and grinding. See STANDARD WELDING TERMS. *See* HAND SHIELD *and* HELMET.

FAHRENHEIT

A thermometric scale on which 32° is the freezing point and 212° is the boiling point of water at standard atmospheric pressure.

Fahrenheit temperature is converted to the Celsius temperature scale by the formula °C = 5/9 (°F – 32). The formula to convert Celsius temperature to Fahrenheit is °F = 9/5 °C + 32.

See Appendix 13.

FALSE RESISTANCE

The resistance of counter electromotive force.

FAN

A common name for the arc stream in atomic hydrogen welding. *See* ATOMIC HYDROGEN WELDING.

FARAD

A unit of measure of electrical capacitance equal to the capacitance of a capacitor with a potential of one volt between its plates when the capacitor is charged with one coulomb of electricity; formulated by physicist Michael Faraday in 1867.

FARADAY

A measure of the quantity of electricity transferred in electrolysis per equivalent weight of the element or ion equal to approximately 96 500 coulombs of electricity.

FARM IMPLEMENT REPAIR

Farm implement repair is of ongoing importance to agricultural communities and the welding shops which serve them, and constitutes a challenging variety of repair work for the welder.

The first step in the repair of farm implements is to identify the metal from which the broken component is made, and that will determine the process and filler metal required for the repair. Many components of farm implements are castings which are made of malleable iron, and should be brazed as described under CAST IRON, Malleable.

Tractor Wheels. Modern tractor wheels are fabricated from forged steel, aluminum, and sometimes magnesium, and can be readily welded. If a spoke is broken loose from a forged steel hub, the repair can be made with shielded metal arc welding (SMAW). *See* SHIELDED METAL ARC WELDING; *See also* ALUMINUM *and* MAGNESIUM.

Older tractor wheels were made with cast iron hubs, with the spokes cast into the hub at the time the hub was made. The spokes were riveted to a steel rim, and repairs were made by brazing. If a spoke of an older wheel is broken loose in the hub, it should be cut free where it is riveted at the rim and then brazed to the hub, using as little heat as possible. After the brazing has been completed between the spoke and the hub, the other end of the spoke can be quickly welded to the rim with steel welding rods, and the distortion of the rim will be very slight. It is necessary, however, to wait until the spoke and the braze at the hub are cold before making the weld in the rim.

Plowshares. Plowshares are made from various grades of steel for service in different types of soil. One type of plowshare is called a crucible share, probably because it was originally made from crucible steel. Most of these shares are made of open-hearth steel containing approximately 0.55 to 0.65% carbon, varying with the manufacturer's specifications.

Another type is a soft-center plowshare. It is a tough plowshare with hard outer surfaces that will withstand rough usage. This type is made of three sheets of steel placed together; the center section is a low-carbon steel and the outside faces are steel with a higher carbon content. These three sheets of steel are preheated and welded together, using SMAW.

A third type of plowshare is made of chilled cast iron (white iron) and is used in districts where the soil is partly composed of sharp sand. Chilled cast iron is very hard and very brittle, consisting largely of cementite. If used in a district where stones or rocks are part of the soil, this type would be subject to breaking.

The soft-center share has a hard surface, and while not as hard as chilled cast iron, it is tougher. The crucible steel share is hardened throughout and is used in many soils where other types are not practical.

Repairs. If the point of the plowshare has worn off, it can be repaired by cutting off the old point and welding a new forged point to replace the old one.

If the edge is completely worn down and the point is gone, it may be necessary to use the "three-piece method" of repair, a process in which three new pieces of high-carbon steel are welded to the old share to build it out to its original shape. In this process, an edge piece, or blade, and two point pieces (one placed under the share and the other on top), are welded together to form a new point. High-carbon or alloy steel welding rods or electrodes are recommended for the edge and in building up the point; but if desired, low-carbon rods can be used on the land side where the wear is not as great.

One-Piece Design. Another method commonly used consists of welding a new part to the old share, which amounts to a rather wide cutting edge and point forged all in one piece. The worn portion of the share is cut off with a cutting torch, and the new section is clamped to the old section or held in a jig. The weld is made with a gas or arc torch.

Forged Point. If the cutting edge of the share is not so badly worn that an entirely new edge is necessary and only the point is worn away, the worn point can be cut off with the cutting torch and a new forged point welded to it. The original shape of the share should be carefully preserved so that it will have a controllable digging effect. These forged points are available in a grade of steel which can be heat treated and will produce an acceptable repair job. The electrode or welding rod must match the grade of steel in the plowshare as closely as possible. If they are not well matched, the repaired section might wear hollow or form a groove along the weld.

Welding Rods and Electrodes

Many welders make the mistake of welding parts, including forged points, to the plowshare with a welding rod or electrode that is too low in carbon. Most plowshares are heat treated after welding, and unless the weld metal is high enough in carbon content, it will remain soft and unaffected by the heat treatment. This means that there will be a soft spot which will wear to a greater extent than the harder metal on both sides of the joint.

Low-carbon rods are not recommended for this type of work. Many high-strength rods and electrodes are available which contain more carbon, and some contain alloying elements such as chromium, nickel, and vanadium, all of which will produce a better grade of weld metal for these repairs. Although these rods are more expensive than the low-carbon grades, the rods should be selected to match the steel in the plowshare, the points, edges and other parts, (which are also expensive). This will accomplish the purpose of the repair, which is to make a serviceable joint. When a soft, low-carbon steel rod is used, the weld metal will not harden in subsequent heat treatment. Some welders make a practice of welding the land side of the share with low-carbon rod, and use a high-carbon rod on the edge and share portion. Even this is poor practice because the combination of unlike steels in the adjacent parts makes it impossible to harden the land side weld in any subsequent heat treatment.

Heat Treatment

After the weld has been made, it should not be hammered while still hot from the heat of the torch or arc, but should be allowed to cool, then reheated to the proper temperature and forged. During welding, strains are set up in the metal and the heat is irregular. If forging or hammering occurs just as the weld is completed, these strains have not yet adjusted, and the entire area surrounding the section being hammered is not at the same temperature. It may be at red heat immediately at the weld area, but this red tapers off to a black, or lower heat. For this reason, it is a much better practice to cool the weld; then reheat the workpiece and forge, reheat again, and cool; subsequently applying such heat treatment as may be necessary to produce the required hardness. Steel which is too high in carbon content and tempered to too great a degree of hardness may be too brittle for the purpose, so the exact heat treatment to produce the required hardness can only be determined by the knowledge and experience of the welder.

Hardfacing. Hardfacing a plowshare can increase the effective service life by three to five times, depending on the abrasiveness of the soil in which it is used. *See* HARDFACING.

The metal used for hardfacing may be deposited on the underside of the plowshare, as indicated in Figure F-1, and on the top of the point, which will permit excellent scouring of the top of the share. In some localities welders prefer to deposit the hardfacing metal on the top and allow the underside to be sharpened by wear. In this application, the hardfacing must be ground smooth so that proper scouring will take place. In some soils scouring is not as important as in others, and the welder may find that a hardfacing deposit on the top side will be preferable.

Another consideration is the type of metal which should be used for building up a badly worn implement. If the part were new, it would be necessary to hardface only the wearing surfaces with a grade of alloy suitable for its expected service. New parts, however, are not always hardfaced, or they are not hardfaced often enough to prevent the points from wearing down and becoming blunt, dull, and very different from their original shapes. When in this condition, the point should built up to its original shape before the hardfacing metal is applied.

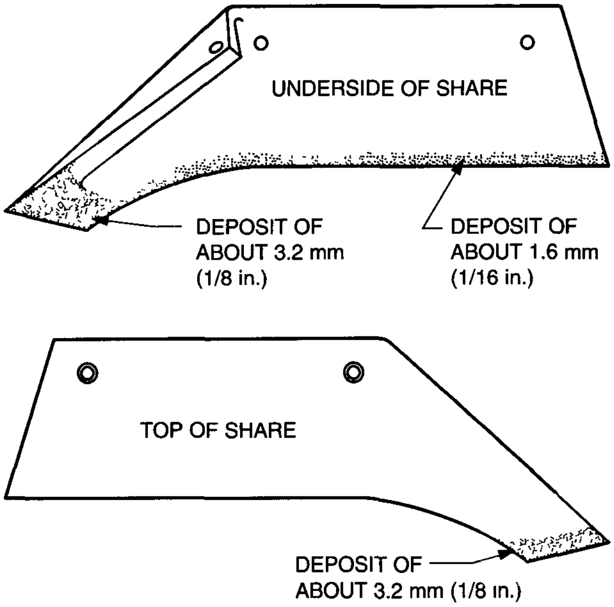


Figure F-1—Hardfacing is Most Effective When Deposited on the Underside of the Plowshare and on Top of the Point

If an ordinary steel welding rod is used to build up the point, the weld metal will be much too soft to stand up during service, and the hardfacing might be pounded down into the softer undercoating. Special high-carbon steel or other alloy rods are made specifically for building up the point to its proper shape before hardfacing rods are applied to it. Since hardfacing rods are made of expensive metals, however, it is an acceptable practice to build up the part almost to its original shape with a less expensive metal which will answer the requirements for hardness and strength, and then overlay the surface with the hardfacing metal.

Broken Gear Teeth

A relatively simple job which frequently comes into the farm shop is repairing cast iron gears with one or more broken teeth. Gear teeth can be repaired or built up using the oxyacetylene welding process with a good grade of cast iron or bronze rod.

With either cast iron or bronze rod, the important requirement is using a flux. The metal should be deposited carefully to minimize postweld grinding. A No. 7 tip with neutral flame is recommended for this purpose.

The job of rebuilding or replacing the internal teeth on the power lift wheel of a plow is somewhat more difficult because it is impossible to grind the teeth to size after the rebuilding job is complete. The teeth must be carefully shaped and sized with the torch during rebuilding. A cast iron deposit seems to offer the only successful solution for jobs of this nature.

Ensilage Cutter Blades

Ensilage cutter blades which have been broken or nicked can be repaired using the following method:

(1) Place a 6 mm (1/4 in.) square bar of medium carbon steel along the tapered side of the blade, with the blade laid flat and resting on the steel bar.

(2) Make several tack welds with the arc welding torch.

(3) Make an arc weld in the groove formed by the square steel bar and the tapered face of the blade.

(4) Turn the blade to rest on the side to which the bar has been welded, which is the back of the blade.

(5) Apply hardfacing. The hardfacing material fills the opening between the square steel bar and the old edge of the blade.

(6) Grind on the back to smooth the hardfacing metal, and grind a new taper on the front of the blade to form an edge in the hardfacing.

Blades can be repaired in this way even though badly chipped or nicked. Often the hardfacing on the back of the blade is applied with the torch. Cutter blades are ordinarily made of high-carbon steel, ranging from about 0.70 to 0.80% carbon.

Based on the representative descriptions of these repair jobs, it is obvious that the job shop welder must master a variety of tasks, although almost every break will be in some way similar to the one which has previously been fixed. *See* CAST IRON, Arc Welding; CAST IRON, OXYACETYLENE WELDING, BRAZING, CARBIDE TOOLS; TOOL BRAZING, TOOL WELDING, HARDFACING, ELECTRODE, STEEL, Cast; MAGNESIUM ALLOYS.

FATIGUE

The phenomenon of the progressive fracturing of a metal by means of a crack which spreads under repeated cycles of stress. Materials subject to vibration stress frequently fail at much lower loads than anticipated. Investigation discloses that each material has a fatigue stress beyond which it is not safe for repeatedly loading it.

FATIGUE LIMIT

A stress level below which the metal will withstand an indefinitely large number of cycles of stress without fracture. When stress is above the fatigue limit, failure occurs by the generation and growth of cracking until fracture results in the remaining structure. If the term is used without qualification, the fatigue limit is usually the number of cycles of stress necessary to produce a complete reverse of flexing stress. *See* FATIGUE STRESS.

FATIGUE STRESS

The maximum stress which a material will endure without failure no matter how many times the stress is repeated.

FATIGUE TEST

A destructive test used to measure the stress to cause failure by fatigue in a material, part, structure, or weldment after applying a fixed number of cycles of load. Generally, the stress to cause failure is plotted against the number of load cycles on a logarithmic scale. In fatigue testing, it is important to decide on and document the repetitive loading cycle, including base (minimum) load and peak (maximum) load, and frequency of loading. Loading is usually expressed as a ratio, R = maximum stress/minimum stress, considering compressive stresses as positive (+), and tensile stresses as negative (–), so that load reversals between tension and compression result in a negative (–) value of R (stress ratio).

Testing for the fatigue strength of a material is so laborious that many materials have not been tested at all, so data is simply not available. In some cases the material has been tested by a user, and the resulting data is often treated as proprietary and is not available in general references or in the open literature. For a hard steel, a test of 2×10^6 cycles duration is necessary to establish a definite fatigue strength. For soft steel, a test of 10^7 cycles duration is necessary, while for aluminum and magnesium and many other non-ferrous metals and alloys, 5×10^8 cycles may be necessary, since these materials exhibit an endurance limit, or stress below which the material could sustain an infinite number of loading cycles without failing.

There are many types of fatigue testing machines. Most commonly used are those which use a rotating beam or rotating cantilever. These rotating tests give a completely reversed stress in which the maximum unit of tensile and compressive stress in the surface of the specimen is equal. The speed of rotation varies with this machine from 2000 rpm to 12 000 rpm.

Fatigue test specimens can be of almost any size, depending on the amount of available material, although certain standard sizes (as opposed to non-standard, and especially, sub-size specimens) are preferred (e.g., by ASTM). Cross-sectional shape is generally, but not necessarily, round. Regardless of size and shape, to give the maximum and most repeatable test results, the surface of fatigue test specimens must be carefully prepared and finished so that they are free of holes, notches, abrupt changes of cross section, machine (kerf) marks and scratches, and even residual stresses from processing (unless these are expected to be used in service in the actual item). The slightest corrosion or flaw will greatly reduce the fatigue limit of a part in service.

FAYING SURFACE

The mating surface of a member that is in contact with or in close proximity to another member to which it is to be joined. See STANDARD WELDING TERMS. *See* Appendix 11(F).

Fe

Chemical symbol for iron.

FEATHER

See STANDARD WELDING TERMS. *See also* ACETYLENE FEATHER.

FEED RATE, Thermal Spraying

A nonstandard term for spraying rate. *See* SPRAYING RATE. *See also* THERMAL SPRAYING.

FERRITE

A solid solution in which alpha iron is solvent; characterized by a body-centered cubic lattice structure. A pure form of iron, it is very soft, ductile and magnetic. Tensile strength is about 275 MPA (40 000 psi). *See* CAST IRON, Hard Spots; CAST IRON, *and* METALLURGY.

FERRITE NUMBER (FN).

An arbitrary, standardized value designating the ferrite content of an austenitic stainless steel weld (or base) metal. It should be used in place of percent ferrite or volume percent ferrite on a direct replacement basis. See STANDARD WELDING TERMS.

FERRO-CHROMIUM (FERRO-CHROME)

A material containing iron and chromium used in manufacturing welding electrode coatings and alloy steels.

FERRO-MANGANESE

A material containing iron and manganese used in manufacturing welding electrode coatings and alloy steels.

FERRO-NICKEL

A compound of iron and nickel used extensively in the manufacture of alloy steels.

FERRO-SILICON

A material containing iron and silicon used in manufacturing welding electrode coatings and alloy steels.

FERRO-TITANIUM

A deoxidizing agent containing iron and titanium, used in the manufacture of alloy steels.

FERRULE

A wide metal band into which the end of a welding hose is inserted to obtain a gas-tight connection without the aid of hose clamps. The ferrule prevents spreading or stretching when the hose is forced over a nipple.

FERRULE, Arc Stud Welding

A ceramic device that surrounds the stud base to contain the molten metal and shield the arc. See STANDARD WELDING TERMS.

FIBER

A characteristic of wrought metal manifested by a fibrous or woody appearance of fractures, indicating directional properties. Fiber is chiefly due to the extension of the material's constituents, both metallic and nonmetallic, in the direction of working.

FIBER STRESS

Local unit stress at a point or line on a section over which the stress is not uniform, such as the cross section of a beam under bending load.

FIBROUS WELD

A poorly executed, porous weld, containing blowholes, craters, and other unwanted features.

FIELD COIL

A coil or winding around the field magnets of a generator or motor.

FIELD WELD

A weld made at a location other than a shop or the place of initial construction. See STANDARD WELDING TERMS.

FILLER MATERIAL

The material to be added in making a welded, brazed, or soldered joint. See STANDARD WELDING

TERMS. *See also* BRAZING FILLER METAL, CONSUMABLE INSERT, DIFFUSION AID; FILLER METAL, SOLDER, WELDING ELECTRODE, WELDING FILLER METAL, WELDING ROD, *and* WELDING WIRE.

FILLER METAL

The metal or alloy to be added in making a welded, brazed, or soldered joint. See STANDARD WELDING TERMS. *See also* BRAZING FILLER METAL, CONSUMABLE INSERT, DIFFUSION AID, FILLER MATERIAL, SOLDER, WELDING ELECTRODE, WELDING FILLER METAL, WELDING ROD, *and* WELDING WIRE.

FILLER METAL START DELAY TIME

The time interval from arc initiation to the start of filler metal feeding. See STANDARD WELDING TERMS.

FILLER METAL STOP DELAY TIME

The time delay interval from beginning of downslope time to the stop of filler metal feeding. See STANDARD WELDING TERMS. *See* Appendix 19(A).

FILLER ROD

The rod or wire which is added to the weld; also referred to as filler metal and welding rod. *See* WELDING ROD *and* ELECTRODE.

FILLER WIRE

A nonstandard term for WELDING WIRE.

FILLET WELD

A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint, T-joint, or corner joint. See STANDARD WELDING TERMS. *See also* Appendix 4.

FILLET WELD BREAK TEST

A test in which the specimen is loaded so that the weld root is in tension. See STANDARD WELDING TERMS.

FILLET WELDING GAUGE

A template or other measuring device for checking the size of a fillet weld. *See* WELDING MICROMETER.

FILLET WELD LEG

The distance from the joint root to the toe of the fillet weld. See STANDARD WELDING TERMS. *See* Appendix 11.

FILLET WELD SIZE

For equal leg fillet welds, the leg lengths of the largest isosceles right triangle that can be inscribed within the fillet weld cross section. For unequal leg fillet welds, the leg lengths of the largest right triangle that can be inscribed within the fillet weld cross section. See STANDARD WELDING TERMS. *See* Appendix 11.

FILLET WELD STRENGTH

In structures or systems where service stresses are high, such as in heavy machinery, ship and building construction, extensive framework and intricate angles may include miles or more of welded joints. Shearing stresses can affect a large percentage of the total system of welds. Correct design of a fillet weld on angles implies an optimum balance between the effective weld length and the contact area between the weld and either base metal part.

A sound engineering approach is mandatory, and allowable shearing stresses must be accurately calculated to specify weld sizes and length which will result in the most economical application of strength, joint efficiency, and safety in service.

In dealing with angles, the welded joints must be proportioned correctly and designed to reduce internal stresses and strains which often cause buckling, distortion, and ultimate failure. These stresses are due to the differential expansion occurring with the heating or cooling of a weld.

When designing a fillet weld, weldability must be a consideration. A careful investigation must include individual welding conditions, e.g., design of the workpiece or structure, section thickness, accessibility, service requirements, and manufacturing cost. It is essential to consider the size instead of the throat of a fillet weld.

In fillet welds in which the cross section is an equal isosceles right triangle, the throat is equal to the product of the size and sine 45°:

$$T = L \text{ sine } 45^\circ = 0.707L.$$

See Appendix 11. Any weld metal outside the triangle limits is omitted in estimating weld strength, so the material between the dashed line and the curved surface of the weld is considered extraneous and disregarded. The convexity of a fillet weld should be reduced, since a 45° flat fillet is the most desirable shape for weld performance. For equivalent strength and rigidity, long fillet welds with smaller leg sizes are the most economical.

When the stress in an angle is transmitted entirely by welds along the toe and heel of the angle, the required weld strength may be calculated as follows:

$$S_1 = \frac{Sx}{d} \quad S_2 = \frac{S\,(d-x)}{d}$$

S_1 = required weld strength at the angle's toe in pounds.
S = total stress in the angle in pounds.
d = width of angle leg between welds in inches
x = distance from back of angle to its center of gravity.
S_2 = required strength of weld at the angle's heel in pounds.

According to the recommendations of AWS D1.1, *Structural Welding Code—Steel,* and the American Institute of Steel Construction for steel in buildings, the allowable shearing unit stress of a section through the throat of a fillet weld is 94 MPa (13 600 psi). This stress is to be used in conjunction with structural steel ASTM A-7, which is for structural steel having an ultimate tensile strength between 414 and 483 (60 000 and 70 000 psi). The factor of safety (about 4) applicable to building construction has been applied to the working stress.

The required area of contact of a weld in a building problem, for example, may be determined by the following:

$$0.707 \times 13\,600 = 9600$$

$$DL = \frac{F}{9600}$$

where D is the weld size; L is the effective weld length in inches; and F is the resultant shearing force on the weld in pounds.

FILLET WELD THROAT

See STANDARD WELDING TERMS. *See* ACTUAL THROAT, EFFECTIVE THROAT, *and* THEORETICAL THROAT.

FILL WELD

A fusion weld made with filler metal. See STANDARD WELDING TERMS.

FILTER

A device consisting of a porous material (e.g., paper, felt or fiberglass) and an activated medium (e.g., activated charcoal) or both, used to remove particulate matter from the cooling water or air for welding equipment, from compressed air, or from the breathing air for welders.

Alternatively, in radiography, a sheet or strips on edge (which may be oscillated) of absorptive material placed between the film and the object being radiographed to reduce blurring in the recorded film image caused by secondary and scattered radiation.

FILTER GLASS

A nonstandard term for FILTER PLATE.

FILTER LENS

A nonstandard term for a round filter plate.

FILTER PLATE

An optical material that protects the eyes against excessive ultraviolet, infrared, and visible radiation. See STANDARD WELDING TERMS.

Filter plates are used in helmets, hand shields, and goggles to protect the eyes.

FIN

Metal exuding from the molten interface of two parts brought together during flash welding. *See* FLASH.

FINAL CURRENT

A current after downslope but prior to current shutoff. See STANDARD WELDING TERMS. *See* Appendix 19(A).

FINAL TAPER CURRENT

The current at the end of the taper interval prior to down slope. See STANDARD WELDING TERMS. *See* Appendix 19(A).

FINES

All material finer than a particular mesh size under consideration. See STANDARD WELDING TERMS.

FINE WIRE WELDING

Fine wire welding is a variation of gas metal arc welding (GMAW), in which small diameter, consumable electrode wire is continuously fed into the arc. The puddle area and surrounding metal are shielded from the atmosphere by a gas flowing from the GMAW torch. It is an all-position welding process originally designed to weld ferrous metals. *See* GAS METAL ARC WELDING.

FIRECRACKER WELDING

A shielded metal arc welding process variation that uses a length of covered electrode placed along the joint in contact with the workpieces during welding. The stationary electrode is consumed as the arc travels the length of the electrode. This is an obsolete or seldom used process variation. See STANDARD WELDING TERMS.

FIRE HAZARDS AND PROTECTION

Safe practices must be the first consideration before starting any welding, cutting, brazing, soldering, bonding, or other shop operation. A specific reference is the American national standard, ANSI/ASC Z49.1, *Safety in Welding, Cutting and Allied Processes*, latest edition, published by the American Welding Society, Miami, Florida.

The main causes of fire accidents in welding are improper maintenance, and incorrect handling and use of the equipment. Some examples are:

Oxyacetylene Flame. Serious fires can be caused if the flame comes in contact with combustible materials in the immediate vicinity of the work.

Electrode Holder. A fire can be started if the holder is handled so that it comes in contact with conducting material or with combustible material.

Hot Metal. Small pieces of metal that drop from the work are dangerous. Glowing bits of iron or steel stay hot enough to start fires for 15 to 20 seconds. Even pieces at black heat in daylight may ignite combustibles on which they fall.

Molten Slag. Molten slag that drips from the work is very hot and extremely hazardous. Even after falling a considerable distance, for example, down a long elevator shaft, it may retain enough heat to start fires.

Sparks. The "sparks" that fly from the work actually consist of small globules of molten metal, which are thrown out in heavy showers, especially in cutting operations, for distances as great as 9 m (30 feet). They are usually hot enough to ignite combustible materials on contact, and as they bounce and roll along floors, they can start unobserved smoldering fires that later can burst into flames.

Safeguards

Production. Welding and flame cutting operators should be provided with protective clothing, suitable to the kind of work to be done. Where welding and cutting are part of the regular production processes, the work area should be kept clear of combustible materials at all times. This precaution should be rigidly enforced, since the presence of anything that will burn constitutes a fire hazard.

Special Work with Portable Equipment. Dangerous conditions are predictable when portable welding or cutting equipment is used in areas containing combustible materials. Almost all fires due to these processes start in areas not normally used for welding or cutting operations that have not been checked for fire safety.

The best practice is to move special welding and cutting jobs to locations where the work can be done with assured safety. When this is impossible, the following routine is mandatory:

Preliminary Survey. The person in charge of the welding or cutting work should carefully examine the site of the proposed job with a qualified person who has local authority, noting all hazardous conditions. Among the factors to be noted are the following:

(1) Wooden floors

(2) Moveable and immovable combustible materials near the work site

(3) Flammable liquids in containers, flammable vapors in the air, and combustible dust in the neighborhood.

(4) The possibility of sparks reaching combustible materials in adjoining spaces through cracks or holes in floors, walls, open or broken windows, and open doorways.

(5) The possibility of fire being started by hot metal or slag dropping from a height.

Work should be undertaken only if it is decided that all hazards can be removed or thoroughly protected. It is impossible to over-emphasize this point: death and widespread destruction can be the result of taking chances.

Before Starting. Remove all combustibles away from the work, at least 8 m (25 ft) when welding, and 11 to 12 m (35 to 40 ft) when cutting. If there are combustibles within these distances that cannot be removed, confine the sparks by surrounding the work with metal shields, fire-proof curtains, or other suitable guards, making sure that sparks cannot fly through any openings or roll out under the guards.

Use fire-resistant coverings to protect objects in the area that are likely to ignite.

When a wooden floor must be protected from burning, or a concrete floor from spalling, place a container of water or a pan of sand immediately under the work to catch slag.

Before starting to cut off a piece of metal, make sure it will not drop where it can start a fire. To prevent the piece from falling, a rod or bar can be welded to the piece and held by a helper while the cut is made.

Check to assure that adequate portable fire extinguishing equipment has been provided. If the area has a sprinkling system, get assurance from the proper authority that the sprinklers are ready for operation. Sprinklers should never be shut down while welding is in progress.

Sweep the floor clean, and if it is made of wood, wet it down.

A written permit form should be obtained from the proper authority to perform cutting operations outside the usual maintenance shop.

Portable Fire Extinguishers

The fire extinguishers available must be appropriate to the hazards present. Where wood or other ordinary combustible materials may be ignited, extinguishers approved for use on Class A fires are required. If flammable liquids or electrical apparatus may be involved, extinguishers approved for use on Class B or Class C fires must also be provided. The types of extinguishers approved for use on different classes of fire are shown in Table F-1.

Table F-1
Portable Fire Extinguishers

	Use on Class of Fire		
Type of Extinguisher	Class A (Ordinary Combustibles)	Class B (Flammable Liquids)	Class C (Electrical Equipment)
Pump Tank	Yes	No	No
Gas Cartridge	Yes	No	No
Foam	Yes	Yes	No
Loaded Stream	Yes	Yes	No
Carbon Dioxide	Only small surface fires	Yes	Yes
Dry Chemical	Yes	Yes	Yes

Reference: NFPA Booklet No. 10, Standard for Portable Fire Extinguishers.

Where any danger of setting fire to combustible materials exists, it is important to station a person with appropriate hand-held extinguishers who will stand by the work throughout its progress, no matter what other precautions have been taken. An extra person is needed for fire extinguishing duty because the cutting or welding operator, wearing dark glasses or a hood, cannot see small fires if they are started.

The watcher should remain at the scene of the work for at least 30 minutes after the work is completed. The watcher should be required to look carefully for smoke or fire before leaving. This is especially important if welding or cutting sparks may have started smoldering fires in wooden structures or in other slow-burning materials.

Reference: National Fire Protection Association.

FISHEYE

A discontinuity found on the fracture surface of a weld in steel that consists of a small pore or inclusion surrounded by an approximately round, bright area. See STANDARD WELDING TERMS.

Fisheyes in welded metal appear as circular and slightly conical spots, 0.4 to 3.2 mm (1/64 to 1/8 in.) diameter, exhibiting a brittle white fracture of two or more concentric rings in contrast with the gray ductile matrix. Fisheyes often contain one or more radial cracks emanating from a central nucleus (an inclusion, a shrinkage or a gas micro-void) and ending in one of the concentric rings. There are several possible causes for the formation of fisheyes:

(1) Microscopic particles of mechanically entrapped slag, regardless of the structural constitution of the deposit, and, depending on interpass temperature, a heterogeneous condition of microstructure possessing differential ductility.

(2) Incipient micro-cracks developed by the drastic quenching undergone by filler metal when deposited on un-preheated base material.

(3) The fact that the high-pressure hydrogen gas contained in small discontinuities exerts an aerostatic stress on the metal surrounding the discontinuity, but is not large enough to rupture without external aid.

It takes an externally applied stress to actually initiate fissuring in steel under stress from hydrogen. When the sum of the aerostatic and applied stress exceeds the strength of the steel, the metal ruptures internally to the extent indicated by the surrounding circular area; the pressure of the gas is reduced, tearing abates and a flake remains in a plane perpendicular to the direction of that stress. The concentric rings are probably associated with the degree of hydrogen embrittlement around the defect. It is believed that the central nucleus, the circular form, and the brittle break identify a hydrogen defect.

5F

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately horizontal, in which the weld is made in the horizontal, vertical, and overhead welding positions. The pipe remains fixed until the welding of the joint is complete. See STANDARD WELDING TERMS. *See* Appendix 4.

5G

A welding test position designation for a circumferential groove weld applied to a joint in a pipe with its axis horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. The pipe remains fixed until the welding of the joint is complete. See STANDARD WELDING TERMS. *See* Appendix 4.

FIXED JOINT

A joint designed so that all of the shrinkage strains are left in the weld metal. *See* RIGID JOINT.

FIXTURE

A device designed to hold and maintain parts in proper relation to each other. See STANDARD WELDING TERMS.

The terms *fixture* and *jig* have essentially the same meaning. The function of a fixture is to facilitate assembly of parts and to hold a workpiece assembly in proper alignment during handling and welding. If the assembly is only tack-welded together it is called a *fitting jig*. The use of a fixture promotes good fitting tolerances in the final product. Most fixtures fall into three major categories: (1) assembly or fitting fixtures, (2) precision fitting and welding fixtures designed to produce accurate fabrications, and (3) robotic welding fixtures.

The design and manufacture of the fixture should reflect the number of parts to be produced. Small quantities may be produced on temporary jigs assembled specifically for the product. For large quantities, the fixture could be an integral part of the whole production system. In this case, the fixture may include automatic clamping on a positioner, and the fixture may accommodate welding by an industrial robot. This type of fixture is expensive to build, but if many parts are produced on it, the fixture is cost effective.

Design

There are few standard commercial fixtures, but many light and heavy duty clamping devices are available which can be incorporated into dedicated fixtures for large production runs, or into adjustable fixtures that can be modified for several short run products. For the most part, fixtures are designed and built by plant operations personnel to facilitate the production of one or more assemblies. A production fixture should be designed to accommodate the following:

(1) Weld joints must be accessible in the fixture.

(2) The fixture must be more rigid than the assembly.

(3) Holddowns, clamps, and threads of bolts and nuts should be protected from weld spatter.

(4) The fixture should allow assembly of the work with a minimum of temporary welds that are visible on completion.

(5) The workpiece must be easy to remove from the fixture after welding is complete.

The designer plans how many welds are to be made while the work is in the jig. For example, the second side of a complete penetration weld may be deposited after the weldment is removed from the fixture. Sufficient welds should be completed in the jig to restrain the assembly from distortion during the completion of welding outside the jig. Since most weldments are fabricated as sub-assemblies, the tolerances are critical. However, often the intermediate dimensions are less important than the end and edge dimensions that control the fit in the final assembly.

Assembly Fixtures

Some assemblies may require stiffening fixtures to maintain shape, and some type of clamping or fixturing may be required to hold the joint alignment for welding and to prevent warpage and buckling from the heat of welding.

For assemblies that are inherently rigid, tack welding alone may suffice. Heavy section thicknesses in themselves offer considerable restraint against buckling and warpage. In intermediate cases, a combination of tack welding, fixturing, and weld sequencing may be required. For joints of low restraint in light gauge materials, clamping is needed. Clamping bars maintain alignment and remove heat to reduce or prevent warpage. Tack welds are usually necessary.

Fixtures also include the jigs and tooling used to facilitate the welding operation. Weld seam trackers and travel carriages are used to guide machine or automatic welding heads.

Precision Jigs

Jigs must be designed to produce a fabrication to close tolerances. A detailed, step-by-step assembly and welding procedure are calculated and built into the design.

Robotic Fixtures

Fixtures for robotic welding have several specific requirements. They must allow access for the robot. Most robots are not equipped with sensing systems; those having sensing systems are primitive in comparison to the vision of a human being. Therefore, the fixture should have low-profile clamps located away from the joint. The fixture should contain at least two reference points that are in a fixed relationship to the weld seams of the workpiece. The robot is then programmed to locate the reference points on the fixture The reference points establish a coordinate system for the robot to find its way along the joint on the workpiece. The fixture should be easy to use, so that the workpieces can be loaded and removed rapidly.

Fixtures are often used in conjunction with turning rolls, rotating turntables and manipulators. *See* POSITIONER.

Brazing Fixtures

When fixtures are needed to maintain alignment or dimensions, the mass of a fixture should be minimized. It should have pinpoint or knife-edge contact with the parts, away from the joint area. Sharp contacts minimize heat loss through conduction to the fixture. The fixture material must have adequate strength at brazing temperature to support the brazement. It must not readily alloy at elevated temperatures with the work at the points of contact. In torch brazing, extra clearance will be needed to access the joint with the torch flame as well as the brazing filler metal. In induction brazing, fixtures are generally made of ceramic materials to avoid putting extraneous metal in the field of the induction coil. Ceramic fixtures may be designed to serve as a heat shield or a heat absorber.

Reference: American Welding Society. *Welding Handbook,* Vol. 1, 8th Edition. Miami, Florida, 1987; American Welding Society: *Welding Handbook,* Vol. 2, 8th Edition. Miami, Florida: American Welding Society, 1991.

FLAGGING

In vertical welding, a term applied to an inward and upward movement of the electrode to avoid undercut.

FLAKES

Internal fissures in large steel castings or massive rolled shapes. In a fractured surface or test piece, they appear as sizeable areas of silvery brightness and have a more coarse grain size than the surrounding metal. Sometimes flakes are known as "chrome cracks," and when revealed by machining, as "hairline cracks."

FLAME

See STANDARD WELDING TERMS. *See* ACETYLENE, Metalworking with Acetylene. *See also* CARBURIZING FLAME, NEUTRAL FLAME, OXIDIZING FLAME, *and* REDUCING FLAME.

FLAME ADJUSTMENT

Flame adjustment is a critical factor in the operation of an oxyfuel torch. The amount of heat produced by the flame depends on the intensity and type of flame used. Three types of flame, carburizing, neutral, and oxidizing, can be achieved by adjusting the torch valves. *See* Figure A-1.

A carburizing flame with acetylene, MPS, or propylene is indicated by trailing feathers on the primary flame cone, or by long, rounded primary flame cone. A carburizing flame is often used to produce a smooth weld finish, and also for stack cutting thin material.

A neutral flame with acetylene, MPS, or propylene is indicated by a sharply defined, dark primary flame cone and a pale blue secondary flame envelope. Propane and propylene base fuels and natural gas have a short, sharply defined cone. This flame is obtained by adding oxygen to a carburizing flame. It is the flame most frequently used for cutting.

An oxidizing flame for acetylene or MPS has a light colored primary cone and a smaller secondary flame shroud. It generally burns with a harsh whistling sound. With propane and propylene base fuels and natural gas, the primary flame cones are longer, less sharply defined, and have a lighter color. An oxidizing flame is obtained by adding some oxygen to the neutral flame. This type of flame is frequently used for fast, low- quality cutting, and selectively in piercing and beveling.

FLAME BLASTING

A process for removing paint, rust and scale from steel structures in new construction or in repainting operations. Flame blasting is accomplished with a multi-flame oxyacetylene torch which is passed over the surface. The extreme heat of the torch removes scale, oxide and paint. *See* FLAME CLEANING.

FLAME, CARBURIZING

See CARBURIZING FLAME.

FLAME CHARACTERISTICS

See ACETYLENE; CARBURIZING FLAME, NEUTRAL FLAME, OXIDIZING FLAME, *and* OXYACETYLENE WELDING.

FLAME CLEANING

A metal surface cleaning process accomplished by movement of a multi-flame oxyacetylene torch over the surface. The quick, intense heat causes deposits of oxide, rust, scale or old paint to be consumed or loosened so that they "pop off" easily. When a workpiece is being primed for painting, the surface may be swept or wiped free of loosened foreign material and painted while at an elevated temperature. This improves paint adherence and extends the life of the paint.

FLAME CUTTING

Flame cutting is a commonly used term for manual or mechanized OXYGEN CUTTING. Oxygen cutting applications are shape cutting, stack cutting, powder cutting, piercing, gouging, and underwater cutting. *See* OXYFUEL GAS CUTTING. *See also* GOUGING, THERMAL SPRAYING, METAL POWDER CUTTING, UNDERWATER CUTTING.

FLAME HARDENING

Flame hardening is a process used to harden steel or other ferrous metals. In this process, an oxyacetylene torch is used to heat the surface of the material to a high temperature, then a rapid quench is administered to produce a hard martensitic surface.

Among the advantages of flame hardening are:

(1) The hardness may be limited to a comparatively thin casing, leaving the balance of the metal unaffected by the heat of the torch. This makes it possible to heat treat a casting or forging for desired core properties, such as ductility, toughness, and resistance to impact, and subsequently harden the surfaces to be exposed to wear.

(2) Because carbon is the principal hardening agent in steel, it is possible in many applications to use a flame-hardened plain carbon steel instead of an expensive alloy.

(3) Flame hardening is done on finished surfaces after all machining has been completed, thus saving the difficulty and expense of machining a hardened metal.

Technique. Flame hardening is done in two stages: heating and quenching. First an oxyacetylene flame is used to raise the surface temperature of the area to be hardened to just over the Ac_3 critical point. Then a rapid quench traps the iron carbide existing in solid solution in the austenite to produce a martensitic structure of high hardness. The degree of hardness produced will depend on three factors: (1) the constitution of the steel before hardening, (2) the rate of cooling, and (3) the temperature of the surface at the moment quenching begins.

FLAME MACHINING

Flame machining is a little-used variation of the oxyfuel gas cutting process. This technique is used to turn down the diameter of a piece of cylindrical stock similar to machining on a lathe. The cutting oxygen stream impinges on the work (a cylindrical piece) at an acute angle, almost tangentially. The oxygen cutting orifices used are the expanding low-stream velocity type, with a comparatively large-diameter exit. Relatively low oxygen pressures are used. The cut is not permitted to penetrate through the work, as in severing, but is restricted to removal of material from the surface.

This change in the angle of impingement of the cutting oxygen stream has created a variety of oxyacetylene cutting operations. Because of the similarity to customary tool machining, these operations are collectively termed *flame machining*. *See* OXYFUEL GAS CUTTING.

FLAME PRIMING

See FLAME CLEANING.

FLAME SHRINKING

An oxyacetylene flame process in which buckled or warped plates are spot-heated and quenched immediately with either water or a mixture of compressed air and water. This sequence accomplishes an upsetting action in the metal, resulting in the shrinking (with consequent straightening, when applied properly) of the plate.

FLAME STRAIGHTENING

Straightening structural steel with an oxyacetylene flame process is based on three combined facts of physics: the expansion of steel as its temperature rises, the lowering of the yield point of steel as the temperature is increased, and the ability of steel to flow plastically when the stress imposed exceeds the yield point. The reverse of the first two facts is also utilized in flame straightening under certain conditions.

As heat is applied to a small area of a given section, there remains enough cold metal to confine, or limit, the expansion in certain directions. The lowered yield point of the heated area is exceeded by the stress caused by expansion, therefore the heat area flows plastically in the confined directions.

The flame straightening procedure must be controlled by a person who thoroughly understands structures and has a working knowledge of the behavior of steel under stress at elevated temperatures.

Flame straightening can also be applied to straighten bent plates, angle frames, pipes, and fabrications.

FLAME PROPAGATION RATE

The speed at which flame travels through a mixture of gases. See STANDARD WELDING TERMS.

FLAME SPRAYER

See STANDARD WELDING TERMS. *See* THERMAL SPRAYER.

FLAME SPRAYING (FLSP)

A thermal spraying process in which an oxyfuel gas flame is the source of heat for melting the surfacing material. Compressed gas may or may not be used for atomizing and propelling the surfacing material to the substrate. See STANDARD WELDING TERMS. *See* THERMAL SPRAYING.

FLAME SPRAYING OPERATOR

See STANDARD WELDING TERMS. *See* THERMAL SPRAYING OPERATOR.

FLANGED BUTT JOINT

A form of a butt joint in which at least one of the members has a flanged edge shape at the joint. See STANDARD WELDING TERMS. *See* Figure F-2.

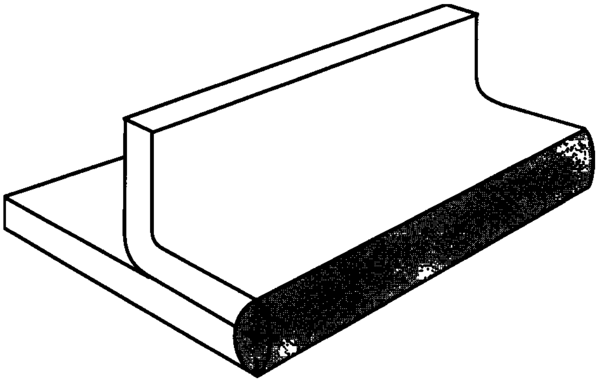


Figure F-2—Edge Weld in a Flanged Corner Joint

FLANGED CORNER JOINT

A form of a corner joint in which the butting member has a flanged edge shape at the joint, and an edge weld is applicable. See STANDARD WELDING TERMS. *See* Figure F-2.

FLANGED EDGE JOINT

A form of an edge joint in which at least one of the members has a flanged edge shape at the joint. See STANDARD WELDING TERMS. *See* Figure F-2.

FLANGED EDGE SHAPE

A type of edge shape produced by forming the member. See STANDARD WELDING TERMS. *See* Appendix 6.

FLANGED JOINT

A form of one of the five basic joint types in which at least one of the joint members has a flanged edge shape at the weld joint. See STANDARD WELDING TERMS. *See* Figure F-2.

FLANGED LAP JOINT

A form of a lap joint in which at least one of the members has a flanged edge shape at the joint, and an edge weld is not applicable. See STANDARD WELDING TERMS. *See* Figure F-3.

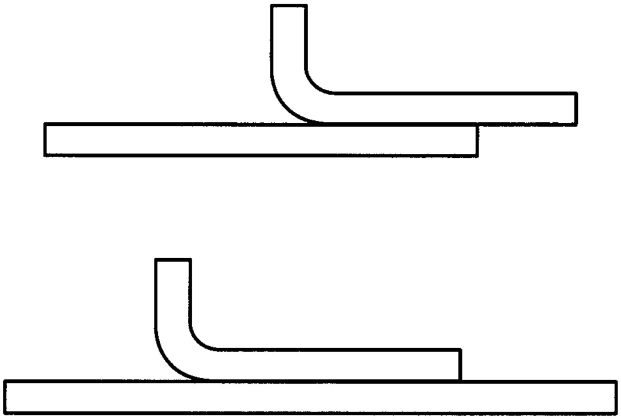


Figure F-3—Flanged Lap Joints

FLANGED T-JOINT

A form of a T-joint in which the butting member has a flanged edge shape at the joint, and an edge weld is not applicable. See STANDARD WELDING TERMS. *See* Figure F-4.

FLANGE WELD

A nonstandard term for a weld in a flanged joint.

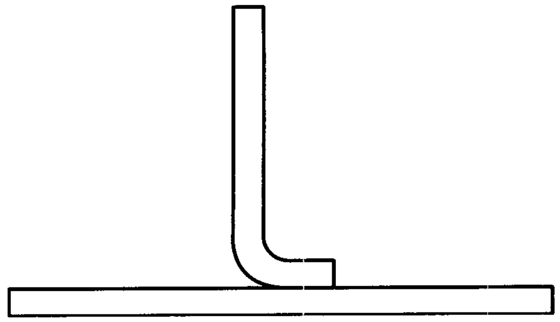


Figure F-4—Flanged T-Joint

FLARE-BEVEL-GROOVE WELD

A weld in the groove formed between a joint member with a curved surface and another with a planar surface. See STANDARD WELDING TERMS. *See* Appendix 6, Sections 4 and 5.

FLARE-GROOVE WELD

A weld in the groove formed between a joint member with a curved surface and another with a planar surface, or between two joint members with curved surfaces. See STANDARD WELDING TERMS. *See* Appendix 6, Sections 4 and 5. *See also* FLARE-BEVEL-GROOVE WELD *and* FLARE-V-GROOVE WELD.

FLARE-V-GROOVE WELD

A weld in a groove formed by two members with curved surfaces. See STANDARD WELDING TERMS. *See* Appendix 6, Sections 4 and 5.

FLASH

Material that is expelled from a flash weld prior to the upset portion of the welding cycle. See STANDARD WELDING TERMS.

Flash, or fin, is metal and oxide expelled from a joint made by a resistance welding process.

Alternatively, in arc welding, the unexpected exposure of the unprotected eye to the rays of a welding arc. *See* EYE PROTECTION.

FLASHBACK

A recession of the flame into or back of the mixing chamber of the oxyfuel gas torch or flame spraying gun. See STANDARD WELDING TERMS.

In this situation, the flame disappears from the end of the tip and the gases burn within the torch or beyond, in the hose, usually with a shrill, hissing sound. This indicates something seriously wrong with the equipment or the method of operation. One or both gases should be shut off immediately to stop combustion within the torch before it is damaged by heat. The torch should be allowed to cool before relighting. If the flashback reaches the hose, that section should be discarded, as it has almost certainly been damaged by the heat. Flashback arresters are available to prevent these potentially dangerous incidents.

For causes of flashback, see BACKFIRE, FLAME PROPAGATION RATE, and PRE-IGNITION. For prevention, see FLASHBACK ARRESTER.

FLASHBACK ARRESTER

A device to limit damage from a flashback by preventing propagation of the flame front beyond the location of the arrester. See STANDARD WELDING TERMS.

FLASH BUTT WELDING

A nonstandard term for FLASH WELDING.

FLASH COAT

A thin coating usually less than 0.05 mm (0.002 in.) in thickness. See STANDARD WELDING TERMS.

FLASHING ACTION

The phenomenon in flash welding wherein points of contact, formed by light pressure across faying surfaces, are melted and explosively ejected because of the extremely high current density at contact points. See STANDARD WELDING TERMS.

FLASH-OFF TIME

A nonstandard term for FLASH TIME.

FLASH TIME

The duration of flashing action during flash welding. See STANDARD WELDING TERMS.

FLASH WELD

A form of resistance butt-welding, generally used on stock that is wide and thin; sometimes advisable when the welding faces are not cut square and true. It is also used in welding tubing to tubing. Flash welding is used in cases where a small amount of stock is to be taken up in the weld, or when the specification is to shear or grind off the fin. The space between the clamping jaws of the butt welding machine is never more than the diameter of the stock when making a flash-weld; generally it is only 70% of the diameter of the work. *See* FLASH WELDING *and* RESISTANCE WELDING.

FLASH WELDING (FW)

A resistance welding process that produces a weld at the faying surfaces of a butt joint by a flashing action and by the application of pressure after heating is substantially completed. The flashing action, caused by the very high current densities at small contact points between the workpieces, forcibly expels the material from the joint as the workpieces are slowly moved together. The weld is completed by a rapid upsetting of the workpieces. See STANDARD WELDING TERMS. *See* Figure F-5.

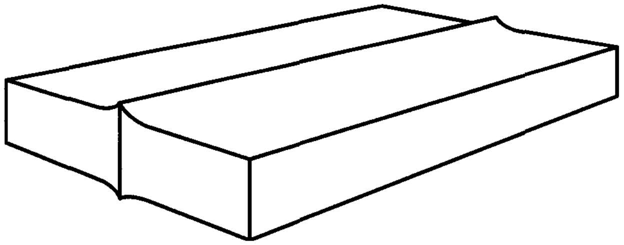


Figure F-5—Example of a Flash Weld

Principles of Operation

Two parts to be joined are clamped in dies (electrodes) connected to the secondary of a resistance welding transformer. Voltage is applied as one part is advanced slowly toward the other. When contact occurs at surface irregularities, resistance heating occurs at these locations. High amperage causes rapid melting and vaporization of the metal at the points of contact, and then minute arcs form. This action is called "flashing." As the parts are moved together at a suitable rate, flashing continues until the faying surfaces are covered with molten metal and a short length of each part reaches forging temperature. A weld is then created by the application of an upset force to bring the molten faying surfaces in full contact and forge the parts together. Flashing voltage is terminated at the start of upset. The solidified metal expelled from the interface is called "flash."

The basic steps in a flash welding sequence are as follows:

(1) Position the parts in the machine.
(2) Clamp the parts in the dies (electrodes).
(3) Apply the flashing voltage.
(4) Start platen motion to cause flashing.
(5) Flash at normal voltage.
(6) Terminate flashing.
(7) Upset the weld zone.
(8) Unclamp the weldment.
(9) Return the platen and unload.

Figure F-6 illustrates these basic steps. Additional steps such as preheat, dual voltage flashing, postheat, and trimming of the flash may be added as the application dictates.

Flashing takes place between the faying surfaces as the movable part is advanced toward the stationary part. Heat is generated at the joint and the temperature of the parts increases with time. Flashing action (metal loss) increases with part temperature.

A graph relating part motion with time is known as the flashing pattern. In most cases, a flashing pattern should show an initial period of constant velocity motion of one part toward the other to facilitate the start of flashing. This linear motion should then merge into an accelerating motion which should closely approximate a parabolic curve. This pattern of motion is known as "parabolic flashing."

Upset occurs when a stable temperature distribution is achieved by flashing and the two parts are brought together rapidly. The movable part should be accelerated rapidly so that the molten metal on the flashing surfaces will be extruded before it can solidify in the joint. Motion should continue with sufficient force to upset the metal and weld the two pieces together.

Upset current is sometimes applied as the joint is being upset to maintain temperature by resistance heating. This permits upset of the joint with lower force than would be required without it. Upset current is normally adjusted by electronic heat control on the basis of either experience or welding tests.

Advantages and Limitations

Butt joints between parts with similar cross section can be made by friction welding and upset welding, as well as by flash welding. Listed below are some important advantages of flash welding:

(1) Cross sectioned shapes other than circular can be flash welded: for example, angles, H sections, and rectangles. Rotation of parts is not required.

(2) Parts of similar cross section can be welded with their axes aligned or at an angle to each other, within limits.

(3) The molten metal film on the faying surfaces and its ejection during upset acts to remove impurities from the interface.

(4) Preparation of the faying surfaces is not critical except for large parts that may require a bevel to initiate flashing.

(5) Rings of various cross sections can be welded.

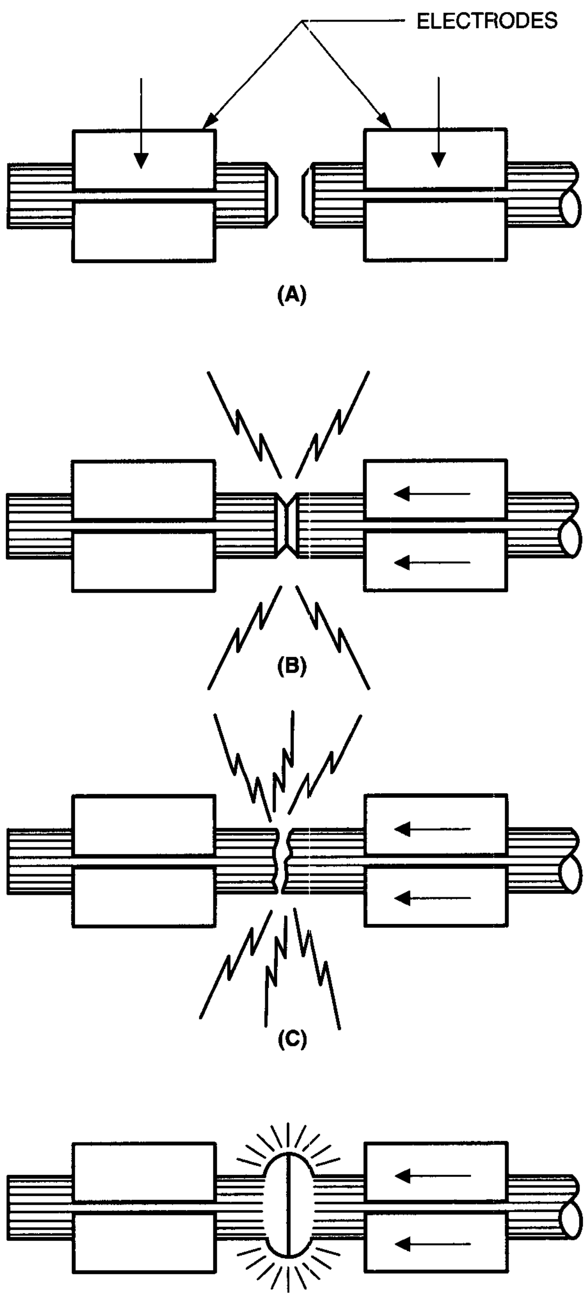


Figure F-6—The Basic Steps in Flash Welding:

(A) Position and Clamp the Parts

(B) Apply Flashing Voltage and Start Platen Motion

(C) Flash

(D) Upset and Terminate Current

(6) The heat-affected zones of flash welds are much narrower than those of upset welds.

The following are some limitations of the process:

(1) The high single-phase power demand produces unbalance on three-phase primary power lines.

(2) The molten metal particles ejected during flashing present a fire hazard, may injure the operator, and may damage shafts and bearings. The operator should wear face and eye protection, and a barrier or shield should be used to block flying sparks.

(3) Removal of flash and upset metal is generally necessary and may require special equipment.

(4) Alignment of workpieces with small cross sections is sometimes difficult.

(5) The parts to be joined must have almost identical cross sections.

Applications

Base Metals. Many ferrous and nonferrous alloys can be flash welded. Typical metals are carbon and low alloy steels, stainless steels, aluminum alloys, nickel alloys, and copper alloys. Titanium alloys can be flash welded, but an inert gas shield to displace air from around the joint is necessary to minimize embrittlement.

Dissimilar metals may be flash welded if their upsetting characteristics are similar. Some dissimilarity can be overcome with a difference in the initial extensions between the clamping dies, adjustment of flashing distance, and selection of welding variables. Typical examples are welding of aluminum to copper or a nickel alloy to steel.

Typical Products. The automotive industry uses wheel rims produced from flash welded rings that are formed from flat cold-rolled steel stock. The electrical industry uses motor and generator frames produced by flash welding plate and bar stock previously rolled into cylindrical form. Cylindrical transformer cases, circular flanges, and seals for power transformer cases are other examples. The aerospace industry uses flash welds in the manufacture of landing gear struts, control assemblies, hollow propeller blades, and rings for jet engines and rocket casings.

The petroleum industry uses oil drilling pipe with fittings attached by flash welding. Several major railroads are using flash welding to join relatively high carbon steel track. In many cases, welding is done in the field using welding machines and portable generating equipment mounted on railroad cars.

Miter joints are sometimes used in the production of rectangular frames for windows, doors, and other architectural trim. These products are commonly made of plain carbon and stainless steels, aluminum alloys, brasses, and bronzes. Usually the service loads are limited, but appearance requirements of the finished joints are stringent.

Equipment

Typical Machines. A typical flash welding machine consists of six major parts:

(1) The machine bed which has platen ways attached

(2) The platens which are mounted on the ways

(3) Two clamping assemblies, one of which is rigidly attached to each platen to align and hold the parts to be welded

(4) A means for controlling the motion of the movable platen

(5) A welding transformer with adjustable taps

(6) Sequencing controls to initiate part motion and flashing current

Flash welding machines may be manual, semi-automatic, or fully automatic in their operations; however, most of them are either semi-automatic or fully automatic.

Controls and Auxiliary Equipment. Electrical controls on flash welding machines are integral types designed to sequence the machine, control the welding current, and precisely control the platen position during flashing and upsetting.

Dies. Flash welding dies, compared to spot and seam welding electrodes, are not in direct contact with the welding area. Dies may be considered work-holding and current-conducting clamps. The dies are usually mechanically fastened to the welding machine platens.

Fixtures and Backups

The functions of fixtures for flash welding are (1) to rapidly and accurately locate two or more parts relative to each other, (2) to hold them in proper location while they are being welded, and (3) to permit easy release of the welded assembly. A fixture is either fastened to the machine or built into it. Parts are loaded directly into the fixture and welded.

Joint Design

In general, the two parts to be welded should have the same cross section at the joint. Bosses may have to be machined, forged, or extruded on parts to meet this requirement. In the flash welding of extruded or rolled shapes with different thicknesses within the cross-section, the temperature distribution during flashing will vary with section thickness. This tendency can often be counteracted by proper design of the clamping dies, provided the ratio of the thicknesses does not exceed about 4 to 1.

Welding Procedures

Every welding operation involves numerous variables that affect the quality of the resulting weld. For this reason, a welding procedure should be developed that prescribes the settings for the welding variables to ensure consistent weld quality. Flash welding involves dimensional, electrical, force, and time variables. These and other considerations in flash welding, such as surface preparation, heat balance, initial die opening, flash removal, process variables, weld quality, testing and inspection, and recommended reading list are covered in the following reference: American Welding Society. *Welding Handbook*, 8th Edition, Vol. 2, Miami, Florida: American Welding Society, 1991.

Safety. Operating personnel should be given instructions on how to operate the machinery in a safe manner. Hands must be kept clear of moving machinery, and contact with electrically charged surfaces must be avoided. The area around the machine must be kept free of combustibles that might be ignited by molten flash. Additional information on safe practices for welding may be found in American National Standard Z49.1, *Safety in Welding and Cutting*, latest edition.

FLAT-COMPOUND GENERATOR

A generator designed to produce a constant output voltage under different loads and speeds.

FLAT POSITION

See STANDARD WELDING TERMS. *See* FLAT WELDING POSITION, *and* WELDING POSITION.

FLAT WELDING POSITION

The welding position used to weld from the upper side of the joint at a point where the weld axis is approximately horizontal, and the weld face lies in an approximately horizontal plane. See STANDARD WELDING TERMS. *See* Appendix 4.

FLAW

An undesirable discontinuity. See STANDARD WELDING TERMS. *See* DEFECT.

FLOOD COOLING, Resistance Seam Welding

The application of liquid coolant directly on the work and the contacting electrodes. See STANDARD WELDING TERMS.

FLOWABILITY

The ability of molten filler metal to flow or spread over a metal surface. See STANDARD WELDING TERMS.

FLOW BRAZING (FLB)

A brazing process that uses heat from molten nonferrous filler metal poured over the joint until brazing temperature is attained. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

FLOW BRIGHTENING, Soldering

Fusion of a metallic coating on a base metal. See STANDARD WELDING TERMS.

FLOW COATING

A finishing method in which a paint or coating is applied with a spray gun or brush to weldments or workpieces which are too large for dipping or are in an inaccessible area. Special paints or coatings are needed for this application, since some do not flow satisfactorily.

FLOW INDICATOR

In welding, a measuring instrument which determines the exact amount of gas being used by a torch. The flow indicator allows an experienced operator to watch the position of the indicator to find the most efficient mixture of gases for a certain class of work, and enables the operator to duplicate the same flame at any time. This instrument also serves as an accurate check on the quantity of gas being used and the efficiency with which the gas is used by the operator.

FLOW METER

A flowmeter measures and control the flow of a liquid or gas, used especially to control the flow of shielding gases in welding operations. When used on a high pressure cylinder, a flowmeter is usually combined with a regulator into a regulator-flowmeter unit which reduces the high-pressure gas in the cylinder or cylinder manifold to a lower working pressure. The lower pressure is received by the flowmeter and the required gas flow to the welding head is controlled by manual adjustment of a throttle valve.

The flow of shielding gas is indicated on a flowmeter tube, which is calibrated in liters per minute (cubic ft per hour) for the particular gas being used. The welder can set the meter for the required flow rate.

The flowmeter tube is calibrated at a positive pressure which normally exceeds any back pressure produced by the welding equipment. This makes it possible to get a true reading of the gas flow.

FLOW RATE

The rate at which gas is caused to flow for oxyfuel cutting or welding, or to provide shielding during arc welding by any of several processes, including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW), or electrogas welding (EGW).

The flow rate is controlled by flow meters that are calibrated either in liters per minute or cubic feet per hour.

The flow rate of shielding gases for GMAW (Mig) should be sufficient to exclude air from the weld location; the flow of gas should maintain adequate and effective coverage of the weld arc. This is influenced by a number of variables: (1) the shielding gas used, (2) design of weld joint, (3) distance of gas nozzle orifice from the work surface, (4) size of the gas nozzle, (5) shape of the gas nozzle, (6) the presence of drafts or air currents, (7) inclination of the torch, (8) arc length, (9) welding speed, (10) size of the weld puddle, (11) position of the workpiece, and (12) metal or alloy being welded.

A flow rate of 3 Lpm (6 cu ft/hr) for helium and 2 Lpm (4 cu ft/hr) for argon generally provides effective shielding in still atmospheres. While these rates are only about one-third the rates normally used for average welding conditions, they indicate that cost control is possible when all other factors are under control.

Excessive gas flow is not only wasteful, but can also be detrimental to the weld metal and the welding operation. Excessive flow may also cause an unstable arc at low welding currents and result in undercutting the work surface by the weld bead.

FLOW WELDING (FLOW)

A braze welding process variation that uses molten filler metal poured over the fusion faces as the heat source. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

FLUORINE

(Chemical symbol: F). A pale yellow gas which forms fluoride compounds with a number of elements, some of which are used as ingredients of welding fluxes.

Atomic weight 19; melting point –223°C (–369°F); specific gravity, (gas) 1.31 (liquid) 1.41 at –200°C.

FLUSH WELD

A term applied to a weld when the top layer is finished perfectly flat or on the same plane as the adjoining material. The weld is made with a minimum of reinforcement, with deposits of a minimum number of layers of weld metal. This application is used when a maximum tensile strength is not critical and must be specified by the designer.

FLUX

A material used to hinder or prevent the formation of oxides and other undesirable substances in molten metal and on solid metal surfaces, and to dissolve or otherwise facilitate the removal of such substances. See STANDARD WELDING TERMS.

Fluxes are used in fusion welding, brazing, and soldering to prevent the formation of oxides. They are used in brazing and soldering to dissolve or facilitate removal of oxides. *See* ACTIVE FLUX *and* NEUTRAL FLUX.

The oxides of all the commercial metals and alloys except steel have higher melting points than the metals themselves. Oxides are usually viscous (some are even insoluble) when the metal is fluid and at its proper welding temperature. An efficient flux combines with oxides to form fusible slag with a melting point lower than the metal. This slag forms a coating over the molten metal and thus serves as a protection against atmospheric oxidation. The chemical characteristics and melting points of the oxides of different metals vary greatly and therefore there is no one flux that will be satisfactory for all applications.

The melting point of a flux must be lower than that of either the metal or the oxides formed so that it will be liquid during the welding operation.

Fluxes are available packed in powder form in metal or plastic containers. Some lose their effectiveness if overexposed to atmosphere, and in such cases small containers are best. Some welders use a flux box, a short section of large pipe welded to a heavy plate about 150 mm (6 inches) square. This prevents the flux from tipping over during a job and holds only a small amount of flux so accidental losses are minimal.

Fluxes differ in their composition according to the metals with which they are used. In cast iron welding, a slag forms on the puddle and the flux serves to break up this slag. Equal parts of carbonate of soda and bicarbonate of soda make a good compound for this purpose. Also, for cast iron arc welding, various fluxes prevent oxidation and rapid cooling of the melt, and by combining with the excess carbon prevent the formation of hard compounds of iron and carbon.

Copper requires a filler rod containing phosphorus to produce weld metal without oxides. Powdered borax is often used as a flux with copper alloys.

Aluminum requires flux because there is a tendency for the heavy slag formed to mix with the melted aluminum and weaken the weld. For sheet aluminum welding it is customary to dissolve the flux in water and apply it to the rod. After welding aluminum, all traces of the flux must be removed.

Flux coatings often increase the speed of arc welding, although this is not universally true. They also concentrate the deposit, reduce spatter, and tend to prevent oxidation of the weld metal, as well as reduce the rate of cooling.

FLUX COATED ELECTRODE

A metal arc welding electrode coated with a flux. The purpose of the flux is (1) to unite with undesirable impurities in the fused metal and float them away as a heavy slag, (2) to protect the weld from the atmosphere, and (3) to slow down the rate of cooling. *See* ELECTRODE. *See also* FLUX CORED ARC WELDING.

FLUX CORED ARC WELDING (FCAW)

An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding gas from a flux contained within the tubular electrode, with or without additional shielding from an externally supplied gas, and without the application of pressure. See STANDARD WELDING TERMS. *See also* FLUX CORED ELECTRODE, GAS SHIELDED FLUX CORED ARC WELDING, *and* SELF-SHIELDED FLUX CORED ARC WELDING.

The feature that distinguishes the FCAW process from other arc welding processes is the enclosure of fluxing ingredients within a continuously fed electrode. The remarkable operating characteristics of the process and the resulting weld properties are attributable to this electrode development. The flux cored electrode is a composite tubular filler metal electrode consisting of a metal sheath and a core of various powdered materials. During welding an extensive slag cover is produced on the face of a weld bead.

Note that metal cored electrodes are not included in this description, because their powdered core materials produce no more than slag islands on the face of a weld bead. Thus, they do not match the definition of flux cored electrodes.

FCAW offers two major process variations that differ in their method of shielding the arc and weld pool from atmospheric contamination (oxygen and nitrogen). One type, self-shielded FCAW, protects the molten metal through the decomposition and vaporization of the flux core by the heat of the arc. The other type, gas shielded FCAW, makes use of a protective gas flow in addition to the flux core action. With both methods, the electrode core material provides a substantial slag covering to protect the solidifying weld metal.

Flux cored electrodes are also used in electrogas welding (EGW). That process is a single pass, vertical-up welding process. *See* ELECTROGAS WELDING.

Flux cored arc welding is normally a semiautomatic process. The process is also used in machine and automatic welding.

Historical Background

Flux cored wires were initially introduced in the 1920s, basically for hardfacing, with the first patents granted to Stoody in 1926. There was little development work in this area for a time because of improvements in the performance of coated electrodes and lack of a suitable power supply to obtain the benefits of flux cored welding. The development of GMAW in the early 1950s renewed interest in the use of flux cored arc welding. Widespread use of the product started in 1957 with the development of competitively priced flux cored wires for welding steel. It was found that a small quantity of flux combined with CO_2 gas protection produced weld metal with very good properties. However, when used in the field for welding steel structures, for example, the wind would often blow the gas away. Welds produced under these conditions would be defective. To correct this problem, a self-shielded flux cored wire was developed. Fluxing materials were introduced into the core that would produce greater quantities of CO_2 to shield the weld.

Process Advantages

The benefits of FCAW are achieved by combining three general features:

(1) The productivity of continuous wire welding

(2) The metallurgical benefits that can be derived from a flux

(3) A slag that supports and shapes the weld bead

FCAW combines characteristics of shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and submerged arc welding (SAW).

The FCAW features, as well as those that distinguish the two major versions of the process, are shown in Figure F-7, illustrating the gas-shielded version, and Figure F-8, illustrating the self-shielded type. Both figures emphasize the melting and deposition of filler metal and flux, together with the formation of a slag covering the weld metal.

In the gas shielded method, shown in Figure F-7, the shielding gas (usually carbon dioxide or a mixture of argon and carbon dioxide) protects the molten metal from the oxygen and nitrogen of the air by forming an envelope around the arc and over the weld pool. Little need exists for de-nitrification of the weld metal because air with its nitrogen is mostly excluded. However, some oxygen may be generated from dissociation of CO_2 to form carbon monoxide and oxygen. The compositions of the electrodes are formulated to provide deoxidizers to combine with small amounts of oxygen in the gas shield.

In the self-shielded method shown in Figure F-8, shielding is obtained from vaporized flux ingredients which displace the air, and by slag compositions that cover the molten metal droplets, to protect the molten weld pool during welding. Production of CO_2 and introduction of deoxidizing and denitriding agents from flux ingredients right at the surface of the weld pool explain why self-shielded electrodes can tolerate stronger air currents than gas shielded electrodes. Thus self-shielded FCAW is the usual choice for field work.

One characteristic of some self-shielded electrodes is the use of long electrode extensions. Electrode extension is the length of unmelted electrode extending beyond the end of the contact tube during welding. Self-shielded electrode extensions of 19 to 95 mm (3/4 to 3-3/4 in.) are generally used, depending on the application. A self-shielded electrode nozzle is shown in Figure F-9.

Increasing the electrode extension increases the resistance heating of the electrode. This preheats the electrode and lowers the voltage drop across the arc. At the same time, the welding current decreases, which lowers the heat available for melting the base metal. The resulting weld bead is narrow and shallow. This makes the process suitable for welding light gauge material and for bridging gaps caused by poor fit-up. If the arc length (voltage) and welding current are maintained (by higher voltage settings at the power supply and higher electrode feed rates), longer electrode extension will increase the deposition rate.

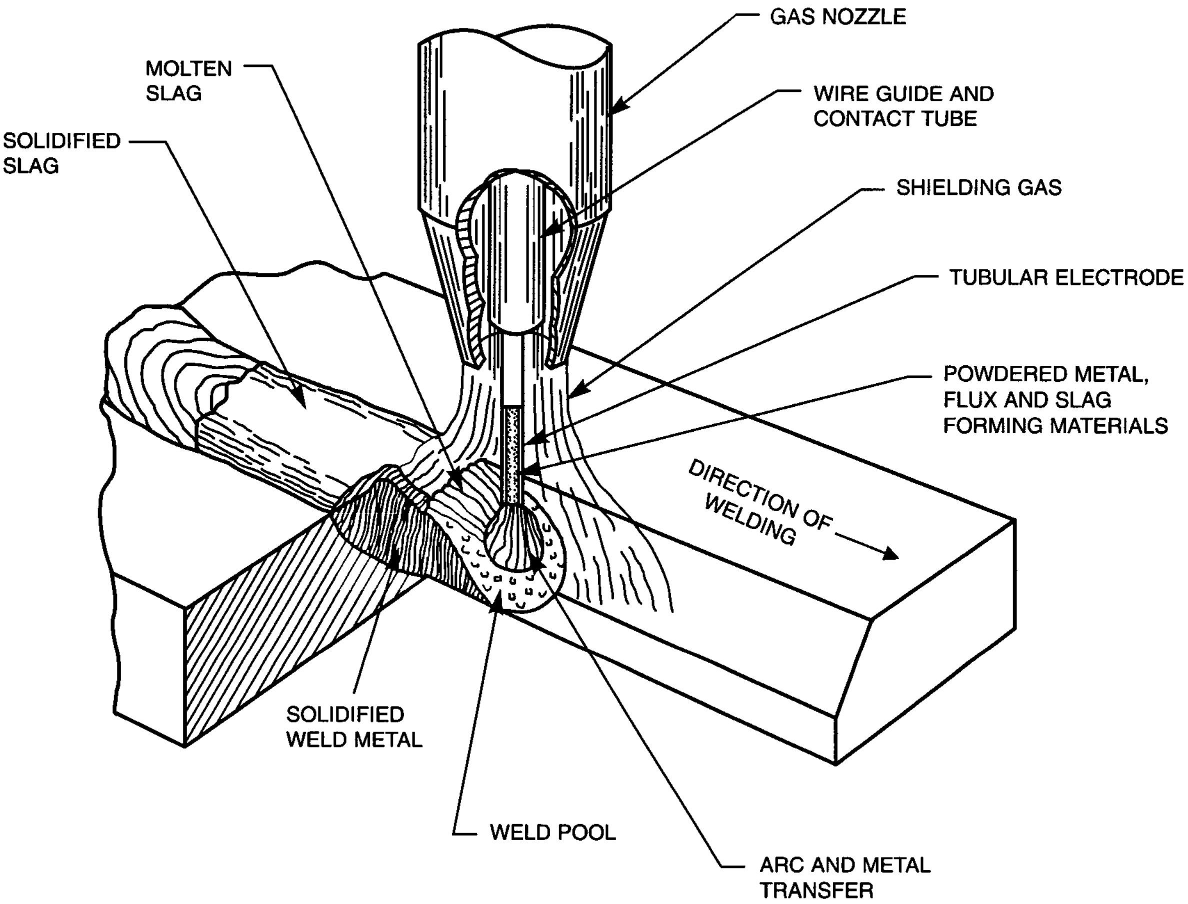


Figure F-7—Gas Shielded Flux Cored Arc Welding

On certain types of self-shielding flux cored electrodes, the polarity should be DCEN (straight polarity). This polarity results in less base metal penetration. As a result, small diameter electrodes such as 0.8 mm (0.030 in.), 0.9 mm (0.035 in.), and 1.2 mm (0.045 in.) have proven to be quite successful for work on thin-gauge materials. Some self-shielded electrodes have been developed specifically to weld the zinc-coated and aluminized steels which are now commonly used in automobile production.

In contrast, the gas-shielded method is suited to the production of narrow, deeply penetrating welds. Short electrode extensions and high welding currents are used for all wire diameters. For fillet welding, compared to SMAW, FCAW welds are narrower with larger throat lengths. The electrode extension principle cannot be equally applied to the gas shielded method because of adverse effects on the shielding.

Principal Applications

Application of the two methods of the FCAW process overlap. However, the specific characteristics of each method make each one suitable for different operating conditions. The process is used to weld carbon and low alloy steels, stainless steels, and cast irons. It is also used for arc spot welding of lap joints in sheet and plate, as well as for cladding and hardfacing.

The type of FCAW used depends on the type of electrodes available, the mechanical property requirements of the welded joints, and the joint designs and fit-up. Generally, the self-shielded method can often be used for applications that are normally done by shielded metal arc welding. The gas shielded method can be used for some applications that are welded by the gas metal arc welding process. The advantages and disadvantages of the FCAW process must be com-

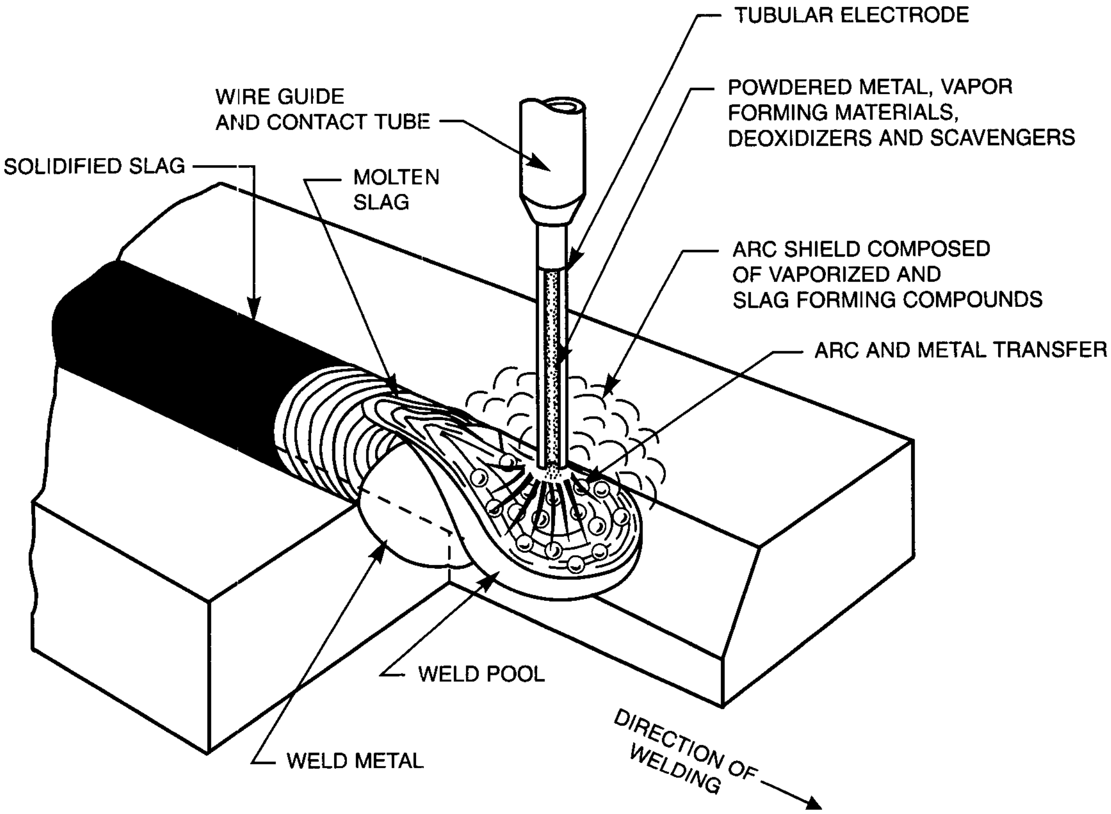


Figure F-8—Self-Shielded Flux Cored Arc Welding

pared to those of other processes when it is evaluated for a specific application.

Higher productivity, compared to shielded metal arc welding, is the chief appeal of flux cored arc welding for many applications. This generally translates into lower overall costs per pound of metal deposited in joints that permit continuous welding and easy FCAW gun and equipment accessibility. The advantages are higher deposition rates, higher operating factors, and higher deposition efficiency (no stub loss).

FCAW has found wide application in fabricating shops, in maintenance, and field erection work. It has been used to produce weldments conforming to the ASME *Boiler and Pressure Vessel Code*, the rules of the American Bureau of Shipping, and ANSI/AWS D1.1, *Structural Welding Code—Steel*. FCAW enjoys prequalified status in ANSI/AWS D1.1.

Stainless steel, self-shielded, and gas shielded flux cored electrodes have been used in general fabrication, surfacing, joining dissimilar metals, and maintenance and repair.

The major disadvantages, compared to the SMAW process, are the higher cost of the equipment, the relative complexity of the equipment in setup and control, and the restriction on operating distance from the electrode wire feeder. Self-shielded FCAW may generate large volumes of welding fumes, which, except in field work, require suitable exhaust equipment. Compared to the slag-free GMAW process, the need for removing slag between passes is an added labor cost. This is especially true in making root pass welds.

Equipment

Semiautomatic Equipment. As shown in Figure F-10, the basic equipment for self-shielded and gas shielded flux cored arc welding is similar. The major difference is the provision for supplying and metering gas to the arc of the gas shielded electrode. The recom-

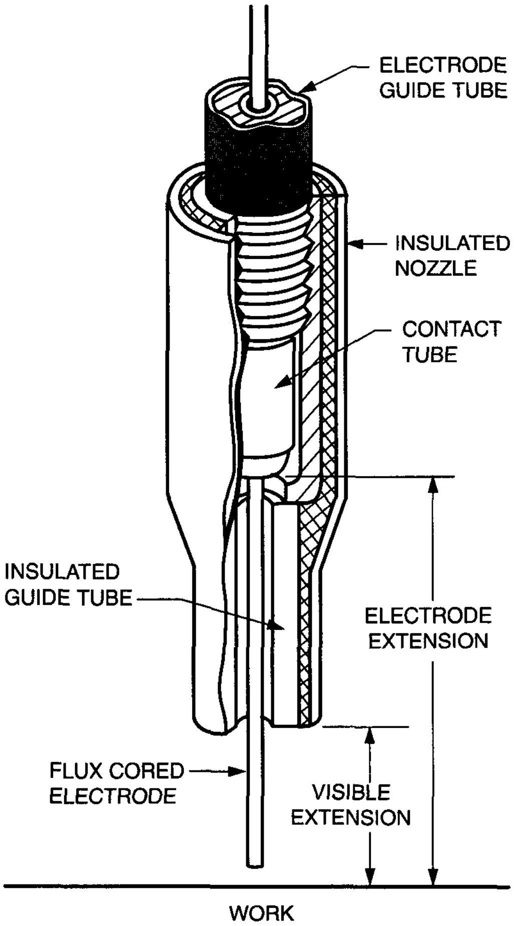


Figure F-9—Cut Away View of a Self-Shielded Electrode Nozzle Showing Electrode Extension

mended power source is the dc constant-voltage type, similar to sources used for gas metal arc welding. The power supply should be capable of operating at the maximum current required for the specific application. Most semiautomatic applications use less than 500 A. The voltage control should be capable of adjustments in increments of one volt or less. Constant-current (dc) power sources of adequate capacity with appropriate controls and wire feeders are also used, but these applications are rare.

The purpose of the wire feed control is to supply the continuous electrode to the welding arc at a constant preset rate. The rate at which the electrode is fed into the arc determines the welding amperage that a constant-voltage power source will supply. If the electrode feed rate is changed, the welding machine automatically adjusts to maintain the preset arc voltage. Electrode feed rate may be controlled by mechanical or electronic means.

Welding guns may be either air cooled or water cooled. Air-cooled guns are favored because there is no requirement to deliver water. However, water-cooled guns are more compact, lighter in weight, and generally have higher current ratings. Capacity ratings range up to 600 A, continuous duty. Guns may have either straight or curved nozzles. The curved nozzle can vary from 40° to 60°. In some applications, the curved nozzle enhances flexibility and ease of electrode manipulation.

Fume Extractors

As a result of safety and health requirements for controlling air pollution, several manufacturers have introduced welding guns equipped with integral fume extractors. A fume extractor usually consists of an exhaust nozzle that encircles the gun nozzle. It can be adapted to gas-shielded and self-shielded guns. The nozzle is ducted to a filter canister and an exhaust pump. The aperture of the fume extracting nozzle is located at a sufficient distance behind the top of the gun nozzle to draw in the fumes rising from the arc without disturbing the shielding gas flow.

FLUX CORED ELECTRODE

A composite tubular filler metal electrode consisting of a metal sheath and a core of various powdered materials, producing an extensive slag cover on the face of a weld bead. External shielding may be required. See STANDARD WELDING TERMS.

A flux cored electrode consists of a mild steel sheath surrounded by a core of flux or alloying compound, or both. The compounds contained in flux core make up about 15% to 20% of the weight of the electrode and serve the following functions:

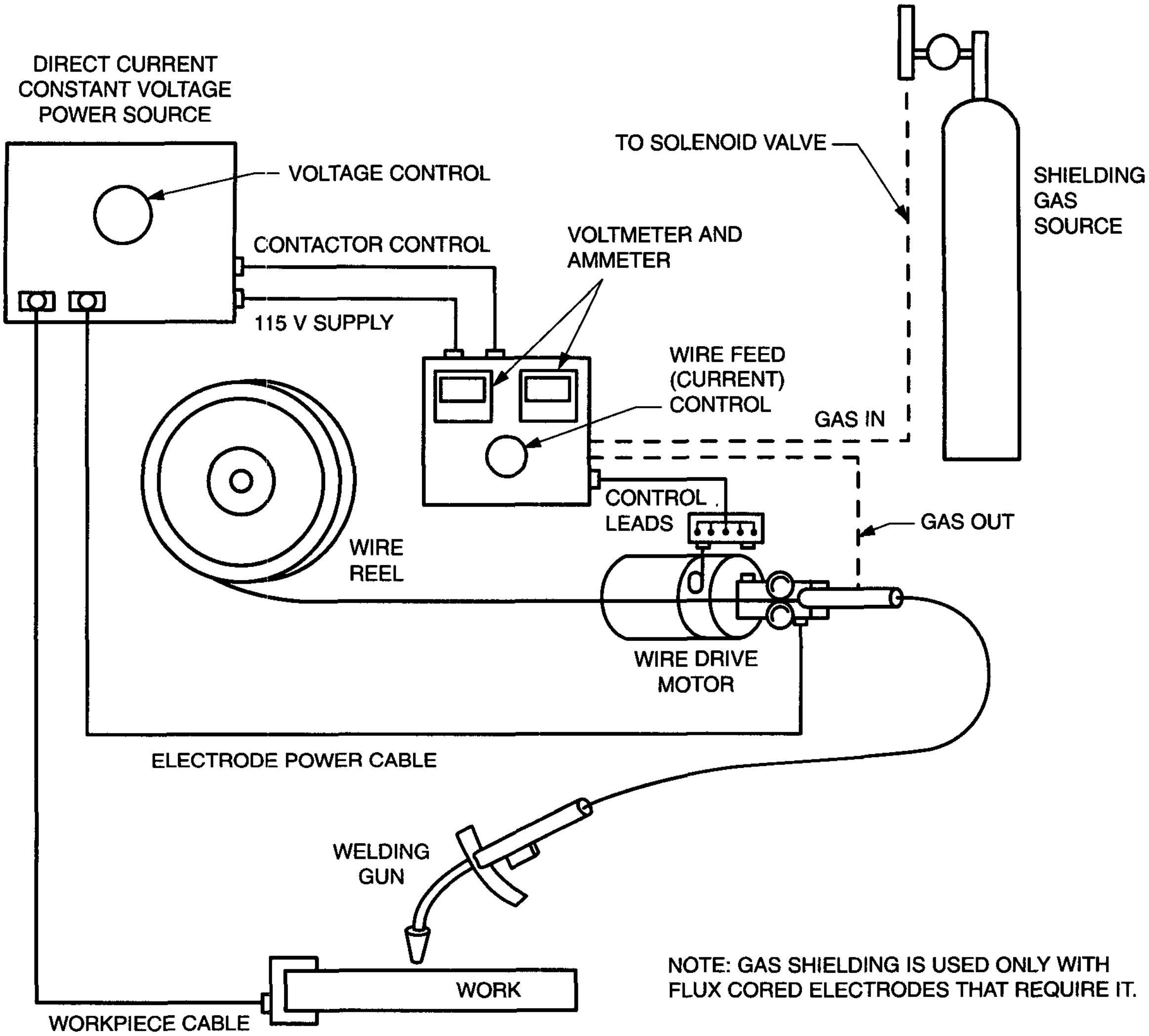
(1) Act as a deoxidizer or scavenger, helping to purify the metal and produce solid weld metal.

(2) Form slag to float on the molten weld pool and protect it from the atmosphere during solidification.

(3) Act as an arc stabilizer, which produces a smooth welding arc and reduces spatter.

(4) Add alloying elements to the weld metal to increase strength and provide other desirable weld metal properties.

(5) Provide for shielding gas. However, to assure weld quality, externally supplied shielding gas is often used to supplement and guarantee weld metal shielding.



NOTE: GAS SHIELDING IS USED ONLY WITH FLUX CORED ELECTRODES THAT REQUIRE IT.

Figure F-10—Basic Equipment for Flux Cored Arc Welding

Metal Transfer Characteristics. Metal transfer from flux cored electrodes is in globular form. Molten droplets appear to form on the sheath of the electrode; as one is transferred, another droplet forms in another location on the sheath. The flux material appears to be transported to the weld deposit independent of the metal transfer. The droplets are larger at low current intensity. This means there is less visible spatter, the arc appears smoother and deposition efficiency is higher when welding is done at high current intensities.

The flux content of a flux cored electrode is less than that for a coated stick electrode of comparable size, because the flux covering on a stick electrode must have a binder to make it adhere to the electrode wire and must also contain materials that aid in the extrusion process. As a result, the fluxing material on a coated stick electrode is about 24% of its weight, compared to a flux content of 15% in flux cored wire.

Advantages

Among the advantages of flux cored welding is that flux cored wires can be used at high current densities, which achieves high deposition rates and good weldability. The efficiency of flux cored welding is greater than stick electrode welding. For coated electrodes, the process efficiency is 65% to 70%, and for flux cored wires, nearly 85%.

Flux cored wire is also good in welding conditions which include narrow grooves. The minimum angle of preparation is 40 to 45°, so joints can be welded with about half of the amount of weld metal in less time. The lower total heat input also minimizes distortion.

Manufacture. Flux cored wire manufacturing is a highly specialized and precise operation. Most flux cored electrode wire is made by passing low-carbon steel strip through a contour forming roll which bends the strip into a U-shape cross section. This cross section is filled with a measured amount of granular flux cored material, after which the U-shape section passes through closing rolls that form it into a tube with tightly compressed core material. This tube, which may have assumed a variety of interior shapes, is then pulled through drawing dies to reduce its diameter and further compress the core material. After the wire has been reduced to the specified diameter, it may or may not be baked, depending on the flux content. It is then wound on 10 or 20 kg (25 or 50 lb) spools or 30 kg (60 lb) coils.

Classification of Electrodes

Figure F-11 illustrates the identification system for mild steel FCAW electrodes. Most mild steel FCAW electrodes are classified according to the requirements of ANSI/AWS A5.20, latest edition, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding.* Table F-2 explains the significance of the last digit of the FCAW designations.

Table F-2
Shielding and Polarity Requirements for Mild Steel FCAW Electrodes

AWS Classification	External Shielding Medium	Current and Polarity
EXXT-1 (Multiple-pass)	CO_2	dc, electrode positive
EXXT-2 (Single-pass)	CO_2	dc, electrode positive
EXXT-3 (Single-pass)	None	dc, electrode positive
EXXT-4 (Multiple-pass)	None	dc, electrode positive
EXXT-5 (Multiple-pass)	CO_2	dc, electrode positive
EXXT-6 (Multiple-pass)	None	dc, electrode positive
EXXT-7 (Multiple-pass)	None	dc, electrode positive
EXXT-8 (Multiple-pass)	None	dc, electrode negative
EXXT-9 (Multiple-pass)	None	dc, electrode negative
EXXT-10 (Single-pass)	None	dc, electrode negative
EXXT-11 (Multiple-pass)	None	dc, electrode negative
EXXT-G (Multiple-pass)	*	*
EXXT-GS (Single-pass)	*	*

*As agreed upon between supplier and user.

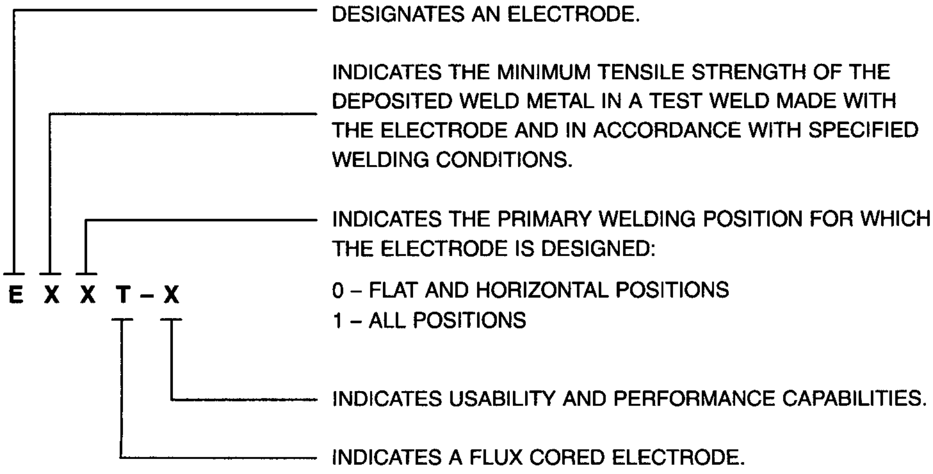


Figure F-11—Identification System for Mild Steel FCAW Electrodes

FLUX COVER, Metal Bath Dip Brazing and Dip Soldering

A layer of molten flux over the molten filler metal bath. See STANDARD WELDING TERMS.

FLUX CUTTING (FOC)

An oxygen cutting process that uses heat from an oxyfuel gas flame, with a flux in the flame to aid cutting. See STANDARD WELDING TERMS.

Flux cutting is primarily intended for cutting stainless steels. The flux is designed to react with oxides of alloying elements, such as chromium and nickel, to produce compounds with melting points near those of iron oxides. A special apparatus is required to introduce the flux into the kerf. With a flux addition, stainless steels can be cut essentially the same as carbon steels. Cutting speeds approaching those for equivalent thicknesses of carbon steel can be attained. The tip sizes will be larger, and the cutting oxygen flow will be somewhat greater than for the carbon steels. *See* OXYFUEL GAS CUTTING.

FLUXED ELECTRODE

A metal electrode provided with a flux.

FLUX INJECTION CUTTING

See OXYFUEL GAS CUTTING, FLUX CUTTING *and* METAL POWDER CUTTING.

FLUX, Magnetic

The magnetic lines of force existing between the two opposite magnetic poles of a magnet.

FLUX OXYGEN CUTTING

A nonstandard term for FLUX CUTTING.

FOCAL POINT

A nonstandard term for FOCAL SPOT.

FOCAL SPOT, Electron Beam Welding and Cutting, and Laser Beam Welding and Cutting

A location at which the beam has the most concentrated energy and the smallest cross-sectional area. See STANDARD WELDING TERMS.

FOCUS FILM DISTANCE

The distance in centimeters (inches) between the focal spot of the X-ray or the radiation source and the film.

FOLLOW-UP, Resistance Welding

The ability of the moveable electrode to maintain proper electrode force and contact with the workpiece as metal movement occurs, especially in projection welding. See STANDARD WELDING TERMS.

FORCE

Energy exerted between two or more bodies which tends to change their relative shapes or positions.

FOREHAND WELDING

A welding technique in which the welding torch or gun is directed toward the progress of welding. See STANDARD WELDING TERMS. *See also* TRAVEL ANGLE, WORK ANGLE, *and* PUSH ANGLE.

FORGE-DELAY TIME, Resistance Welding

The time elapsing between a preselected point in the welding cycle and the initiation of the forging force. See STANDARD WELDING TERMS.

FORGE FORCE

A compressive force applied to the weld after the heating portion of the welding cycle is essentially complete. See STANDARD WELDING TERMS.

FORGE WELDING (FOW)

A solid-state welding process that produces a weld by heating the workpieces to welding temperature and applying blows sufficient to cause permanent deformation at the faying surfaces. See STANDARD WELDING TERMS. *See also* COLD WELDING, DIFFUSION WELDING, *and* HOT PRESSURE WELDING.

Forge welding was the earliest welding process and the only one in common use until well into the nineteenth century. Blacksmiths used this process. Pressure vessels and steel pipe were among the industrial items once fabricated by forge welding. The process finds some application with modern methods of applying the heat and pressure necessary to achieve a weld. The chief present day applications are in the production of tubing and clad metals.

Principles of Operation

The sections to be joined by forge welding may be heated in a forge, furnace, or by other appropriate means until they are very malleable. A weld is accomplished by removing the parts from the heat source, superimposing them, and then applying pressure or hammer blows to the joint.

Heating time is the major variable that affects joint quality. Insufficient heat will fail to bring the surfaces to the proper degree of plasticity, and welding will not take place. If the metal is overheated, a brittle joint of very low strength may result. The overheated joint is likely to have a rough, spongy appearance where the metal is severely oxidized. The temperature must be uniform throughout the joint interfaces to yield a satisfactory weld.

Process Modes

Hammer Welding. In hammer welding, coalescence is produced by heating the parts to be welded in a forge or other furnace and then applying pressure by means of hammer blows. Manual hammer welding is the oldest technique. Pressure is applied to the heated members by repeated high-velocity blows with a comparatively light sledge hammer. Modern automatic and semiautomatic hammer welding is accomplished by blows of a heavy power-driven hammer operating at low velocity. The hammer may be powered by steam, hydraulic, or pneumatic equipment.

The size and quantity of parts to be fabricated will determine the choice of either manual or power-driven hammer welding. This process may still be used in some maintenance shops, but it largely has been replaced by other welding processes.

Die Welding. This is a forge welding process where coalescence is produced by heating the parts in a furnace and then applying pressure by means of dies. The dies also shape the work while it is hot.

Metals Welded

Low carbon steels in the form of sheets, bars, tubing, pipe and plates are the metals most commonly joined by forge welding.

The major influences on the grain structure of the weld and heat-affected zone are the amount of forging applied and the temperature at which the forge welding takes place. A high temperature is generally necessary for the production of a sound forge weld. Annealing can refine the grain size in a forge welded steel joint and improve joint ductility.

Thin, extruded sections of aluminum alloy are joined edge-to-edge by a forge welding process with automatic equipment to form integrally stiffened panels. The panels are used for lightweight truck and trailer bodies. Success of the operation depends upon the use of correct temperature and pressure, effective positioning and clamping devices, edge preparation, and other factors. Although the welding of aluminum for this application is called forge welding, it could be classified as hot pressure welding because the edges to be joined are heated to welding temperature and then upset by the application of pressure.

Joint Design. The five joint designs applicable to manual forge welding are the lap, butt, cleft, jump, and scarf types shown in Figure F-12. The joint surfaces for these welds are slightly rounded or crowned. This shape ensures that the center of the pieces will weld first so that any slag, dirt, or oxide on the surfaces will be forced out of the joint as pressure is applied. *Scarfing* is the term applied to the preparation of the workpieces of forge welding. Similarly, the prepared surface is referred to as a scarfed surface. Each workpiece to be welded must be upset sufficiently for an adequate distance from the scarfed surface to provide metal for mechanical working during welding.

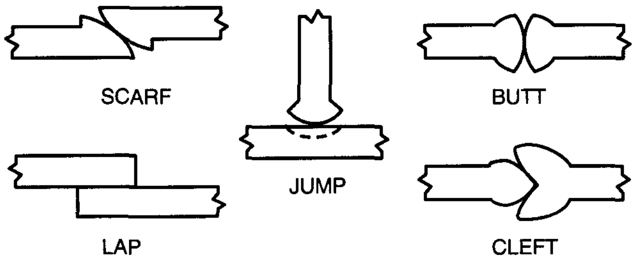


Figure F-12—Typical Joint Designs Used for Manual Forge Welding

Flux

In the forge welding of certain metals, a flux must be used to prevent the formation of oxide scale. The flux and the oxides present combine to form a protective coating on the heated surfaces of the metal. This coating prevents the formation of additional oxide and lowers the melting point of the existing oxide.

Two commonly used fluxes for steels are silica sand and borax (sodium tetra borate). Flux is not required for very low-carbon steels (ingot iron) and wrought iron because their oxides have low melting points. The flux most commonly used in the forge welding of high-carbon steels is borax. Because it has a relatively low fusion point, borax may be sprinkled on the metal while it is in the process of heating. Silica sand is suitable as a flux in the forge welding of low-carbon steel.

FORGING SPEED, Friction Welding

The relative velocity of the workpieces at the instant the forge force is applied. See STANDARD WELDING TERMS.

FORGING STRAINS

Strains resulting from forging or from cooling from the forging temperature.

4F, Plate

A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the overhead welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

4F, Pipe

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis vertical, in which the weld is made in the overhead welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

4G

A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the overhead welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

FRACTURE

A crack or break which the welder is required to repair.

FRANGIBLE DISC

A thin disc, usually of metal, which closes the discharge channel of a gas cylinder under normal conditions but is intended to rupture at a predetermined pressure to allow the escape of gas.

FREE BEND TEST

A bending test in which the specimen is bent without constraint of a jig. Since this test can be hazardous, its use is not recommended.

FREEZING

A term applied when the metallic electrode sticks to the workpiece when the arc is struck. In most welding circuits, when the electrode is touched to the workpiece the current exceeds the normal welding current by 40% to 50%. The arc formed by this excess current instantly fuses a portion of the electrode end to the workpiece against which it is struck. The workpiece, however, is usually cold, so that the fused metal is solidified or "frozen" almost instantly, and if the end of the electrode is not withdrawn quickly it becomes attached to the solidified metal.

FREQUENCY

The number of complete alternations per second in an alternating current. *See* CYCLE.

FRICTION SOLDERING

A nonstandard term for ABRASION SOLDERING.

FRICTION SPEED, Friction Welding

The relative velocity of the workpieces at the time of initial contact. See STANDARD WELDING TERMS. *See* Figures D-6 and I-8.

FRICTION STIR WELDING (FW-S)

A variation of friction welding that produces a weld between two butted workpieces by the friction heating and plastic material displacement caused by a high speed rotating tool that traverses along the weld joint. See STANDARD WELDING TERMS.

A solid phase, autogenous welding method introduced in 1991 that has been used successfully in welding the 2000, 5000, and 6000 series of aluminum sheet alloys.

Welding is accomplished by rotating a nonconsumable probe and entering it into the abutting edges of the sheets to be welded. The frictional heat generated between the tool and the workpieces produces plastic deformation, then the tool is moved along the joint. The base material fills in behind the probe to complete the weld. No melting occurs during the operation, so the process is solid phase in nature. For certain aluminum alloys, no shielding gas is required.

The joining of aluminum alloys, especially those that are often difficult to weld, has been the initial target for developing and judging the performance of friction stir welding. As the technology for this process is developed, its use will be applied to other materials.

Applications

Friction stir welding has potential applications in major industries such as aerospace, aluminum production, automotive, construction, rail car manufacturing, refrigeration, shipbuilding, and storage tanks and pressure vessels.

Advantages

(1) The electromechanical machine tool equipment is energy efficient (a single pass 12.5 mm [0.5 in.] deep weld can be made in 6xxx alloy with a gross power of 3 kW), requires very little maintenance, and apart from welding tools and electric power, relies on no other consumable.

(2) A high level of operator skill and training is not required.

(3) The welding process requires neither filler metals nor weld pool shielding gas.

(4) Special joint edge profiling is unnecessary.

(5) Oxide removal immediately prior to welding is unnecessary.

(6) The technique is ideally suited to automation.

(7) If necessary, the welding operation can take place in all positions from flat to overhead.

Limitations

(1) Single-pass welding speeds in some sheet alloys are slower than for some mechanized arc welding techniques.

(2) The parts must be rigidly clamped against a backing bar to prevent weld metal breakout, if full penetrations are required.

(3) At the end of each weld run a hole is left where the tool pin is withdrawn. In many cases it may be necessary to fill the hole by an alternative process, such as friction taper plug welding.

(4) Run-on/run-off plates are necessary where continuous welds are required from one edge of a plate to the other.

(5) Due to workpiece clamping and access requirements, applications where portable equipment could be used may be limited.

FRICTION SURFACING

A process variation of friction welding. *See* FRICTION WELDING.

FRICTION UPSET DISTANCE

The decrease in length of work pieces during the time of friction welding force application. See STANDARD WELDING TERMS. *See* Figures D-6 and I-8.

FRICTION WELDING (FRW)

A solid-state welding process that produces a weld under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. See STANDARD WELDING TERMS. *See* Figures D-6 and I-8.

While considered a solid-state welding process, under some circumstances a molten film may be produced at the interface. However, even then the final weld should not exhibit evidence of a molten state because of the extensive hot working during the final stage of the process. Filler metal, flux, and shielding gas are not required with this process. The basic steps in friction welding are shown in Figure F-13.

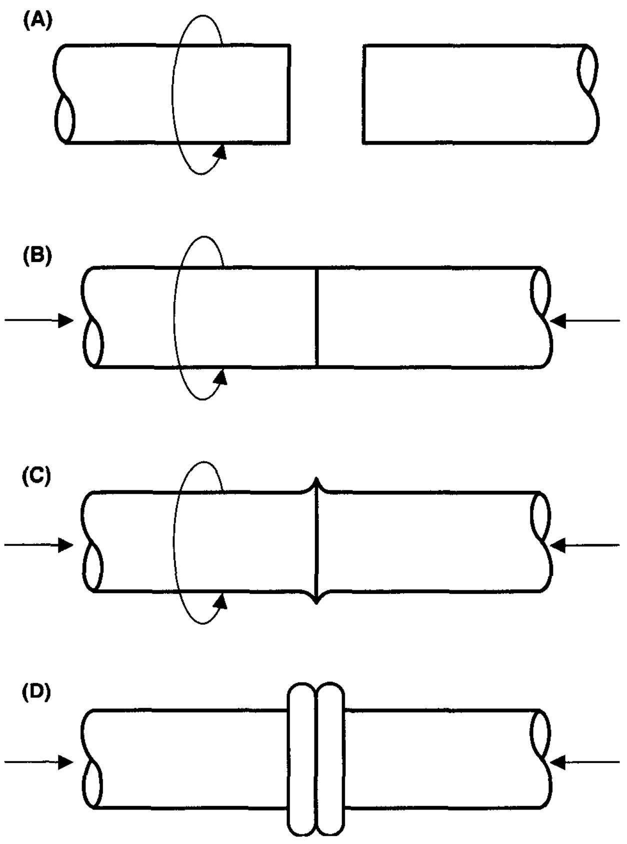


Figure F-13—Basic Steps in Friction Welding

First, one workpiece is rotated and the other is held stationary, as shown in Figure F-13(A). When the appropriate rotational speed is reached, the two workpieces are brought together and an axial force is applied, as in Figure F-13(B). Rubbing at the interface heats the workpiece locally and upsetting begins, as in Figure F-13(C). Finally, rotation of one of the workpieces stops and upsetting is completed, as in Figure F-13(D).

The weld produced is characterized by a narrow heat-affected zone, the presence of plastically deformed material around the weld (flash), and the absence of a fusion zone.

Energy Input Methods

There are two methods of supplying energy in friction welding. Direct drive friction welding, sometimes called conventional friction welding, uses a continuous input. Inertia friction welding, sometimes called flywheel friction welding, uses energy stored in a flywheel.

Friction Surfacing

This process variation uses rotational motion of one of the parts, but at the same time adds a relative motion in a direction perpendicular to the axis of rotation. This process is used to deposit material in a solid-state mode to a variety of configurations from flat plates to circular or cylindrical shapes. This variation is shown in Figure F-14.

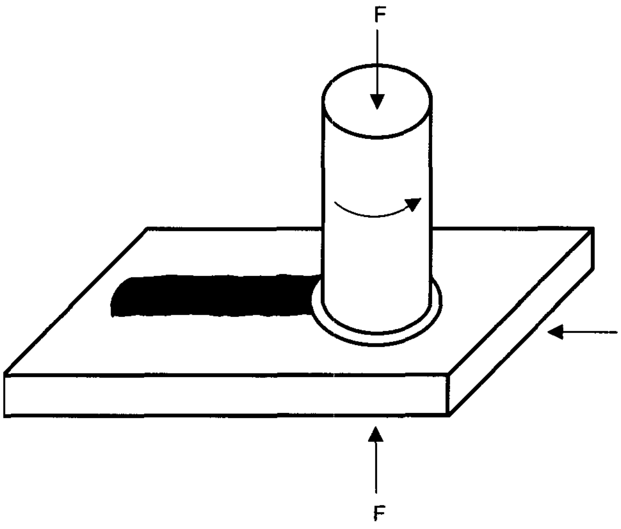


Figure F-14—Friction Surfacing

Advantages

Friction welding, like any welding process, has its specific advantages and disadvantages. The following are some advantages of friction welding:

(1) No filler metal is needed.

(2) Flux and shielding gas are not required.

(3) The process is environmentally clean; no arcs, sparks, smoke or fumes are generated by clean parts.

(4) Surface cleanliness is not as significant, compared with other welding processes, since friction welding tends to disrupt and displace surface films.

(5) There are narrow heat-affected zones.

(6) Friction welding is suitable for welding most engineering materials and is well suited for joining many dissimilar metal combinations.

(7) In most cases, the weld strength is as strong or stronger than the weaker of the two materials being joined.

(8) Operators are not required to have manual welding skills.

(9) The process is easily automated for mass production.

(10) Welds are made rapidly compared to other welding processes.

(11) Plant requirements (space, power, special foundations, etc.) are minimal.

Limitations

Some limitations of the process are as follows:

(1) In general, one workpiece must have an axis of symmetry and be capable of being rotated about that axis.

(2) Preparation and alignment of the workpieces may be critical for developing uniform rubbing and heating, particularly with diameters greater than 50 mm (2 in).

(3) Capital equipment and tooling costs are high.

(4) Dry bearing and nonforgeable materials cannot be welded.

(5) If both parts are longer than 1 m (3 ft), special machines are required.

(6) Free-machining alloys are difficult to weld.

Materials Welded

Friction welding can be used to join a wide range of similar and dissimilar materials, including: metals, some metal matrix composites, ceramics, and plastics. Some combinations of materials that have been joined according to the literature and equipment manufacturers' data are indicated in Figure F-15. This table should only be used as a guide. Specific weldability may depend upon a number of factors including specific alloy compositions, applicable process variation, component design, and service requirements.

Applications

Friction welded parts in production applications span the aerospace, agricultural, automotive, defense, marine, and oil industries. Everything from tong holds on forging billets to critical aircraft engine components are friction welded in production.

Automotive parts which are manufactured by friction welding include gears, engine valves, axle tubes, drive line components, strut rods and shock absorbers. Hydraulic piston rods, track rollers, gears, bushings, axles and similar parts are commonly friction welded by the manufacturers of agricultural equipment. Friction welded aluminum/copper joints are in wide usage in the electrical industry. Stainless steels are friction welded to carbon steel in various sizes for use in marine drive systems and water pumps for home and industrial use. Friction welded assemblies are often used to replace expensive castings and forgings.

THIS LIST WAS COMPILED FROM AVAILABLE FRICTION WELDING LITERATURE. EACH MANUFACTURER OF FRICTION WELDING EQUIPMENT HAS DIFFERENT KNOW-HOW AND EXPERIENCE IN WELDING SOME OF THESE MATERIALS.	ZIRCONIUM ALLOYS	VALVE MATERIAL (AUTOMOTIVE)	VANADIUM	URANIUM	TUNGSTEN CARBIDE (CEMENTED)	TUNGSTEN	TITANIUM ALLOYS	TITANIUM	THORIUM	TANTALUM	STEELS, TOOL	STEELS, STAINLESS	STEELS, SINTERED	STEELS, MARAGING	STEELS, FREE MACHINING	STEELS, CARBON	STEELS, ALLOY	SILVER ALLOYS	SILVER	NIOBIUM ALLOYS	NIOBIUM	NIMONIC	NICKEL ALLOYS	NICKEL	MONEL	MOLYBDENUM	MAGNESIUM ALLOYS	MAGNESIUM	LEAD	IRON, SINTERED	COPPER NICKEL	COPPER	COLUMBIUM	COBALT	CERAMIC	CAST IRON	CARBIDES, CEMENTED	BRONZE	BRASS	ALUMINUM ALLOYS	ALUMINUM
ALUMINUM	X				X		X	X				X				X	X							X			X					X			X				X	X	X
ALUMINUM ALLOYS												O				O	O															O			X					X	
BRASS																																							X		
BRONZE																X																						X			
CARBIDES, CEMENTED											X					X																									
CAST IRON																																									
CERAMIC																																									
COBALT																X	X																								
COLUMBIUM																																	X								
COPPER	X							X				X				X			X													X									
COPPER NICKEL												X				X															X										
IRON SINTERED																X																									
LEAD																													X												
MAGNESIUM																												X													
MAGNESIUM ALLOYS																											X														
MOLYBDENUM																										X															
MONEL												X		X	O	X	X								X																
NICKEL											X	X		X	O	X	X							X																	
NICKEL ALLOYS		X									X	X		X	O	X	X						X																		
NIMONIC		X									X	X		X	O	X	X					X																			
NIOBIUM																					X																				
NIOBIUM ALLOYS																				X																					
SILVER																																									
SILVER ALLOYS																		O																							
STEELS, LOW ALLOY		X									X	X	O	X	O	X	X																								
STEELS, CARBON		X									X	X	O	X	O	X																									
STEELS, FREE MACHINING		O									O	O		O	O																										
STEELS, MARAGING		X									X	X		X																											
STEELS, SINTERED												O	O																												
STEELS, STAINLESS	O	X					O	O				X																													
STEELS, TOOL											X																														
TANTALUM								X		X																															
THORIUM									O																																
TITANIUM								X																																	
TITANIUM ALLOYS							X																																		
TUNGSTEN						X																																			
TUNGSTEN CARBIDE, CEMENTED																																									
URANIUM				X																																					
VANADIUM																																									
VALVE MATERIAL (AUTOMOTIVE)		X																																							
ZIRCONIUM ALLOYS	X																																								

X = FULL STRENGTH METALLURGICAL BOND. (IN SOME CASES IT MAY BE NECESSARY TO PERFORM AN APPROPRIATE POST WELD HEAT TREATMENT TO REALIZE THE FULL WELD STRENGTH.)

O = CAN BE FRICTION WELDED, BUT WILL NOT PRODUCE A FULL STRENGTH BOND.

Figure F-15—Material Combinations Weldable by Friction Welding

Safety

Friction welding machines are similar to machine tool lathes in that one workpiece is rotated by a drive system. They are also similar to hydraulic presses in that one workpiece is forced against the other with high loads. Safe practices for lathes and power presses should be used as guides for the design and operation of friction welding machines. Typical hazards include high noise levels, high rotational speeds, and flying particles.

Machines should be equipped with appropriate mechanical guards and shields as well as two-hand operating switches and electrical interlocks. These devices should be designed to prevent operation of the machine when the work area, rotating drive, or force system is accessible to the operator or other personnel.

Operating personnel should wear appropriate eye and ear protection and safety apparel commonly used with machine tool operations. Ear protection should be provided to guard against high noise levels produced during friction welding. In any case, applicable OSHA standards should be strictly observed.

The machine manufacturer's literature should be studied for complete safety precautions.

Technical Resources

Further information on friction welding, such as types of relative motion, relationship between variables, joint design, friction welding equipment, welding procedures, tooling and fixtures, heat treatment, testing and inspection, and recommended reading list can be found in the *Welding Handbook*, 8th Edition, Vol 2, published by the American Welding Society, Miami, Florida, 1991. *See also* DIRECT DRIVE FRICTION WELDING *and* INERTIA FRICTION WELDING.

FRICTION WELDING FORCE

The compressive force applied to the faying surfaces during the time there is relative movement between the workpieces from the start of welding until the application of the forge force. See STANDARD WELDING TERMS. *See* Figures D-6 and I-8.

FRITTING

In powder metallurgy, a term for a condition in which the temperature applied exceeds the melting point of any of the metal powders used in a mixture. *See* POWDER METALLURGY *and* SINTERING.

FUEL GAS

A gas such as acetylene, natural gas, hydrogen, propane, stabilized methyl acetylene propadiene, and other fuels normally used with oxygen in one of the oxyfuel processes and for heating. See STANDARD WELDING TERMS.

To be suitable for welding operations, a fuel gas must have the following characteristics when combined with oxygen: (1) high flame temperature, (2) high rate of flame propagation, (3) adequate heat content, (4) minimum chemical reaction of the flame with the base and filler metals.

Among commercially available fuel gases for welding, only acetylene meets all these requirements. Other fuel gases, such as methyl-acetylene propadiene products (MPS), propylene, propane, natural gas, hydrogen, and proprietary gases based on these, offer sufficiently high flame temperature, but exhibit lower flame propagation rates. When oxygen-to-fuel gas ratios are high enough to produce usable heat transfer rates, the flames produced by these gases are excessively oxidizing. However, methylacetylene propadiene and hydrogen are sometimes used for oxyfuel gas welding of low-melting metals.

Such gases as methylacetylene propadiene products (MPS), propylene, propane, natural gas, and proprietary gases based on these are used for oxyfuel gas cutting, torch brazing, torch soldering, and other operations where demands on the flame characteristics and heat transfer rates are not the same as those for welding. *See* OXYACETYLENE WELDING *and* OXYFUEL GAS CUTTING.

FULLY AUTOMATIC WELD

A weld made entirely by automatic equipment.

FULL FILLET WELD

A fillet weld equal in size to the thickness of the thinner member joined. See STANDARD WELDING TERMS.

FULL PENETRATION

A nonstandard term for COMPLETE JOINT PENETRATION.

FUME COLLECTOR

A vacuum system for removing and filtering fumes and smoke produced in welding operations.

FUMES, ARC WELDING

See WELDING FUMES.

FURNACE

An enclosure heated by a suitable fuel which provides an atmosphere of controlled heat.

When furnaces are used for heat treating in welding operations, it is important to assure correct heat control, particularly when heat treating is applied to pressure vessels and similar equipment which are subject to high temperatures or high stress. When metallurgical requirements are rigid, the most suitable combustible fuels are natural gas, liquid petroleum gas, and oil.

Temperature

The temperature required determines the method in which heat treating furnaces are fired. For those used in low-temperature operations, usually under 600 °C (1100 °F), the recirculating type of furnace is used, in which gas or oil is burned in a separate chamber and the resulting products of combustion are circulated through the furnace by a fan.

For temperatures up to 1000°C (1900°F), indirect firing is generally used. In this type, the combustion chambers may be above, below or on one side, separated from the heat chamber by baffles.

The third type of furnace is the direct-fired furnace, which is used for temperatures above 1000°C (1900°F). The burner is fired directly into the heat chamber, usually above the charge. It is possible, but not usual, to design direct fired gas furnaces which will operate satisfactorily between 500 and 1000°C (1000 and 1900°F).

Electric Furnaces

Electric furnaces used for heat treating applications are usually the resistor type, and are ordinarily limited to applications for which temperatures do not exceed 1000°C (1900°F). Above that temperature the operating life of the resistor elements is greatly shortened. If carbon resistor elements are used rather than metal elements, however, the furnace may be used at temperatures up to 1300°C (2300°F). Furnaces with metallic elements and protective atmospheres have been successfully operated at 1100°C (2100°F) for brazing applications.

Electric furnaces operate quietly, cleanly and without the necessity for mufflers. They provide uniformity of temperature in applications for which electric heat is specified. The greatest advantages are the consistency of operation after initial set-up, and freedom from human error resulting from adjustments of fuel.

The main disadvantage of the electric furnace is that it is slow to heat up from a cold condition. Where it is possible, an electric furnace can be connected across the line to save the expense of a transformer. Frequently however, elements based on line voltage are too light for satisfactory life and transformers are necessary.

Operating Fuel-Fired Furnaces

Disastrous results can occur if fuel fired furnaces are not handled correctly. To operate these furnace safely, there are several precautions which must be rigidly followed. On all fuel fired furnaces, all doors are to be opened before lighting the furnace. When lighting burners, oil, gas or the two-pipe (blast) type, turn on the air first, then the fuel. When lighting burners of the low-pressure proportional mixing type, always open the gas supply valve wide open. All regulation of fuel is by air flow and the ratio adjusting screw on the mixer. When shutting off an oil or gas burner of any type, always shut off the fuel first.

Material Handling Methods

Furnaces for heat treating applications are further classified as one of several types, depending on the method of handling the material to be heated. In a batch method, the pieces are handled in groups. The furnace may be a stationary hearth solid bottom, stationary hearth roller bottom, car bottom, or a furnace with removable covers and pits. In a semi-continuous handling method, a stationary hearth or car bottom furnace is used in conjunction with cranes designed to remove the material. This reduces the time between changes to several minutes. The continuous system conveys the parts through the furnace, and consists of a pusher (direct or on pans or shoes), tunnel kilns, with cars, chain conveyor and moving finger, walking beam, roller hearth, rotary hearth, rotation retort or miscellaneous special types.

Furnace Design

For the most efficiency, furnaces should be designed by a furnace manufacturer or combustion engineer. There are many variables, and the size of a furnace required depends on the amount and size of material to be heated per hour, the heating time, and the amount of heat that can be liberated without damage to the furnace. *See* ANNEALING, HEAT TREATMENT *and* METALLURGY.

FURNACE BRAZING (FB)

A brazing process in which the workpieces are placed in a furnace and heated to the brazing temperature. See STANDARD WELDING TERMS. *See also* BRAZING.

Base Materials

Compatibility with base metals is an important factor when considering brazing processes. Some materials are readily brazed in their commercially available state, while others require one or more types of treatment prior to brazing.

Most materials used in the fabrication of assemblies for high-temperature service, such as 18-8 chromium-nickel and the nickel-chromium-cobalt materials, have oxides which are readily reduced by pure dry hydrogen or high-vacuum atmospheres. These materials can be adequately furnace brazed, therefore, without the use of flux and will come out of the furnace bright and clean.

Materials containing more than trace quantities of such elements as aluminum or titanium, if not treated prior to brazing, will form hydrides or oxides not reducible in a pure dry hydrogen atmosphere. With such base metals it is necessary to use a high-vacuum atmosphere in the furnace, or to treat them with a special surface preparation such as nickel plating or acid treatments prior to brazing in a hydrogen atmosphere. Zirconium, selenium and magnesium are other elements which can introduce problems in furnace brazing.

Brazing Stainless Steels

When brazing stainless steels in pure dry hydrogen, an atmosphere in the furnace having a dew point of –40°C (–40°F) or below is required to adequately reduce chromium oxide. Reduction of chromium oxide is necessary to facilitate flow and wetting of the nickel-chromium brazing alloy. The atmosphere requirements of stainless steels cannot be met by a brick-lined furnace, because the refractories or metal oxides will themselves reduce under the brazing conditions required.

Advantages of Furnace Brazing

Furnace brazing as a stainless steel joining process offers a number of specific advantages:

(1) Furnace brazing can be used to simultaneously assemble as many as a thousand joints, depending on size. This means high production and reduced brazing costs.

(2) Distortion can be prevented in the furnace brazing of many assemblies.

(3) Dimensional control and contour stability are much improved in furnace brazing when compared to processes involving localized heating.

(4) Assemblies can be fabricated by furnace brazing that cannot readily be manufactured by other joining methods.

(5) Complex assemblies can be mass produced by furnace brazing without highly skilled personnel.

(6) Furnace brazing has no deteriorating effect on welded areas; it has been used behind a weld to fill the "crack" for positive joint sealing.

(7) Furnace brazing, when used to back up spot welds, improves the fatigue characteristics of the joints.

Furnace Atmospheres for Brazing

Specialized equipment is required for brazing base metal alloys for high-temperature service. This equipment generally includes a tightly sealed container or box, such as a retort furnace, in which pure dry hydrogen and other atmospheres can be maintained. A vacuum atmosphere is one of the modes used for certain applications.

While a pure dry hydrogen atmosphere is the most frequently used for brazing stainless steels, other atmospheres such as dissociated ammonia, argon, helium and vacuum can be used. The dissociated ammonia atmospheres are usually avoided when brazing alloys containing boron are used, because boron is readily nitrided and the brazing alloy will neither melt nor flow.

Argon and helium atmospheres are very compatible with nickel-chromium-boron brazing alloys, because the boron content makes the alloy self-fluxing, resulting in excellent wetting and flow properties. Similarly, at high temperatures, reduction or dissociation of metal oxides actually occurs; this is probably due to the increase in dissociated pressure of the metal oxide.

Joint Design

The lap joint is the most frequently used in the design of brazed joint assemblies. A lap of approximately 4 to 5 times the thinner sheet thickness is generally preferred. Such a joint will seldom fail; rather, any failure in the brazed assembly will occur in the base metal.

Butt joints exhibit higher unit strength than lap joints, but are seldom used in brazed assemblies because of the difficulty in controlling clearance and alignment of adjoining sheet metal thicknesses. Many combination lap-butt joints are successfully brazed, however.

A poor braze is likely to result from a design in which the joint is either totally enclosed or located in a blind hole. Air bubbling through the brazed joint while cooling will cause porosity. In such cases a vent must be left in the chamber to eliminate the pressure and to purge the part if furnace brazing is used.

One important requirement of brazed designs is the need for inspection to assure brazing alloy flow. To provide a means of inspection, holes are incorporated in the back sides of a joint. When one side of the joint is sealed within the assembly, it is a good practice to put the brazing alloy on the inside. This forces the alloy to flow to the outside of the assembly, and permits easy and positive inspection.

When brazing with alloys such as nickel-chromium-boron and other nickel-base brazing alloys, certain characteristics of these brazing materials must be considered in the design of the assembly. The nickel-base brazing alloy is soluble in stainless steel base metals. It will, therefore, readily alloy with the base metal while flowing through the joint. It is this solubility and the resulting alloying action which provides the desired high-temperature strength, but it can cause some difficulties in the brazing operation itself if the assembly is not carefully designed. The primary problem is caused by erosion, which occurs when too much brazing alloy is applied in a single location, or when the brazing alloy flows to the bottom of the joint. The erosion problem is easily solved by providing proper flow paths for the brazing alloy, and by applying the correct quantity of alloy in the correct manner.

The erosion phenomenon is not confined to nickel-base brazing alloys. Aluminum brazing of all kinds, silver brazing of copper, copper brazing of nickel copper, and many others require the same attention to design and the same care in applying the brazing alloy to avoid the erosion problem.

Erosion can generally be avoided by providing a clearance of 0.05 to 0.10 mm (0.002 to 0.004 in.) for a joint of 3.2 mm (1/8 in.) or longer. This clearance allows sufficient time for the alloy to proceed through the joint before it picks up sufficient base metal to bring its melting point above the brazing temperature.

As in all designs, the proof of effectiveness is the service test of the actual part. Service tests of many assemblies brazed with nickel-base alloys indicate excellent performance at operating temperatures as high as 1100 °C (2000 °F).

FURNACE SOLDERING (FS)

A soldering process in which the workpieces are placed in a furnace and heated to the soldering temperature. See STANDARD WELDING TERMS.

There are many applications, especially in high-volume soldering, where furnace soldering produces consistent and satisfactory results. Furnace or oven heating should be considered under the following circumstances:

(1) When entire assemblies can be brought to the soldering temperature without damage to any of the components

(2) When production is sufficiently great to allow expenditure for jigs and fixtures to hold the parts during soldering

(3) When the assembly is complicated, making other heating methods impractical

Proper clamping fixtures are important during oven or furnace soldering. Movement of the joint during solidification of the solder may result in a poor joint.

Furnace or oven soldering is usually carried out with inorganic fluxes because of the temperature and time requirements. The use of a reducing atmosphere in the oven allows joints to be made with less aggressive types of fluxes, depending on the metal and solder combination. The use of inert atmospheres will prevent further oxidation of the parts but still requires adequate and appropriate fluxing.

It is often advantageous to accelerate the cooling of the parts on their removal from the oven. An air blast has been found satisfactory.

Furnaces should be equipped with adequate temperature controls since the flow of solder has an optimum temperature range, depending upon the flux used. The optimum heating condition exists when the heating capacity of the furnace is sufficient to heat the parts rapidly under controlled flux application.

FUSE

Fuse (verb): to melt metal and cause fusion, or amalgamation of sections to be welded. Fuse (noun): A safety device in an electrical circuit to prevent overloading. It consists of a short length of conducting metal which melts at a certain heat and thereby breaks the circuit.

FUSED FLUX, Submerged Arc Welding

A type of granular flux produced by dry mixing the ingredients followed by melting in a furnace. The molten material is cooled to its solid state and processed to produce the desired particle size. See STANDARD WELDING TERMS.

FUSED THERMAL SPRAY DEPOSIT

A self-fluxing thermal spray deposit that is subsequently heated to coalescence within itself and with the substrate. See STANDARD WELDING TERMS.

FUSED ZONE

A nonstandard term for FUSION ZONE.

FUSIBLE PLUG

A plug made of metal or an alloy which closes the discharge channel of a gas cylinder and is designed to melt at a predetermined temperature to permit the escape of gas.

FUSING

A nonstandard term for FUSION.

FUSION, Fusion Welding

The melting together of filler metal and base metal, or of base metal only, to produce a weld. See STANDARD WELDING TERMS. *See* DEPTH OF FUSION.

FUSION FACE

A surface of the base metal that will be melted during welding. See STANDARD WELDING TERMS. *See* Figure D-3.

FUSION LINE

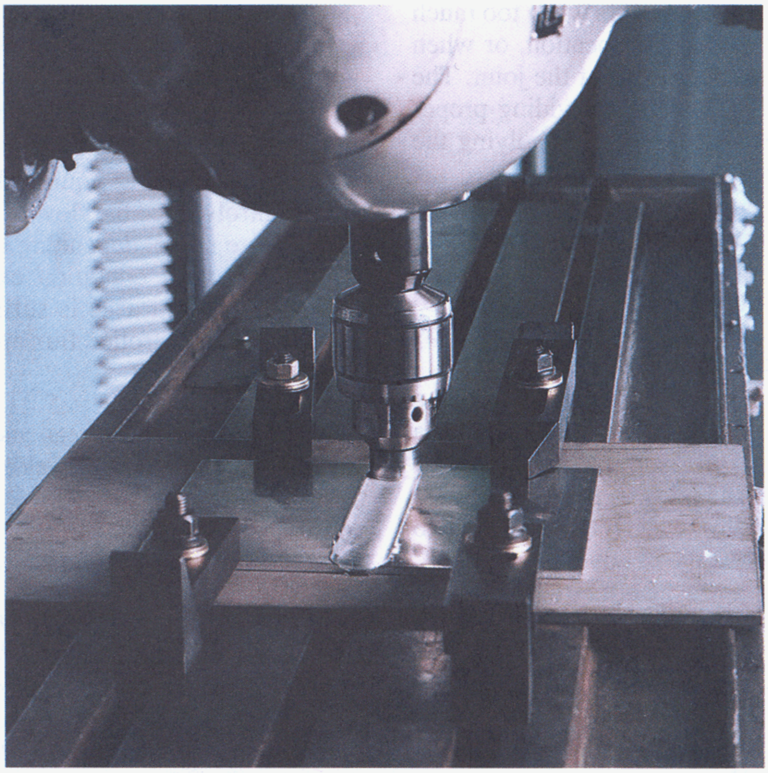
A nonstandard term for WELD INTERFACE.

FUSION WELDING

Any welding process that uses fusion of the base metal to make the weld. See STANDARD WELDING TERMS.

FUSION ZONE

The area of base metal melted as determined on the cross section of a weld. See STANDARD WELDING TERMS. *See* Figure D-3.



Close-up of friction stir welding at Edison Welding Institute

G

G

Symbol for *giga,* a metric system prefix meaning 10^9, or one billion. *See* METRIC SYSTEM.

GAGE

See GAUGE.

GALLING

Adhesion or cohesion of localized areas of two bearing surfaces of metal, followed by the tearing out of small fragments from one or the other of the surfaces when they are separated.

GALLIUM

(Chemical symbol: Ga). A rare metallic element belonging to the aluminum group. It is used in low-melting alloys, and also in semiconductor technology. Like mercury, gallium can be a liquid at room temperature. Atomic number, 31; atomic weight 69.72; melting point, 30.1 °C (86.2°F); specific gravity, 5.94 at 22°C (72°F).

GALVANI

(1737–1798) An Italian physician and physicist, the discoverer of galvanism, an electrical current produced by chemical action.

GALVANIZE

To coat a metal with zinc to increase resistance to corrosion. The following processes are used to apply a coating of zinc to iron or steel:

(1) Hot-dip galvanizing (dipping in molten zinc)
(2) Metallizing (spraying with molten zinc)
(3) Painting with zinc-rich paint
(4) Zinc plating (electro-galvanizing)
(5) Sherardization (heating with zinc dust in a rotation furnace)

GALVANIZED IRON, WELDING

Galvanized iron, whether in pipe, sheet or other form, is iron or steel coated with zinc to protect it from corrosion. After cleaning, the workpiece is dipped in a galvanizing tank containing molten zinc.

Gas Welding. Zinc has a melting point of about 420°C (786°F), and will volatilize when heated to about 930°C (1700°F). If galvanized iron parts are welded with steel welding rods or electrodes, the zinc coating is heated to the melting temperature of steel, about 1510°C (2750°F), and is burned away in the path of the weld, forming clouds of white zinc oxide. The zinc oxide smoke produced when zinc volatilizes is harmful to the welder. Alternatively, bronze melts at about 885°C (1625°F), below the volatilization point of the zinc; and when a bronze rod is carefully used with the oxyacetylene process, no fumes result.

Galvanized sheets or pipes should generally be bronze welded with Tobin bronze, or manganese bronze, or a high-strength bronze rod if an oxyacetylene torch is used. The zinc coating alloys with the bronze rod and spreads on each side of the joined edges, serving as a protective agent and leaving no bare steel for exposure to corrosion.

A good way to protect the galvanizing on the underside of the sheets is to make a paste of flux and water and paint it on the underside of the sheets with a paint brush. This flux coating prevents the hot sheet from exposure to the oxygen in the surrounding air, and avoids oxidation. The flux paste may also be painted on the upper side from which the seam is welded. Another way to apply flux is to heat the welding rod and dip it into the flux box, and the flux will cling to it.

The seam should be a butt seam, and the sheets should be held in a jig during welding. When correctly done, the bronze will appear on the lower side of the seam.

Galvanized pipe is easily brazed, using bronze rods and a brazing flux. The pipe is beveled to an angle of at least 30°, and if cut with a cutting torch, all oxide should be removed.

If Tobin or manganese bronze rods are used, the torch flame may be adjusted for a slight excess of acetylene, or it may be neutral. However, with some bronze rods, manufacturers recommend a slightly oxidizing flame. Specific rods will often require varying flame adjustments and techniques.

GAMMA IRON

A crystal form of iron, the atoms of which are arranged in the face-centered cubic lattice. Gamma iron dissolves carbon; its grain size depends on temperature, time and degree of working; it is non-magnetic. Gamma iron is denser than alpha iron.

GAMMA RAY INSPECTION OF WELDS

A nondestructive method of testing welds using gamma waves emitted by radio isotopes to produce radiographs. *See* RADIOGRAPHIC EXAMINATION.

GAP

A nonstandard term when used for ARC LENGTH, JOINT CLEARANCE, and ROOT OPENING.

GAS BACKUP

A term for protecting the back side of a weldment using an inert gas. Argon and helium are satisfactory for the gas backup purge when welding all materials. Nitrogen may be used satisfactorily for welds in austenitic steels, copper and copper alloys.

GAS BRAZING

A nonstandard term for TORCH BRAZING.

GAS CARBON ARC WELDING (CAW-G)

A carbon arc welding process variation that uses a shielding gas. This is an obsolete or seldom used process. See STANDARD WELDING TERMS.

GAS CUP

A nonstandard term for GAS NOZZLE.

GAS CUTTER

A nonstandard term for OXYGEN CUTTER. *See also* THERMAL CUTTER.

GAS CUTTING

A nonstandard term for OXYGEN CUTTING.

GAS CYLINDER

A portable container used for transportation and storage of compressed gas. See STANDARD WELDING TERMS.

GAS, Safe Practices

Oxygen. Oxygen is nonflammable but it supports the combustion of flammable materials. It can initiate combustion and vigorously accelerate it. Therefore, oxygen cylinders and liquid oxygen containers should not be stored in the vicinity of combustibles or with cylinders of fuel gas. Oxygen should never be used as a substitute for compressed air, for example, to power compressed air tools, because they are almost always lubricated with oil.

It is very dangerous to use oil or grease on oxygen cylinders or regulators because contact with oxygen causes oil and grease to ignite spontaneously. It is a dangerous practice to use or store oxygen cylinders where oil and oxygen will be brought together. Also, it is dangerous to attempt to use cylinders which have contained petroleum products for oxygen, because they will contain a certain amount of residual oily deposit. Only apparatus that has been manufactured expressly for oxygen service should be used, and manufacturers specifications should be followed.

Fuel gases commonly used in oxyfuel gas welding and cutting are acetylene, methyl acetylene-propadiene (MPS), natural gas, propane and propylene. Hydrogen is used in a few applications. Gasolene is sometimes used as fuel for oxygen cutting. These gases should always be referred to by the correct name.

Acetylene. Acetylene cylinders must be handled carefully. They should never be used at pressures over 100 kPa (15 psi). If heated, the gas in the cylinder could become unstable; if shocked, an explosion could occur.

As a safety measure, the cylinders are equipped with fusible safety plugs that melt at 99°C (210°F). Therefore, if acetylene cylinders are in a fire, the safety plugs should vent the internal pressure rather than let the pressure build up and cause an explosion.

Acetylene and MPS should never be used in contact with silver, mercury, or alloys containing 70% or more copper. These gases react with these metals to form unstable compounds that may detonate under shock or heat. Valves on fuel gas cylinders should never be opened to clean the valve outlet, especially not near possible sources of flame ignition or in confined spaces.

When fuel gases are used for a brazing furnace atmosphere, they must be burned or vented to a safe location. Prior to filling a furnace or retort with fuel gas, the equipment must first be purged with a nonflammable gas, such as nitrogen or argon, to prevent formation of an explosive air-fuel mixture.

Special attention must be given when using hydrogen. Flames of hydrogen may be difficult to see and parts of the body, clothes, or combustibles may come in contact with hydrogen flames without the operator's knowledge.

Shielding Gases. Argon, helium, nitrogen, and carbon dioxide (CO_2) are used for shielding with some welding processes. All, except CO_2, are used as brazing atmospheres. They are odorless and colorless and are hazardous because they can displace air needed for breathing.

Confined spaces filled with these gases must be well ventilated before personnel enter them. If there is any question, the space should be checked first for adequate oxygen concentration with an oxygen analyzer. If an analyzer is not available, an air-supplied respirator should be worn by anyone entering the space. Containers of these gases should not be stored in confined places.

GASES FOR SHIELDING

See SHIELDING GAS.

GAS FLOW RATE

The measure in liters per minute (cubic feet per hour) of the flow of shielding gas in gas metal arc welding, gas tungsten arc welding, and other processes.

GAS GOUGING

A nonstandard term for OXYGEN GOUGING.

GAS HAZARDS

Gases can be explosive, toxic, corrosive, and asphyxiating. For safe handling and use, refer to the specific gas; also refer to the manufacturer's Materials Safety Data Sheets. *See* GAS, Safe Practices; *see also* Appendix 12.

GAS HOSE

Flexible tubing used to convey gas from a regulator to the welding or cutting equipment. *See* HOSE, Welding.

GAS LASER

A laser in which the lasing medium is a gas. See STANDARD WELDING TERMS.

GAS LENS

One or more fine mesh screens located in the torch nozzle to produce a stable stream of shielding gas. Primarily used for gas tungsten arc welding. See STANDARD WELDING TERMS.

GAS METAL ARC CUTTING (GMAC)

An arc cutting process that uses a continuous consumable electrode and a shielding gas. See STANDARD WELDING TERMS. This is an obsolete process.

Gas metal arc cutting was developed soon after the commercial introduction of the gas metal arc welding process. Gas metal arc cutting first occurred accidentally during a welding operation, when it was found that if the electrode feed rate was set too high, it would penetrate through the plate. When the torch was moved, a cut was made. GMAC is used to cut shapes in stainless steel and aluminum. Using gas metal arc welding equipment and a 2.4 mm (3/32 in.) diameter electrode, stainless steel up to 38 mm (1-1/2 in.) thick, and aluminum up to 75 mm (3 in.) thick can be cut.

The chief limitations to GMAC are the high consumption of welding electrodes and the high currents (up to 2000 amperes) required for cutting.

GAS METAL ARC SPOT WELDING

Gas metal arc spot welding is a variation of continuous GMAW, in which two pieces of sheet metal are fused together by penetrating entirely through one piece into the other. The process has been used for joining light-gauge materials, up to approximately 5 mm (3/16 in.) thick. No joint preparation is required other than cleaning the overlapping areas. Heavier sections can also be spot welded with this technique by drilling or punching a hole in the upper piece, through which the arc is directed for joining to the underlying piece. This is called a *plug weld.* A comparison between a gas metal arc spot weld and a resistance spot weld is shown in Figure G-1.

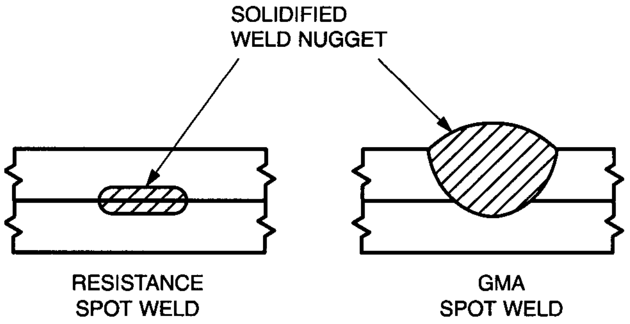


Figure G-1—Comparison of a Resistance Spot Weld with a Gas Metal Arc Spot Weld

GAS METAL ARC WELDING (GMAW)

An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of pressure. See STANDARD WELDING TERMS. *See also* PULSED GAS

METAL ARC WELDING *and* SHORT CIRCUIT GAS METAL ARC WELDING.

The basic concept of GMAW was introduced in the 1920s, but it was not until 1948 that it was made commercially available. At first it was considered to be fundamentally a high current density, small diameter, bare-metal electrode process using an inert gas for arc shielding. Its primary application was for welding aluminum. As a result, the term MIG (Metal Inert Gas) was used to describe the process and is still a common reference. The term MIG has been superseded by GMAW.

Subsequent process developments included operation at low-current densities and pulsed direct current, application to a broader range of materials, and the use of reactive gases (particularly CO_2) and gas mixtures. This latter development has led to the formal acceptance of the term *gas metal arc welding* (GMAW) for the process, because both inert and reactive gases are used.

A variation of the GMAW process uses a tubular electrode in which metallic powders make up the bulk of the core materials (metal cored electrode). Such electrodes require a gas shield to protect the molten weld pool from atmospheric contamination.

Metal cored electrodes are considered a segment of GMAW by the American Welding Society. Foreign welding associations may group metal cored electrodes with flux cored electrodes.

GMAW may be operated in semiautomatic, machine, or automatic modes. All commercially important metals such as carbon steel, high-strength, low-alloy steel, stainless steel, aluminum, copper, titanium, and nickel alloys can be welded in all positions with this process by choosing the appropriate shielding gas, electrode, and welding variables.

In addition to joining, the GMAW process is widely used for surfacing where an overlay weld deposit may provide desirable wear or corrosion resistance or other properties. Overlays are normally applied to carbon or manganese steels and must be carefully engineered and evaluated to assure satisfactory results.

Uses and Advantages

The uses of the process are, of course, dictated by its advantages, the most important of which are the following:

(1) It is the only consumable electrode process that can be used to weld all commercial metals and alloys.

(2) GMAW overcomes the restriction of limited electrode length encountered with shielded metal arc welding.

(3) Welding can be done in all positions, a feature not found in submerged arc welding.

(4) Deposition rates are significantly higher than those obtained with shielded metal arc welding.

(5) Welding speeds are higher than those with shielded metal arc welding because of the continuous electrode feed and higher filler metal deposition rates.

(6) Because the wire feed is continuous, long welds can be deposited without stops and starts.

(7) When spray transfer is used, deeper penetration is possible than with shielded metal arc welding, which may permit the use of smaller size fillet welds for equivalent strengths.

(8) Minimal postweld cleaning is required due to the absence of a heavy slag.

These advantages make the process particularly well suited to high production and automated welding applications. This has become increasingly evident with the advent of robotics, where GMAW has been the predominant process choice.

Limitations

As with any welding process, there are certain limitations which restrict the use of gas metal arc welding. Some of these are the following:

(1) The welding equipment is more complex, more costly, and less portable than that for SMAW.

(2) GMAW is more difficult to use in hard-to-reach places because the welding gun is larger than a shielded metal arc welding holder, and the welding gun must be close to the joint, between 10 and 20 mm (3/8 and 3/4 in.), to ensure that the weld metal is properly shielded.

(3) The welding arc must be protected against air drafts that will disperse the shielding gas. This limits outdoor applications unless protective shields are placed around the welding area.

(4) Relatively high levels of radiated heat and arc intensity can result in operator resistance to the process.

Fundamentals of the Process

The GMAW process incorporates the automatic feeding of a continuous, consumable electrode that is shielded by an externally supplied gas. The process is illustrated in Figure G-2. After initial settings by the operator, the equipment provides for automatic self-regulation of the electrical characteristics of the arc. Therefore, the only manual controls required by the

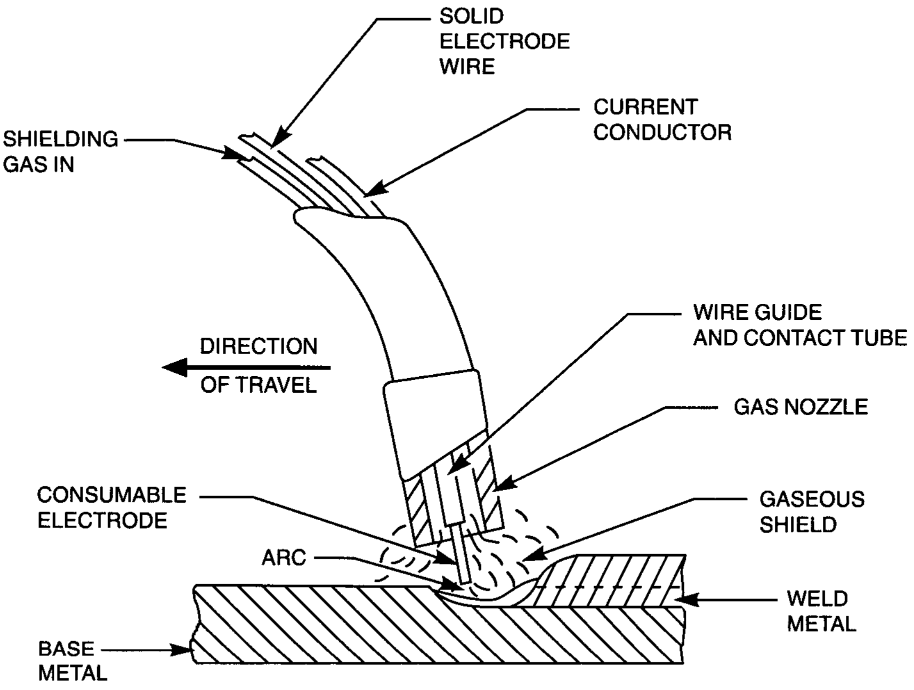


Figure G-2—Gas Metal Arc Welding Process

welder for semiautomatic operation are the travel speed and direction, and gun positioning. Given proper equipment and settings, the arc length and the current (wire feed speed) are automatically maintained.

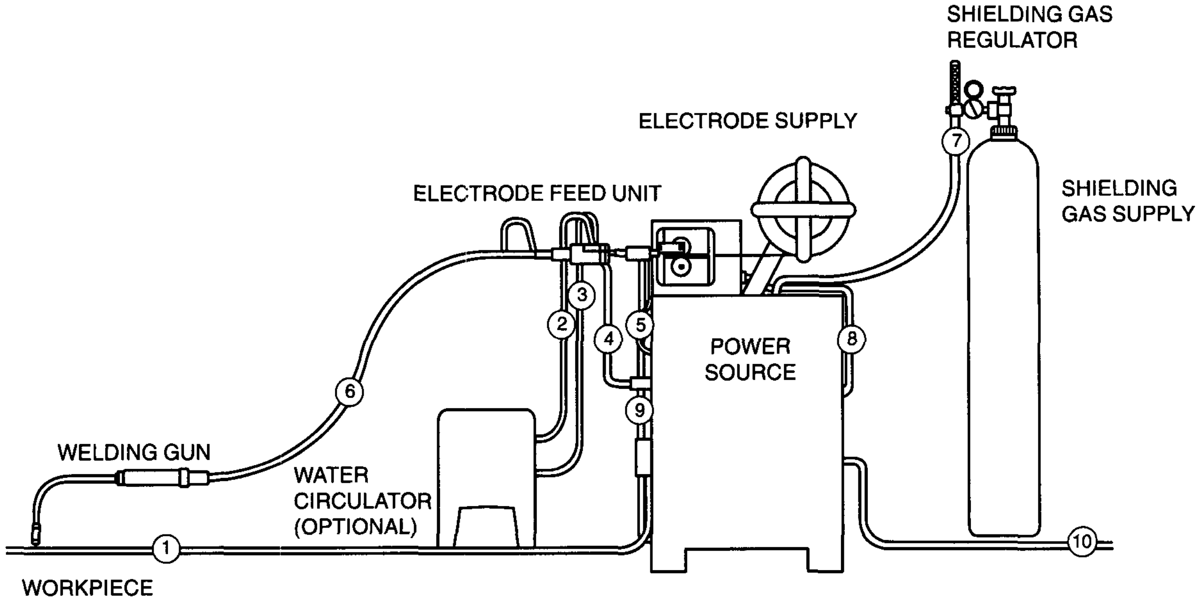
Equipment

Equipment required for GMAW is shown in Figure G-3. The basic equipment components are the welding gun and cable assembly, electrode feed unit, power supply, and source of shielding gas.

The gun guides the consumable electrode and conducts the electric current and shielding gas to the work, thus providing the energy to establish and maintain the arc and melt the electrode, as well as the needed protection from the ambient atmosphere. Two combinations of electrode feed units and power supplies are used to achieve the desirable self-regulation of arc length. Most commonly this regulation consists of a constant-potential (CP) power supply (characteristically providing an essentially flat volt-ampere curve) in conjunction with a constant-speed electrode feed unit. Alternatively, a constant-current power supply provides a drooping volt-ampere curve, and the electrode feed unit is arc-voltage controlled.

With the constant-potential/constant wire feed combination, changes in the torch position cause a change in the welding current that exactly matches the change in the electrode stick-out (electrode extension), thus the arc length remains fixed. For example, an increased stick-out produced by withdrawing the torch reduces the current output from the power supply, thereby maintaining the same resistance heating of the electrode.

In the alternative system, self-regulation results when arc voltage fluctuations readjust the control circuits of the feeder, which appropriately changes the wire feed speed. In some cases (when welding aluminum, for example), it may be preferable to deviate from these standard combinations and utilize a constant-current power source with a constant-speed electrode feed unit. This combination provides only a small degree of automatic self-regulation, and therefore requires more operator skill for semiautomatic welding. However, some users think this combination affords a range of control over the arc energy (current)



① WORK LEAD
② WATER TO GUN
③ WATER FROM GUN
④ GUN SWITCH CIRCUIT
⑤ SHIELDING GAS TO GUN
⑥ CABLE ASSEMBLY
⑦ SHIELDING GAS FROM CYLINDER
⑧ WELDING CONTACTOR CONTROL
⑨ POWER CABLE
⑩ PRIMARY INPUT POWER

Figure G-3—Gas Metal Arc Equipment

that may be important in coping with the high thermal conductivity of aluminum base metals.

Slope. The static volt-ampere characteristic (static output) of a CP power source is illustrated in Figure G-4. The slope of the output is the algebraic slope of the volt ampere curve and is customarily given as the voltage drop per 100 amperes of current rise.

Slope has a major function in the short circuiting transfer mode of GMAW in that it controls the magnitude of the short circuit current, which is the amperage that flows when the electrode is shorted to the workpiece. In GMAW, the separation of molten drops of metal from the electrode is controlled by an electrical phenomenon called the *electromagnetic pinch effect.* Pinch is the magnetic "squeezing" force on a conductor produced by the current flowing through it. For short circuiting transfer, the effect is illustrated in Figure G-5.

In short circuiting transfer the amount of short circuit current is important since the resultant pinch effect determines the way a molten drop detaches from the electrode. This in turn affects the arc stability. When little or no slope is present in the power supply circuit, the short circuit current will rise rapidly to a

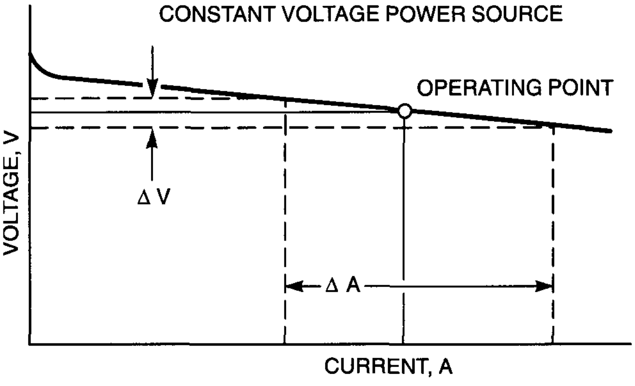


Figure G-4—Static Volt-Ampere Output Curve of a Constant Potential Power Supply

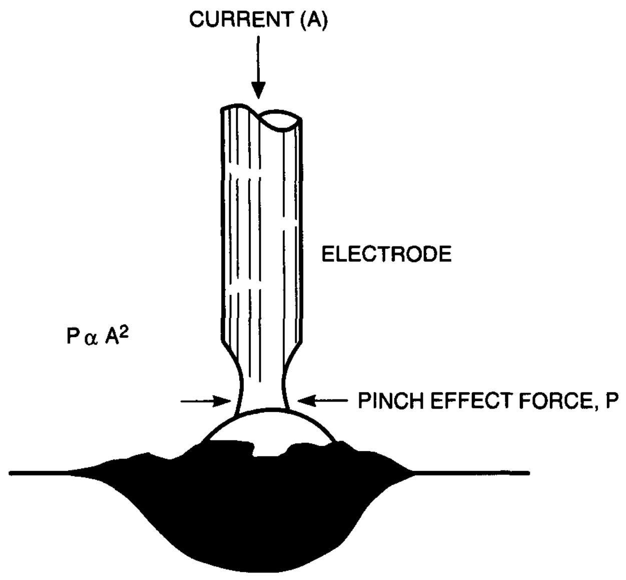


Figure G-5—Short Circuiting Transfer Caused by the Electromagnetic Pinch Effect

high level. The pinch effect will also be high, and the molten drop will separate violently from the wire. The excessive pinch effect will abruptly squeeze the metal aside, clear the short circuit, and create excessive spatter.

Inductance. When the electrode shorts to the work, the current increases rapidly to a higher level. The circuit characteristic affecting the time rate of this increase in current is inductance, usually measured in henrys. The effect of inductance is illustrated by the curves plotted in Figure G-6. Curve A is an example of a current-time curve immediately after a short circuit when some inductance is in the circuit. Curve B illustrates the path the current would have taken if there were no inductance in the circuit.

The maximum amount of pinch effect is determined by the final short circuit current level. The instantaneous pinch effect is controlled by the instantaneous current, and therefore the shape of the current-time curve is significant. The inductance in the circuit controls the rate of current rise. Without inductance the pinch effect is applied rapidly and the molten drop will be violently "squeezed" off the electrode and cause excessive spatter. Higher inductance results in a decrease in the short circuits per second and an increase in the "arc-on" time. Increased arc-on time makes the puddle more fluid and results in a flatter, smoother weld bead.

In spray transfer, the addition of some inductance to the power source will produce a softer arc start without affecting the steady-state welding conditions. Power source adjustments required for minimum spatter conditions vary with the electrode material and diameter. As a general rule, higher short circuit currents and higher inductance are needed for larger diameter electrodes.

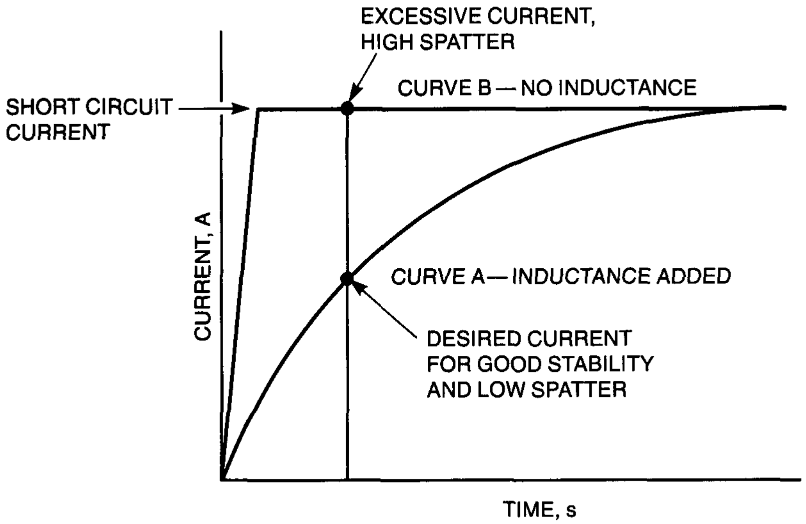


Figure G-6—Effect of Inductance in a GMAW Circuit

Power sources are available with fixed, stepped, or continuously adjustable inductance levels.

Metal Transfer Mechanisms

The characteristics of the GMAW process are best described in terms of the three basic means by which metal is transferred from the electrode to the work:

(1) Short circuiting transfer
(2) Globular transfer
(3) Spray transfer

The type of transfer is determined by a number of factors, the most influential of which are the following:

(1) Magnitude and type of welding current
(2) Electrode diameter
(3) Electrode composition
(4) Electrode extension
(5) Shielding gas

Process Variables

The following are some of the variables that affect weld penetration, bead geometry, and overall weld quality:

(1) Welding current (electrode feed speed)
(2) Polarity (DCEN or DCEP)
(3) Arc voltage (arc length)
(4) Travel speed
(5) Electrode extension (stick-out)
(6) Electrode orientation (trail or lead angle)
(7) Weld joint position
(8) Electrode diameter
(9) Shielding gas composition and flow rate

Knowledge and control of these variables is essential to produce welds of satisfactory quality consistently. These variables are not completely independent, and changing one generally requires changing one or more of the others to produce the desired results. Considerable skill and experience are needed to select optimum settings for each application. The optimum values are affected by (1) type of base metal, (2) electrode composition, (3) welding position, and (4) quality requirements. Thus, there is no single set of parameters that gives optimum results in every case.

Welding Current

When all other variables are held constant, the welding amperage varies with the electrode feed speed or melting rate in a nonlinear relation. As the electrode feed speed is varied, the welding amperage will vary in a like manner if a constant-voltage power source is used. This relationship of welding current to wire feed speed for carbon steel electrodes is shown in Figure G-7.

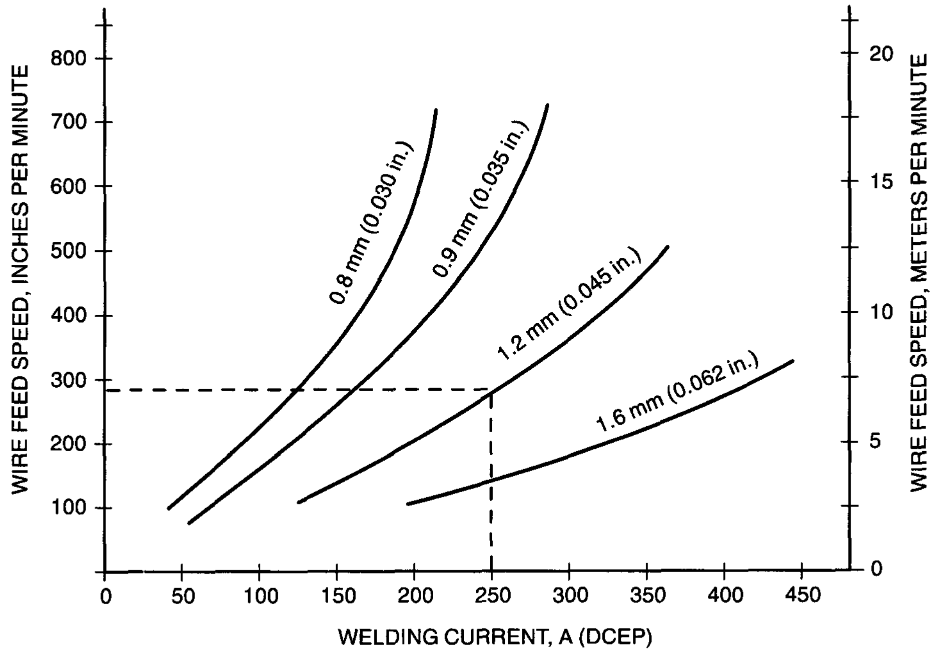


Figure G-7—Welding Current as a Function of Wire Feed Speed for Various Diameters of Carbon Steel Wires

At the low-current levels for each electrode size, the curve is nearly linear. However, at higher welding currents, particularly with small diameter electrodes, the curves become nonlinear, progressively increasing at a higher rate as welding amperage increases. This is attributed to resistance heating of the electrode extension beyond the contact tube.

With all other variables held constant, an increase in welding current (electrode feed speed) will result in the following:

(1) An increase in the depth and width of the weld penetration

(2) An increase in the deposition rate

(3) An increase in the size of the weld bead

Pulsed spray welding is a variation of the GMAW process in which the current is pulsed to obtain the advantages of the spray mode of metal transfer at average currents equal to or less than the globular-to-spray transition current.

Since arc force and deposition rate are exponentially dependent on current, operation above the transition current often makes the arc forces uncontrollable in the vertical and overhead positions. By reducing the average current with pulsing, the arc force and deposition rates can both be reduced, allowing welds to be made in all positions and in thin sections.

With solid wires, another advantage of pulsed power welding is that larger diameter wires, i.e., 1.6 mm (1/16 in.) can be used. Although deposition rates are generally no greater than those with smaller diameter wires, the advantage is in the lower cost per unit of metal deposited. There is also an increase in deposition efficiency because of reduced spatter loss.

With metal cored wires, pulsed power produces an arc that is less sensitive to changes in electrode extension (stickout) and voltage compared to solid wires. Thus, the process is more tolerant of operator guidance fluctuations. Pulsed power also minimizes spatter from an operation already low in spatter generation.

Polarity

The term *polarity* is used to describe the electrical connection of the welding gun with relation to the terminals of a direct current power source. When the gun power lead is connected to the positive terminal, the polarity is designated as direct current electrode positive (DCEP), arbitrarily called *reverse polarity.* When the gun is connected to the negative terminal, the polarity is designated as direct current electrode negative (DCEN), originally called *straight polarity.* The vast majority of GMAW applications use direct current electrode positive (DCEP). This condition yields a stable arc, smooth metal transfer, relatively low spatter, good weld bead characteristics, and greatest depth of penetration for a wide range of welding currents.

Direct current electrode negative (DCEN) is seldom used because axial spray transfer is not possible without modifications that have had little commercial acceptance. DCEN has a distinct advantage of high melting rates that cannot be exploited because the transfer is globular. With steels, the transfer can be improved by adding a minimum of 5% oxygen to the argon shield (requiring special alloys to compensate for oxidation losses) or by treating the wire to make it thermionic (adding to the cost of the filler metal). In both cases, the deposition rates drop, eliminating the only real advantage of changing polarity. However, because of the high deposition rate and reduced penetration, DCEN has found some use in surfacing applications.

Attempts to use alternating current with the GMAW process have generally been unsuccessful. The cyclic wave form creates arc instability due to the tendency of the arc to extinguish as the current passes through the zero point. Although special wire surface treatments have been developed to overcome this problem, the expense of applying them has made the technique uneconomical.

Arc Voltage (Arc Length)

Arc voltage and *arc length* are terms that are often used interchangeably. It should be pointed out, however, that they are different even though they are related. With GMAW, arc length is a critical variable that must be carefully controlled. For example, in the spray-arc mode with argon shielding, an arc that is too short experiences momentary short circuits. They cause pressure fluctuations which pump air into the arc stream, producing porosity or embrittlement due to absorbed nitrogen. Should the arc be too long, it tends to wander, affecting both the penetration and surface bead profiles. A long arc can also disrupt the gas shield.

With all variables held constant, arc voltage is directly related to arc length. Even though the arc length is the variable of interest and the variable that should be controlled, the voltage is more easily monitored. Because of this, and the normal requirement that the arc voltage be specified in the welding procedure, it is the term that is more commonly used. *See* Appendix 10.

Electrode Extension

The electrode extension is the distance between the end of the contact tube and the end of the electrode, as shown in Appendix 10. An increase in the electrode extension results in an increase in its electrical resistance. Resistance heating in turn causes the electrode temperature to rise, and results in a small increase in electrode melting rate. Overall, the increased electrical resistance produces a greater voltage drop from the contact tube to the work. This is sensed by the power source, which compensates by decreasing the current. That immediately reduces the electrode melting rate, which then lets the electrode shorten the physical arc length. Thus, unless there is an increase in the voltage at the welding machine, the filler metal will be deposited as a narrow, high-crowned weld bead.

The desirable electrode extension is generally from 6 to 12 mm (1/4 to 1/2 in.) for short circuiting transfer and from 12 to 25 mm (1/2 to 1 in.) for other types of metal transfer.

Weld Joint Position

Most spray type GMAW is done in the flat or horizontal positions, while at low-energy levels, pulsed and short circuiting GMAW can be used in all positions. Fillet welds made in the flat position with spray transfer are usually more uniform, less likely to have unequal legs and convex profiles, and are less susceptible to undercutting than similar fillet welds made in the horizontal position.

To overcome the pull of gravity on the weld metal in the vertical and overhead positions of welding, small diameter electrodes are usually used, with either short circuiting metal transfer or spray transfer with pulsed direct current. Electrode diameters of 1.1 mm (0.045 in.) and smaller are best suited for out-of-position welding. The low-heat input allows the molten pool to freeze quickly. Downward welding progression is usually effective on sheet metal in the vertical position.

When welding is done in the flat position, the inclination of the weld axis with respect to the horizontal plane will influence the weld bead shape, penetration, and travel speed. In flat position circumferential welding, the work rotates under the welding gun and inclination is obtained by moving the welding gun in either direction from top dead center.

Consumables

In addition to equipment components, such as contact tips and conduit liners that wear out and have to be replaced, the process consumables in GMAW are electrodes and shielding gases. The chemical composition of the electrode, the base metal, and the shielding gas determine the weld metal chemical composition. This weld metal composition, in turn, largely determines the chemical and mechanical properties of the weldment. The following are factors that influence the selection of the shielding gas and the welding electrode:

(1) Base metal

(2) Required weld metal mechanical properties

(3) Base metal condition and cleanliness

(4) Type of service or applicable specification requirement

(5) Welding position

(6) Intended mode of metal transfer

Electrodes

The electrodes (filler metals) for gas metal arc welding are covered by various AWS filler metal specifications. Other standards writing societies also publish filler metal specifications for specific applications. For example, the Aerospace Materials Specifications are written by SAE, and are intended for aerospace applications. The AWS specifications, designated as A5.XX standards, and a listing of GMAW electrode specifications are shown in Table G-1. They define requirements for sizes and tolerances, packaging, chemical composition, and sometimes mechanical properties. The AWS also publishes *Filler Metal Comparison Charts,* in which manufacturers may show their trade name for each of the filler metal classifications.

Table G-1
Specifications for Various GMAW Electrodes

Base Material Type	AWS Specification
Carbon Steel	A5.18
Low Alloy Steel	A5.28
Aluminum Alloys	A5.10
Copper Alloys	A5.7
Magnesium	A5.19
Nickel Alloys	A5.14
300 Series Stainless Steel	A5.9
400 Series Stainless Steel	A5.9
Titanium	A5.16

Shielding Gases

The primary function of the shielding gas is to exclude the atmosphere from contact with the molten weld metal. This is necessary because most metals, when heated to their melting point in air, exhibit a strong tendency to form oxides and, to a lesser extent, nitrides. Oxygen will also react with carbon in molten steel to form carbon monoxide and carbon dioxide. These varied reaction products may result in weld deficiencies, such as trapped slag, porosity, and weld metal embrittlement. Reaction products are easily formed in the atmosphere unless precautions are taken to exclude nitrogen and oxygen.

In addition to providing a protective environment, the shielding gas and flow rate also have a pronounced effect on the following:

(1) Arc characteristics
(2) Mode of metal transfer
(3) Penetration and weld bead profile
(4) Speed of welding
(5) Undercutting tendency
(6) Cleaning action
(7) Weld metal mechanical properties

Reference: American Welding Society. *Welding Handbook*, 8th Edition, Vol. 2, Welding Processes. Miami, Florida: American Welding Society, 1991.

GAS MIXTURES

Combining gases to utilize the best features of the component gases. Some of the gases may be chemically inert, others can be reactive. *See* SHIELDING GAS, or the specific gas by name.

GAS NOZZLE

A device at the exit end of the torch or gun that directs shielding gas. See STANDARD WELDING TERMS. *See* Appendix 10.

GASOLINE TANK WELDING

See TANKS, Safe Practices.

GAS POCKET

A nonstandard term for POROSITY.

GAS PREFLOW

Starting the flow of the shielding gas prior to arc ignition. Selection of the preflow technique and the duration of the preflow depend on the specific welding conditions and materials. Gas preflow can improve weld quality. *See* SHIELDING GAS.

GAS PRESSURE

Gas pressure can be expressed as *gauge pressure,* the pressure above atmospheric pressure, or as *absolute pressure,* the gauge pressure plus the atmospheric pressure. For welding applications, pressure is measured in kilopascals, (kPa) or in pounds force per square inch, (psi).

GAS PRESSURE WELDING

See PRESSURE GAS WELDING.

GAS REGULATOR

A device for controlling the delivery of gas at some substantially constant pressure. See STANDARD WELDING TERMS. *See* REGULATOR.

GAS SAVER

A double-valve device used in oxyacetylene welding which turns off both oxygen and acetylene simultaneously when the torch is hung on a hook lever. When the torch is removed from the lever both gases are turned on as originally adjusted, and relighted by a pilot light.

GAS SHIELDED ARC WELDING

A group of processes including ELECTROGAS WELDING, FLUX CORED ARC WELDING, GAS METAL ARC WELDING, GAS TUNGSTEN ARC WELDING, and PLASMA ARC WELDING. See STANDARD WELDING TERMS.

GAS SHIELDED FLUX CORED ARC WELDING (FCAW-G)

A flux cored arc welding process variation in which shielding gas is supplied through the gas nozzle, in addition to that obtained from the flux within the electrode. See STANDARD WELDING TERMS.

GAS SHIELDING

See SHIELDING GAS.

GAS SYSTEMS

Gas piping systems for welding and cutting should be manufactured and installed in accordance with National Fire Protection Association (NFPA) standards, such as NFPA 51 *Oxygen-Fuel Gas Systems for Welding and Cutting*, and NFPA 50 *Bulk Oxygen System at Consumer Sites.* Other standards that should be consulted are Compressed Gas Association (CGA) CGA E-1 *Regulator Connection Standards* and CGA E-2 *Standard Hose Connection Specification.* In addition, refer to American National Standards Institute (ANSI) standard ANSI Z49.1 *Safety in Welding, Cut-*

ting and Allied Processes for safe practices in the use of gases when welding and cutting.

GAS TORCH

A nonstandard term for WELDING TORCH and CUTTING TORCH.

GAS TUNGSTEN ARC CUTTING (GTAC)

An arc cutting process that uses a single tungsten electrode with gas shielding. See STANDARD WELDING TERMS.

This process used a standard GTAW torch with a small diameter shielding cup, high arc current, DCEN, and gas flow rates in the range of 25 L/min (50 ft^3/h) to sever metals. It is generally considered a temporary procedure.

Principles of Operation

Gas tungsten arc cutting can be used to sever nonferrous metals and stainless steel in thicknesses up to 1/2 in. using standard gas tungsten arc welding equipment. Metals cut include aluminum, magnesium, copper, silicon-bronze, nickel, copper-nickel, and various types of stainless steels. This cutting process can be used either manually or mechanized. The same electric circuit is used for cutting as for welding. Higher current is required to cut a given thickness of plate than to weld it. An increased gas flow is also required to melt through and sever the plate.

In practice, a 4 mm (5/32 in.) diameter, 2% thoriated tungsten electrode is extended approximately 6 mm (1/4 in.) beyond the end of a 9.5 mm (3/8 in.) diameter metallic or ceramic gas cup. A mixture of approximately 65% argon and 35% hydrogen is delivered to the torch at a flow rate of 30 L/min (60 ft^3/h). Nitrogen can also be used, but the quality of the cut is not as good as that obtained with an argon-hydrogen mixture. Best cutting results are obtained using DCSP, but alternating current with superimposed high frequency has produced satisfactory cuts on material up to 6 mm (1/4 in.) thick.

Arc starting can be accomplished with either a high-frequency spark or by scratching the electrode on the workpiece. An electrode-to-work distance of 1.6 to 3.2 mm (1/16 to 1/8 in.) is used, but this is not a critical factor. As the torch is moved over the plate, a small section of the plate is melted by the heat of the arc and the molten metal is blown away by the gas stream to form the kerf. At the end of the cut, the torch is raised from the workpiece to break the arc.

One face of the cut is usually dross-free, with dross adhering to the side of the workpiece away from the work lead. The cut quality on the dross-free side is usually acceptable while the other requires considerable cleanup.

Equipment

Standard gas tungsten arc welding torches can be used for cutting. Cutting currents up to 600 amperes are used. Welding torches can be used for cutting at currents up to 175% of their nominal ratings because there is little reflected heat from the cutting operation. For example, a 300-ampere torch can be used for cutting with 500 amperes for short periods.

A constant-current d-c power supply with a minimum open circuit voltage of 70 V is recommended for cutting. Cuts made with a-c power have a plate thickness limitation of 6 mm (1/4 in.). The major difficulty encountered when using a-c power is the loss of tungsten from the electrode at the high currents required.

GAS TUNGSTEN ARC CUTTING TORCH

A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of shielding gas. See STANDARD WELDING TERMS.

GAS TUNGSTEN ARC WELDING (GTAW)

An arc welding process that uses an arc between a tungsten electrode (nonconsumable) and the weld pool. The process is used with shielding gas and without the application of pressure. See STANDARD WELDING TERMS. *See also* HOT WIRE WELDING *and* PULSED GAS TUNGSTEN ARC WELDING.

Gas tungsten arc welding (GTAW) may be used with or without the addition of filler metal. Figure G-8 shows the gas tungsten arc welding process.

GTAW has become indispensable as a tool for many industries because of the high-quality welds produced and low equipment costs. The following information presents the fundamentals of the GTAW process, the equipment and consumables used, the process procedures and variables, applications, and safety considerations.

Historical Background

The possibility of using helium to shield a welding arc and molten weld pool was first investigated in the 1920s[1]. However, little was done with this method until the beginning of World War II, when a great need

---

[1] M. Hobart U.S. Patent 1,746,081, 1926 and P. K. Devers U.S. patent 1,746,191, 1926.

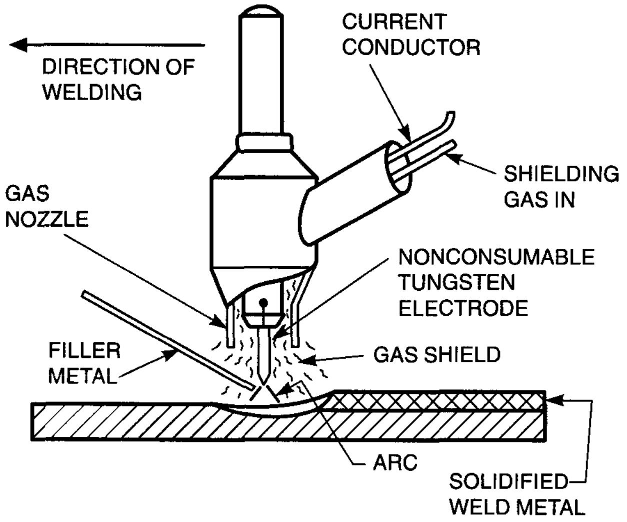


Figure G-8—Schematic View of the Gas Tungsten Arc Welding Operation

developed in the aircraft industry to replace riveting for joining reactive materials such as aluminum and magnesium. Using a tungsten electrode and direct current arc power with the electrode negative, a stable, efficient heat source was produced with which excellent welds could be made[2].

Since the early days of the invention, numerous improvements have been made to the process and equipment. Welding power sources have been developed specifically for the process. Some provide pulsed dc and variable-polarity a-c welding power. Water-cooled and gas-cooled torches were developed. The tungsten electrode has been alloyed with small amounts of active elements to increase its emissivity; this has improved arc starting, arc stability, and electrode life. Shielding gas mixtures have been identified for improved welding performance.

Process Description

Typical equipment used for the gas tungsten arc welding process is illustrated in Figure G-9. The process uses a nonconsumable tungsten (or tungsten alloy) electrode held in a torch. Shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal from contamination by the atmosphere. The electric arc is produced by the passage of current through the conductive, ionized shielding gas. The arc is established between the tip of the electrode and the work. Heat generated by the arc melts the base metal. Once the arc and weld pool are established, the torch is moved along the joint and the arc progressively melts the faying surfaces. Filler wire, if used, is usually added to the leading edge of the weld pool to fill the joint.

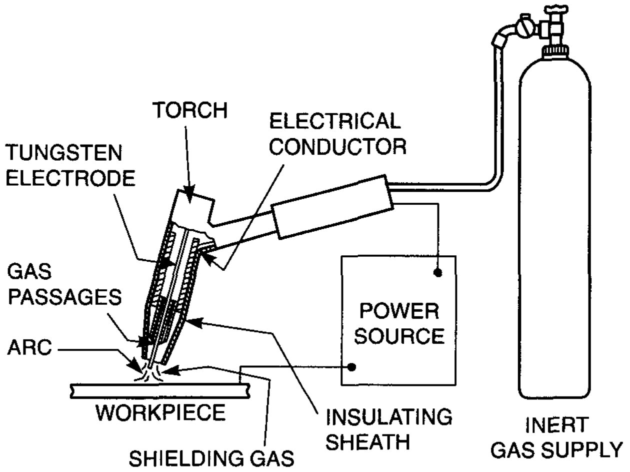


Figure G-9—Typical Equipment Used for Gas Tungsten Arc Welding

Advantages

The following are some advantages of the gas tungsten arc process:

(1) It produces superior quality welds, generally free of defects.

(2) It is free of the spatter which occurs with other arc welding processes.

(3) It can be used with or without filler metal as required for the specific application.

(4) It allows excellent control of root pass weld penetration.

(5) It can produce inexpensive autogenous welds at high speeds.

(6) It can use relatively inexpensive power supplies.

(7) It allows precise control of the welding variables.

(8) It can be used to weld almost all metals, including dissimilar metal joints.

(9) It allows the heat source and filler metal additions to be controlled independently.

Limitations

The following are some limitations of the gas tungsten arc process:

---

[2] R. Meredith, U.S. Patent 2,274,631, 1941.

(1) Deposition rates are lower than the rates possible with consumable electrode arc welding processes.

(2) There is a need for slightly more dexterity and welder coordination than with gas metal arc welding or shielded metal arc welding for manual welding.

(3) It is less economical than the consumable electrode arc welding processes for sections thicker then 10 mm (3/8 in.).

(4) There is difficulty in shielding the weld zone properly in drafty environments.

Potential problems with the process include:

(1) Tungsten inclusions can occur if the electrode is allowed to contact the weld pool.

(2) Contamination of the weld metal can occur if proper shielding of the filler metal by the gas stream is not maintained.

(3) There is low tolerance for contaminants on filler or base metals.

(4) Possible contamination or porosity can be caused by coolant leakage from water-cooled torches.

(5) Arc blow or arc deflection, as with other processes.

This process has been called *Heliarc*® (a registered trade mark of Union Carbide Corporation), named for the helium shielding gas originally used, and TIG (tungsten inert gas) welding, However, the AWS terminology for this process is *gas tungsten arc welding* (GTAW), because shielding gas mixtures which are not inert can be used for certain applications.

Process Variables

The primary variables in GTAW are arc voltage (arc length), welding current, travel speed, and shielding gas. The amount of energy produced by the arc is proportional to the current and voltage. The amount transferred per unit length of weld is inversely proportional to the travel speed. The arc in helium is more penetrating than that in argon. However, because all of these variables interact strongly, it is impossible to treat them as truly independent variables when establishing welding procedures for fabricating specific joints.

Arc Current. As a general statement, arc current controls the weld penetration, the effect being directly proportional, if not somewhat exponential. Arc current also affects the voltage, with the voltage at a fixed arc length increasing in proportion to the current. For this reason, to keep a fixed arc length, it is necessary to change the voltage setting when the current is adjusted.

The process can be used with either direct or alternating current, the choice depending largely on the metal to be welded. Direct current with the electrode negative (DCEN) offers the advantages of deep penetration and fast welding speeds, especially when helium is used as the shield. Helium is the gas of choice for mechanized welding.

Alternating current provides a cathodic cleaning (sputtering) which removes refractory oxides from the surfaces of aluminum and magnesium during the portion of the a-c wave that the electrode is positive with respect to the workpiece. In this case, argon must be used for the shield because sputtering cannot be obtained with helium. Argon is the gas of choice for manual welding whether used with direct current or alternating current.

A third power option also is available, that of using direct current with the electrode positive. This polarity is used only rarely because it causes electrode overheating.

Arc Voltage. The voltage measured between the tungsten electrode and the work is commonly referred to as the *arc voltage.* Arc voltage is a strongly dependent variable, affected by the following:

(1) Arc current

(2) Shape of the tungsten electrode tip

(3) Distance between the tungsten electrode and the work

(4) Type of shielding gas

The arc voltage is changed by the effects of the other variables, and is used in describing welding procedures only because it is easy to measure. Since the other variables such as the shield gas, electrode shape, and current have been predetermined, arc voltage becomes a way to control the arc length, a critical variable. Arc length is important with this process because it affects the width of the weld pool; pool width is proportional to arc length. Therefore, in most applications other than those involving sheet, the desired arc length is as short as possible.

Of course, recognition needs to be given to the possibility of short circuiting the electrode to the pool or filler wire if the arc is too short. However, with mechanized welding, using a helium shield, direct current electrode negative (DCEN) power, and a relatively high current, it is possible to submerge the electrode tip below the plate surface to produce deeply penetrating but narrow welds at high speeds. This technique has been called *buried arc.*

Travel Speed. Travel speed affects both the width and penetration of a gas tungsten arc weld. However, its effect on width is more pronounced than that on penetration. Travel speed is important because of its effect on cost. In some applications, travel speed is defined as an objective, with the other variables selected to achieve the desired weld configuration at that speed. In other cases, travel might be a dependent variable, selected to obtain the weld quality and uniformity needed under the best conditions possible with the other combination of variables. Regardless of the objectives, travel speed generally is fixed in mechanized welding while other variables such as current or voltage are varied to maintain control of the weld.

Wire Feed. In manual welding, the way filler metal is added to the pool influences the number of passes required and the appearance of the finished weld.

In machine and automatic welding, wire feed speed determines the amount of filler deposited per unit length of weld. Decreasing wire feed speed will increase penetration and flatten the bead contour. Feeding the wire too slowly can lead to undercut, centerline cracking, and lack of joint fill. Increasing wire feed speed decreases weld penetration and produces a more convex weld bead.

Equipment

Equipment for GTAW includes torches, electrodes, and power supplies. Mechanized GTAW systems may incorporate arc voltage controls, arc oscillators, and wire feeders.

Welding Torches. GTAW torches hold the tungsten electrode which conducts welding current to the arc, and provide a means for conveying shielding gas to the arc zone.

The majority of torches for manual applications have a head angle (angle between the electrode and handle) of 120°. Torches are also available with adjustable angle heads, 90° heads, or straight-line (pencil type) heads. Manual GTAW torches often have auxiliary switches and valves built into their handles for controlling current and gas flow. Torches for machine or automatic GTAW are typically mounted on a device which centers the torch over the joint, may move the torch along the joint, and may change or maintain the torch-to-work distance.

Gas-Cooled Torches. The heat generated in the torch during welding is removed either by gas cooling or water cooling. Gas-cooled torches (sometimes called air-cooled) provide cooling by the flow of the relatively cool shielding gas through the torch. Gas-cooled torches are limited to a maximum welding current of about 200 amperes.

Water-Cooled Torches. Water-cooled torches are cooled by the continuous flow of water through passageways in the holder. As illustrated in Figure G-10, cooling water enters the torch through the inlet hose, circulates through the torch, and exits through an outlet hose. The power cable from the power supply to the torch is typically enclosed within the cooling water outlet hose.

Water-cooled torches are designed for use at higher welding currents on a continuous duty cycle than similar sizes of gas-cooled torches. Typical welding currents of 300 to 500 amperes can be used, although some torches have been built to handle welding currents up to 1000 amperes. Most machine or automatic welding applications use water-cooled torches.

Collets. Electrodes of various diameters are secured in the electrode holder by appropriately sized collets or chucks. Collets are typically made of a copper alloy. The electrode is gripped by the collet when the torch cap is tightened in place. Good contact between the electrode and the inside diameter of the collet is essential for proper current transfer and electrode cooling.

Nozzles. Shielding gas is directed to the weld zone by gas nozzles or cups which fit onto the head of the torch. Also incorporated in the torch body are diffusers, or carefully patterned jets, which feed the shield gas to the nozzle. Their purpose is to assist in producing a laminar flow of the exiting gas shield. Gas nozzles are made of various heat-resistant materials in different shapes, diameters, and lengths. These nozzles are either threaded to the torch or held by friction fit.

Nozzles are also available with elongated trailing sections or flared ends which provide better shielding for welding metals such as titanium, which is highly susceptible to contamination at elevated temperatures.

Gas Lenses. One device used for assuring a laminar flow of shielding gas is an attachment called a *gas lens*. Gas lenses contain a porous barrier diffuser and are designed to fit inside the gas nozzle and around the electrode or collet. Gas lenses produce a longer, undisturbed flow of shielding gas. They enable operators to weld with the nozzle 25 mm (1 in.) or more from the work, improving their ability to see the weld pool and allowing them to reach places with limited access, such as inside corners.

Electrodes

In GTAW, the word *tungsten* refers to the pure element tungsten and its various alloys used as electrodes. Tungsten electrodes are nonconsumable if the

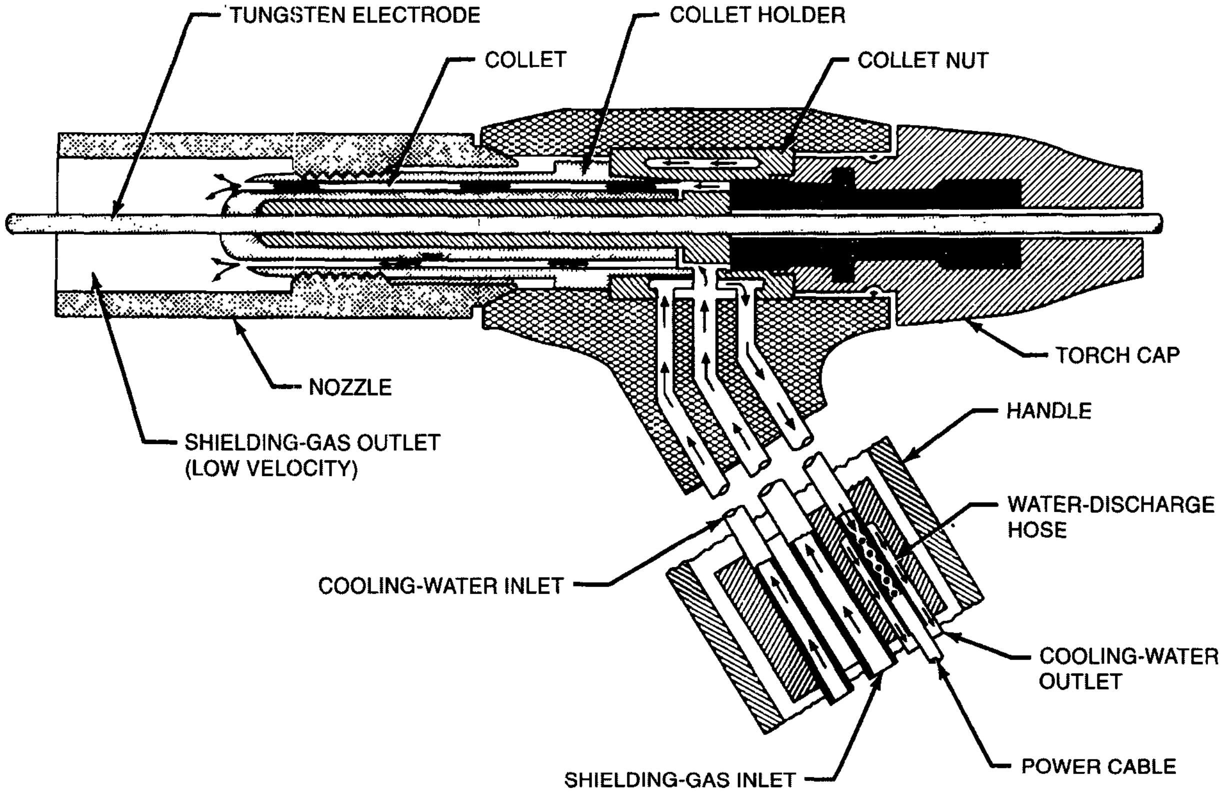


Figure G-10—Cross-Sectional View of a Typical Water-Cooled Torch for Manual GTAW

process is properly used, because they do not melt or transfer to the weld. In other welding processes, such as SMAW, GMAW, and SAW, the electrode is the filler metal. The function of a tungsten electrode is to serve as one of the electrical terminals of the arc which supplies the heat required for welding. Its melting point is 3410°C (6170°F). Approaching this high temperature, tungsten becomes thermionic; it is a ready source of electrons. It reaches this temperature by resistance heating and, were it not for the significant cooling effect of electrons boiling from its tip, resistance heating would cause the tip to melt. In fact, the electrode tip is much cooler than that part of the electrode between the tip and the externally-cooled collet.

Classification of Electrodes. Tungsten electrodes are classified on the basis of their chemical compositions, as specified in Table G-2. Requirements for tungsten electrodes are given in the latest edition of ANSI/AWS A5.12, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*. The color code identification system for the various classes of tungsten electrodes is shown in Table G-2.

Electrodes are produced with either a clean finish or ground finish. Electrodes with a clean finish have been chemically cleaned to remove surface impurities after the forming operation. Those with a ground finish have been centerless ground to remove surface imperfections.

Electrode Sizes and Current Capacities. Tungsten and tungsten alloy electrode sizes and current ranges are listed in Table G-3, along with shield-gas cup diameters recommended for use with different types of welding power. Table G-3 provides a useful guide for selecting the correct electrode for specific applications involving different current levels and power supplies.

Current levels in excess of those recommended for a given electrode size and tip configuration will cause the tungsten to erode or melt. Tungsten particles may

Table G-2
Color Code and Alloying Elements for Various Tungsten Electrode Alloys

AWS Classification	Color[a]	Alloying Element	Alloying Oxide	Nominal Weight of Alloying Oxide Percent
EWP	Green	—	—	—
EWCe-2	Orange	Cerium	CeO_2	2
EWLa-1	Black	Lanthanum	La_2O_3	1
EWTh-1	Yellow	Thorium	ThO_2	1
EWTh-2	Red	Thorium	ThO_2	2
EWZr-1	Brown	Zirconium	ZrO_2	.25
EWG	Gray	Not Specified[b]	—	—

a. Color may be applied in the form of bands, dots, etc., at any point on the surface of the electrode.
b. Manufacturer must identify the type and nominal content of the rare earth oxide addition.

Table G-3
Recommended Tungsten Electrodes[a] and Gas Cups for Various Welding Currents

Electrode Diameter		Use Gas Cup I.D.	Direct Current, A		Alternating Current, A	
mm	in.	in.	Straight Polarity[b] DCEN	Reverse Polarity[b] DCEP	Unbalanced Wave[c]	Balanced Wave[c]
0.25	0.010	1/4	up to 15		up to 15	up to 15
0.50	0.020	1/4	5–20		5–15	10–20
1.00	0.040	3/8	15–80		10–60	20–30
1.6	1/16	3/8	70–150	10–20	50–100	30–80
2.4	3/32	1/2	150–250	15–30	100–160	60–130
3.2	1/8	1/2	250–400	25–40	150–210	100–180
4.0	5/32	1/2	400–500	40–55	200–275	160–240
4.8	3/16	5/8	500–750	55–80	250–350	190–300
6.4	1/4	3/4	750–1100	80–125	325–450	325–450

a. All values are based on the use of argon as the shielding gas.
b. Use EWCe-2, EWLa-1, or EWTh-2 electrodes.
c. Use EWP electrodes.

fall into the weld pool and become defects in the weld joint. Current too low for a specific electrode diameter can cause arc instability.

Direct current with the electrode positive (DCEP) requires a much larger diameter to support a given level of current because the tip is not cooled by the evaporation of electrons but heated by their impact. In general, a given electrode diameter on DCEP would be expected to handle only 10% of the current possible with the electrode negative. With alternating current, the tip is cooled during the electrode negative cycle and heated when positive. Therefore, the current-carrying capacity of an electrode on ac is between that of DCEN and DCEP. In general, it is about 50% less than that of DCEN.

EWP Electrode Classification. Pure tungsten electrodes (EWP) contain a minimum of 99.5% tungsten, with no intentional alloying elements. Pure tungsten electrodes are used mainly with ac for welding aluminum and magnesium alloys. The tip of the EWP electrode maintains a shiny, balled end, which provides good arc stability.

EWTh Electrode Classifications. The thermionic emission of tungsten can be improved by alloying it with metal oxides that have very low work functions.

As a result, the electrodes are able to handle higher welding currents without failing. Thorium oxide is one such additive. To prevent identification problems with these and other types of tungsten electrodes, they are color coded as shown in Table G-2. Two types of thoriated tungsten electrodes are available. The EWTh-1 and EWTh-2 electrodes contain 1% and 2% thorium oxide (ThO_2) called *thoria,* respectively, evenly dispersed through their entire lengths. They were designed for DCEN applications. They are not often used with ac because it is difficult to maintain the balled end, which is necessary with ac welding, without splitting the electrode.

Thorium is a very low-level radioactive material. The level of radiation has not been found to represent a health hazard. However, if welding is to be performed in confined spaces for prolonged periods of time, or if electrode grinding dust might be ingested, special precautions relative to ventilation should be considered. The user should consult the appropriate safety personnel.

A discontinued classification of tungsten electrodes is the EWTh-3 class. This "striped" tungsten electrode had a longitudinal or axial segment which contained 1.0% to 2.0% thoria. The average thoria content of the electrode was 0.35% to 0.55%. Advances in powder metallurgy and other processing developments have caused this electrode classification to be discontinued, and it is no longer commercially available.

EWCe Electrode Classification. Ceriated tungsten electrodes were first introduced into the United States in the early 1980s. These electrodes were developed as possible replacements for thoriated electrodes because cerium, unlike thorium, is not a radioactive element. The EWCe-2 electrodes are tungsten electrodes containing 2% cerium oxide (CeO_2), referred to as *ceria.* Compared with pure tungsten, the ceriated electrodes exhibit a reduced rate of vaporization or burn-off. These advantages of ceria improve with increased ceria content. EWCe-2 electrodes will operate successfully with ac or dc.

EWLa Electrode Classification. EWLa-1 electrodes were developed around the same time as the ceriated electrodes and for the same reason: that lanthanum is not radioactive. These electrodes contain 1% lanthanum oxide (La_2O_3), referred to as *lanthana.* The advantages and operating characteristics of these electrodes are very similar to the ceriated tungsten electrodes.

EWZr Electrode Classification. Zirconiated tungsten electrodes (EWZr) contain a small amount of zirconium oxide (ZrO_2), as listed in Table G-2. Zirconiated tungsten electrodes have welding characteristics that generally fall between those of pure and thoriated tungsten. They are used for ac welding because they combine the desirable arc stability characteristics and balled end typical of pure tungsten with the current capacity and starting characteristics of thoriated tungsten. They have higher resistance to contamination than pure tungsten, and are preferred for radiographic quality welding applications where tungsten contamination of the weld must be minimized.

EWG Electrode Classification. The EWG electrode classification was assigned for alloys not covered by the above classes. These electrodes contain an unspecified addition of an unspecified oxide or combination of oxides (rare earth or others). The purpose of the addition is to affect the nature or characteristics of the arc, as defined by the manufacturer. The manufacturer must identify the specific addition or additions and the nominal quantity or quantities added.

Several EWG electrodes are either commercially available or are being developed. These include additions of yttrium oxide or magnesium oxide. This classification also includes ceriated and lanthanated electrodes which contain these oxides in amounts other than as listed above, or in combination with other oxides.

Electrode Tip Configurations. The shape of the tungsten electrode tip is an important process variable in GTAW. Tungsten electrodes may be used with a variety of tip preparations. With ac welding, pure or zirconiated tungsten electrodes form a hemispherical balled end. For dc welding, thoriated, ceriated, or lanthanated tungsten electrodes are usually used. For the latter, the end is typically ground to a specific included angle, often with a truncated end.

Grinding. To produce optimum arc stability, grinding of tungsten electrodes should be done with the axis of the electrode perpendicular to the axis of the grinding wheel. The grinding wheel should be reserved for grinding only tungsten to eliminate possible contamination of the tungsten tip with foreign matter during the grinding operation. Exhaust hoods should be used when grinding thoriated electrodes to remove the grinding dust from the work area.

Wire Feeders

Wire feeders are used to add filler metal during automatic and machine welding. Either room temperature (cold) wire or preheated (hot) wire can be fed into the molten weld pool. Cold wire is fed into the leading edge and hot wire is fed into the trailing edge of the molten pool.

Cold Wire. The system for feeding of cold wire has three components: (1) wire drive mechanism, (2) speed control, and (3) wire guide attachment to introduce the wire into the molten weld pool.

The drive consists of a motor and gear train to power a set of drive rolls which push the wire. The control is essentially a constant-speed governor which can be either a mechanical or an electronic device. The wire is fed to the wire guide through a flexible conduit.

An adjustable wire guide is attached to the electrode holder. It maintains the position at which the wire enters the weld and the angle of approach relative to the electrode, work surface, and the joint. In heavy-duty applications, the wire guide is water cooled. Wires ranging from 0.4 to 2.4 mm (0.015 to 3/32 in.) in diameter are used. Special wire feeders are available to provide continuous, pulsed, or intermittent wire feed.

Hot Wire. The process for hot wire addition is similar to that for cold wire, except that the wire is resistance heated to a temperature close to its melting point just before it contacts the molten weld pool. When using a preheated (hot) wire in machine and automatic gas tungsten arc welding in the flat position, the wire is fed mechanically to the weld pool through a holder from which inert gas flows to protect the hot wire from oxidation. This system is illustrated in Figure G-11. Normally, a mixture of 75% helium-25% argon is used to shield the tungsten electrode and the molten weld pool.

Deposition rate is greater with hot wire than with cold wire, as shown in Figure G-12. This rate is comparable to that in gas metal arc welding. The current flow is initiated when the wire contacts the weld surface. The wire is fed into the molten pool directly behind the arc at a 40 to 60° angle with respect to the tungsten electrode. The wire is resistance-heated by alternating current from a constant-voltage power source. Alternating current is used for heating the wire to avoid arc blow. When the heating current does not exceed 60% of the arc current, the arc oscillates 30° in the longitudinal direction. The oscillation increases to 120° when the heating and arc currents are equal. The amplitude of arc oscillation can be controlled by limiting the wire diameter to 1.2 mm (0.045 in.) and reducing the heating current below 60% of the arc current.

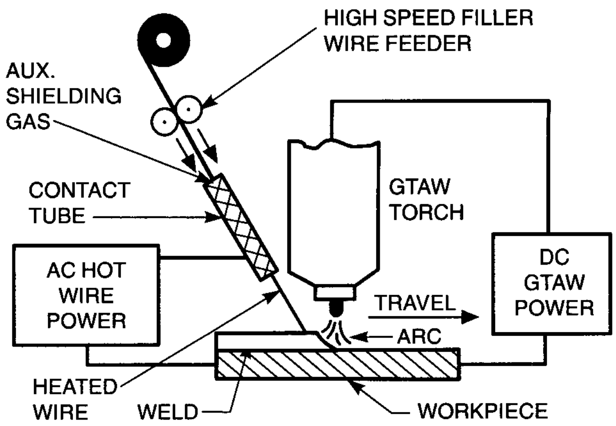


Figure G-11—Gas Tungsten Arc Hot Wire System

Preheated filler wire has been used successfully for joining carbon and low-alloy steels, stainless steels, and alloys of copper and nickel. Preheating is not recommended for aluminum and copper because the low resistance of these filler wires requires high heating current, which results in excessive arc deflection and uneven melting.

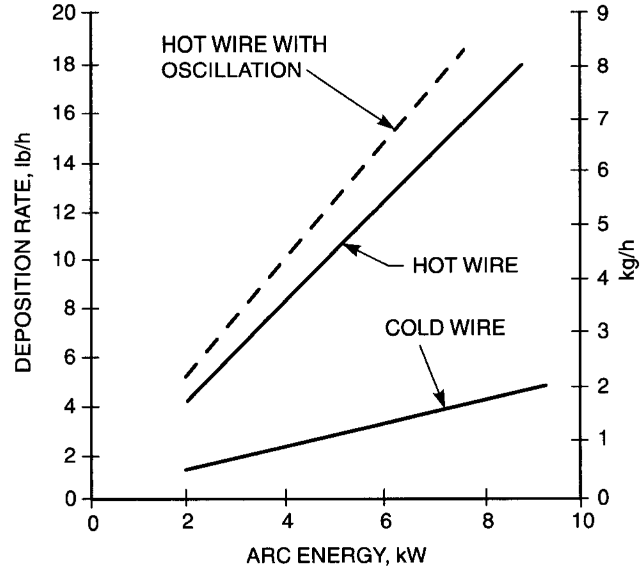


Figure G-12—Deposition Rates for GTAW with Cold and Hot Steel Filler Wire

Power Supplies

Constant-current type power sources are used for GTAW. Power required for both a-c and d-c GTAW can be supplied by transformer-rectifier power supplies or from rotating a-c or d-c generators. Advances in semiconductor electronics have made transformer-rectifier power sources popular for both shop and field GTAW, but rotating-type power sources continue to be widely used in the field.

GTAW power sources typically have either drooping or nearly true constant-current static output characteristics, such as those shown in Figure G-13. The static output characteristic is a function of the type of welding current control used in the power source design.

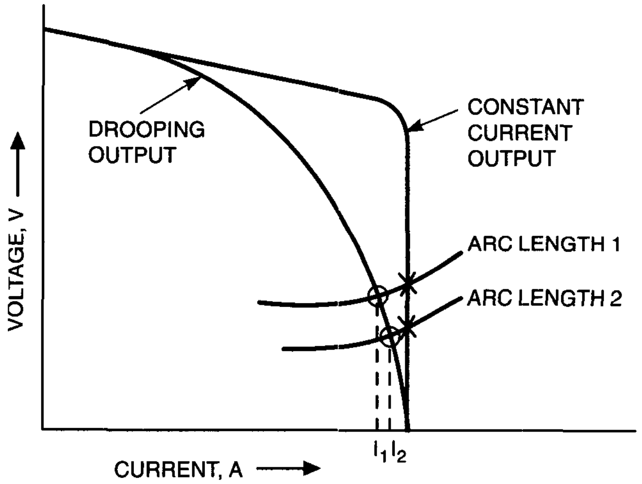


Figure G-13—Static Volt-Ampere Output Characteristics for Drooping and Constant Current Power Supplies

A drooping volt-ampere characteristic is typical of magnetically controlled power source designs including the moving coil, moving shunt, moving core reactor, saturable reactor, or magnetic amplifier designs and also rotating power source designs. A truly constant-current output is available from electronically controlled power sources. The drooping characteristic is advantageous for manual welding where a remote foot pedal current control is not available at the site of welding. With a drooping characteristic, the welder may vary the current level slightly by changing the arc length. The degree of current control possible by changing arc length can be inferred from Figure G-13.

In most of the magnetically controlled power sources, the current-level control is accomplished in the ac portion of the power source. As a result, these power sources are not typically used to provide pulsed current because of their slow dynamic response. The addition of a rectifier bridge allows these power sources to provide both a-c and d-c welding current. Those power sources which use a moving component for current control cannot readily be remotely controlled with a foot pedal, while the others typically can.

The advantages of magnetically controlled power sources are that they are simple to operate, require little maintenance in adverse industrial environments, and are relatively inexpensive. The disadvantages are that they are large in size and weight and have a lower efficiency compared to electronically controlled power sources. Also, most magnetic-control techniques are open-loop, which limits repeatability, accuracy, and response. An essentially constant-current volt-ampere characteristic can be provided by electronically controlled power sources, such as the series linear regulator, silicon controlled rectifier, secondary switcher, and inverter designs.

The advantages of electronically controlled power sources are that they offer rapid dynamic response, provide variable current waveform output, have excellent repeatability, and offer remote control. The disadvantages are that they are more complex to operate and maintain and are relatively expensive.

It is important to select a GTAW power source based on the type of welding current required for a particular application. The types of welding current include a-c sine-wave, a-c square-wave, dc, and pulsed dc. Many power sources are available with a variety of additional controls and functions such as water and shielding gas control, wire feeder and travel mechanism sequencing, current up-slope and down-slope, and multiple-current sequences.

Shielding Gases

Shielding gas is directed by the torch to the arc zone and weld pool to protect the electrode and the molten weld metal from atmospheric contamination. Backup purge gas can also be used to protect the underside of the weld and its adjacent base metal surfaces from oxidation during welding. Uniformity of root bead contour, freedom from undercutting, and the desired amount of root bead reinforcement are more likely to be achieved when using gas backup under controlled conditions. In some materials, gas backup reduces root cracking and porosity in the weld.

Types of Shielding Gases. Argon and helium, or mixtures of the two, are the most common types of inert gas used for shielding. Argon-hydrogen mixtures are used for special applications.

Argon. Welding grade argon is refined to a minimum purity of 99.95%. This is acceptable for GTAW of most metals except the reactive and refractory metals, for which a minimum purity of 99.997% is required. Often, such metals are fabricated in chambers from which all traces of air have been purged prior to initiating the welding operation.

Argon is used more extensively than helium because of the following advantages:

(1) Smoother, quieter arc action

(2) Reduced penetration

(3) Cleaning action when welding materials such as aluminum and magnesium

(4) Lower cost and greater availability

(5) Lower flow rates for good shielding

(6) Better cross-draft resistance

(7) Easier arc starting

The reduced penetration of an argon shielded arc is particularly helpful when manual welding of thin material, because the tendency for excessive melt-through is lessened. This same characteristic is advantageous in vertical or overhead welding, since the tendency for the base metal to sag or run is decreased.

Helium. Welding grade helium is refined to a purity of at least 99.99%.

For given values of welding current and arc length, helium transfers more heat into the work than argon. The greater heating power of the helium arc can be advantageous for joining metals of high thermal conductivity and for high-speed mechanized applications. Also, helium is used more often than argon for welding heavy plate. Mixtures of argon and helium are useful when some balance between the characteristics of both is desired.

Characteristics of Argon and Helium. The chief factor influencing shielding effectiveness is the gas density. Argon is approximately one and one-third times as heavy as air and ten times heavier than helium. Argon, after leaving the torch nozzle, forms a blanket over the weld area. Helium, because it is lighter, tends to rise around the nozzle. Experimental work has consistently shown that to produce equivalent shielding effectiveness, the flow of helium must be two to three times that of argon. The same general relationship is true for mixtures of argon and helium, particularly those high in helium content.

The other influential characteristic is that of arc stability. Both gases provide excellent stability with direct current power. With alternating current power, which is used extensively for welding aluminum and magnesium, argon provides much better arc stability and the highly desirable cleaning action, which makes argon superior to helium in this respect.

Argon-Hydrogen Mixtures. Argon-hydrogen mixtures are employed in special cases, such as mechanized welding of light-gauge stainless steel tubing, where the hydrogen does not cause adverse metallurgical effects such as porosity and hydrogen-induced cracking. Increased welding speeds can be achieved in almost direct proportion to the amount of hydrogen added to argon because of the increased arc voltage. However, the amount of hydrogen that can be added varies with the metal thickness and type of joint for each particular application. Excessive hydrogen will cause porosity. Hydrogen concentrations up to 35% have been used on all thicknesses of stainless steel where a root opening of approximately 0.25 to 0.5 mm (0.010 to 0.020 in.) is used. Argon-hydrogen mixtures are limited to use on stainless steel, nickel-copper, and nickel-base alloys.

Safe Practices

The general subject of safety and safe practices in welding, cutting, and allied processes is covered in ANSI Z49.1, latest edition, *Safety in Welding and Cutting*. This publication is available from the American Welding Society. All welding personnel should be familiar with the safe practices discussed in this document. The potential hazard areas in arc welding and cutting include, but are not limited to, the handling of cylinders and regulators, gases, fumes, radiant energy and electric shock. *See* SAFE PRACTICES *and* Appendix 12.

Reference: American Welding Society, *Welding Handbook*, 8th Edition, Vol 2, Welding Processes. Miami, Florida: American Welding Society, 1991.

GAS TUNGSTEN ARC WELDING, Manual

Manual gas tungsten arc welding requires a fair degree of hand-eye coordination. It is necessary to keep the end of the filler metal inside the argon shield whenever it is hot enough to react with the atmosphere. If this is not done, the operator will bring the oxidized end of the filler metal into the puddle, which results in contamination.

Manual Welding Procedure

Starting an Arc. To start an arc in alternating current welding, the electrode does not have to touch the workpiece. The superimposed high-frequency current jumps the gap between the welding electrode and the work, thus establishing a path for the welding current to follow. To strike an arc, the power supply is first turned on, and the torch held in a position about 2 in. above the workpiece. Then the end of the torch is quickly swung down toward the workpiece, so that the end of the electrode is about 1/8 in. above the plate. The arc will then strike. This downward motion should be made rapidly to provide the maximum gas protection to the weld zone.

In direct current welding, the same torch motion is used for striking an arc. In this case, however, the electrode must touch the workpiece in order for the arc to strike. As soon as the arc is struck, the electrode should be withdrawn approximately 1/8 in. above the workpiece to avoid contaminating the electrode in the molten puddle.

Making a Butt Weld. After the arc has been struck, the torch is held at about a 75° angle to the surface of the workpiece. The starting point of the work is first preheated by moving the torch in small circles until a molten puddle is formed. (*See* Figure G-14). The end of the electrode should be held approximately 1/8 in. above the workpiece. When the puddle becomes bright and fluid, the torch should be moved slowly and steadily along the joint at a speed that will produce a bead of uniform width. No oscillation or other movement of the torch, except for the steady forward motion, is required.

When filler metal is needed to provide reinforcement, the welding rod is held at about a 75° angle to the work and about 1 in. away from the starting point. First the starting point is preheated, and the puddle developed as previously described. When the puddle becomes bright and fluid, the arc is moved to the rear of the puddle, and filler metal added by quickly touching the rod to the leading edge of the puddle. The rod is removed, and the arc brought back to the leading edge of the puddle. As soon as the puddle is again bright, the same steps are repeated. This sequence, continued for the entire length of the seam, is illustrated in Figure G-15.

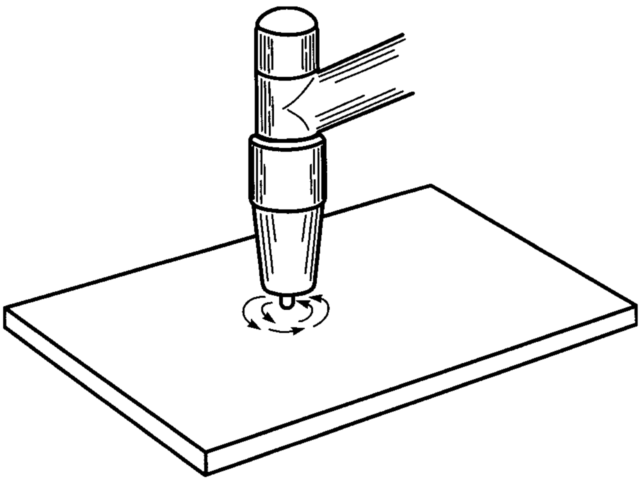


Figure G-14—Before Starting the Weld, Preheat a Small Area

Making a Lap Weld. The first step of starting a lap weld or joint is developing a puddle on the bottom sheet. When the puddle becomes bright and fluid, the arc is shortened to about 1.6 mm (1/16 in.). The torch is oscillated directly over the joint until the sheets are firmly joined. Once the weld is started, the oscillating movement is no longer necessary. The torch is then moved along the seam with the end of the electrode just above the edge of the top sheet.

In lap welding, the puddle developed will be boomerang or V-shaped. The center of the puddle is called the "notch," and the speed at which this notch travels will determine how fast the torch can be moved ahead. Care must be taken that this notch is completely filled in for the entire length of the seam. *See* Figure G-16. Otherwise, it is impossible to get 100 percent fusion and good penetration.

When filler metal is used, faster welding speeds are possible as the rod helps fill the notch. It is important to get complete fusion. Just laying in bits of filler rod on the cold, unfused base metal must be avoided. The rod should be alternately dipped into the puddle and withdrawn 1/4 in. or so, as illustrated in Figure G-17. By carefully controlling the melting rate of the top edge, and by adding just the right amount of filler metal where needed, a good uniform bead of proper proportions can be obtained.

Making a Corner or Edge Joint. This is the easiest type of weld to make. A puddle is developed at the starting point, and the torch moved straight along the joint. Travel speed is regulated to produce a uniform looking bead. Too slow a welding speed will cause molten metal to roll off the edge. Irregular or too high speeds will produce a rough, uneven surface. No filler metal is required.

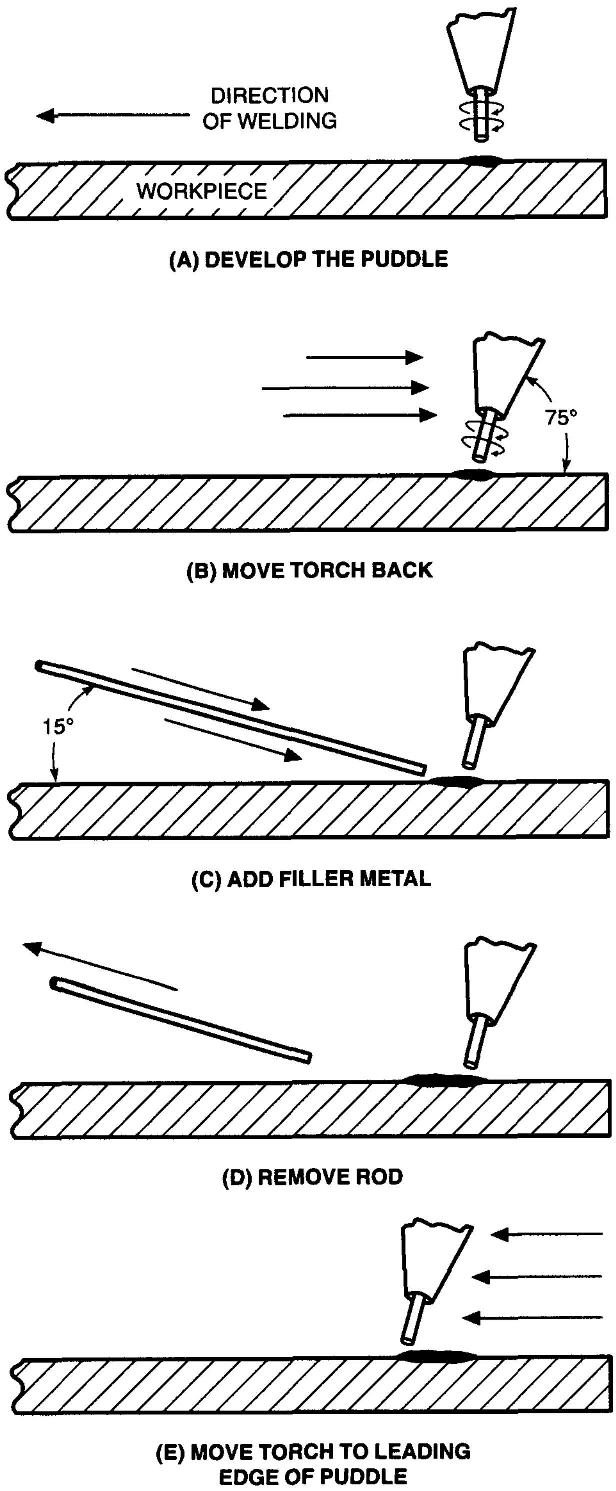


Figure G-15—Method of GTAW with Filler Metal Addition

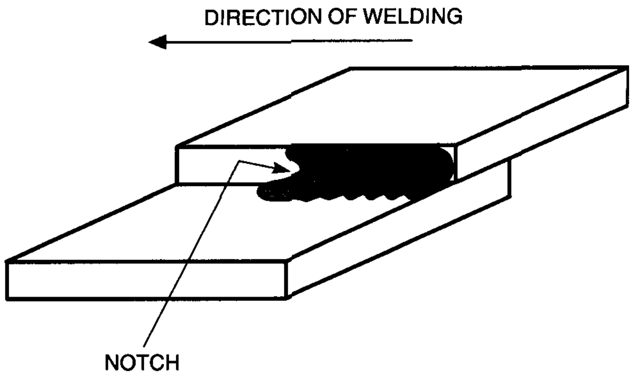


Figure G-16—Be Sure to Fill the Notch that Occurs when Making a Lap Weld with GTAW

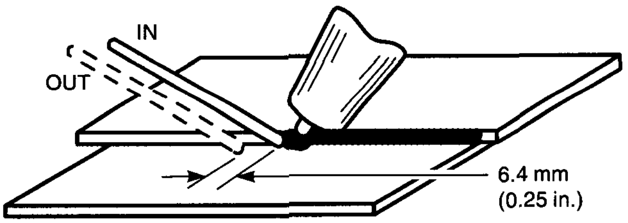


Figure G-17—Progress of the Weld with Filler Rod

GAS TUNGSTEN ARC WELDING TORCH

A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas. See STANDARD WELDING TERMS.

GAS WELDING

A nonstandard term for OXYFUEL GAS WELDING.

GAUGE

As applied to metals, a standard or scale of measurement of thickness. As applied to gas regulators, instruments which indicate pressure. *See* PRESSURE GAUGE.

GEAR TEETH, REPAIR

Broken gear teeth are usually replaced by rebuilding new teeth. The important precaution in this operation is to preheat the gear, wholly or in part, to be sure of equal expansion. The gear should be kept heated while the welding is being done. *See* TOOL WELDING, Fabrication and Repair, *and* FARM IMPLEMENT REPAIR.

GENERATOR

A motor or machine that converts mechanical energy into electric energy, used as a power source for arc welding processes. The mechanical power can be from an internal combustion engine, an electric motor, or from a power take-off from other equipment. For welding, two basic types of rotating power sources are used: the generator, which produces direct current, and the alternator type, which produces alternating current, and is capable of producing low d-c power. Both have a rotating member, called a *rotor* or an *armature*, and a stationary member, called a *stator.* A system of excitation is needed for both types.

Welding power sources are available that produce both constant current and constant voltage. These units are used for field applications where either may be needed at the job site and utility power is not available. In many designs, electronic solid-state circuitry is integrated to produce a variety of volt-ampere *characteristics. See* Power Source under specific process; i.e., GAS METAL ARC WELDING.

GLEEBLE

A commercially available unit which is used to simulate the thermal cycling encountered by the base metal heat-affected zone of a welded specimen. The gleeble uses the electrical resistance heating technique and is capable of producing (1) very rapid heating, (2) short holding time at peak temperature, and (3) controlled cooling to closely simulate a defined thermal cycle as might be anticipated in a specific base metal section with a given welding process.

GLOBULAR ARC

A nonstandard term for GLOBULAR TRANSFER.

GLOBULAR TRANSFER, Arc Welding

The transfer of molten metal in large drops from a consumable electrode across the arc. See STANDARD WELDING TERMS. *See* Figure G-18. *See also* SHORT CIRCUITING TRANSFER *and* SPRAY TRANSFER.

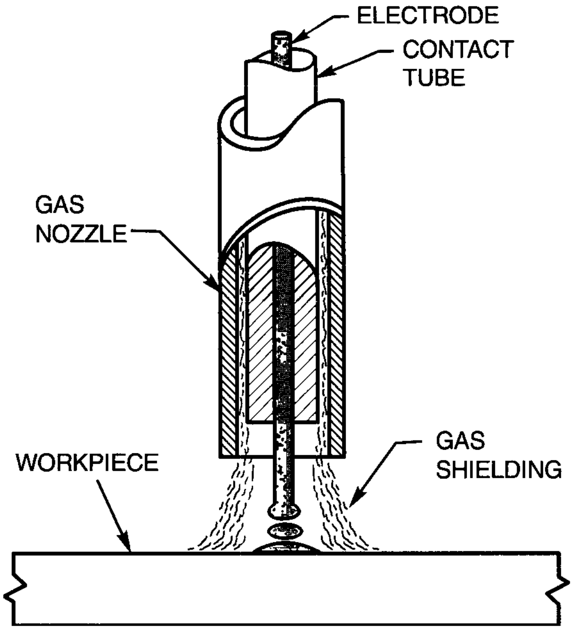


Figure G-18—Globular Transfer in GMAW

Consumable electrode arc welding processes are used extensively because filler metal is deposited more efficiently and at higher rates than is possible with other welding processes. To be most effective, the filler metal needs to be transferred from the electrode with small losses due to spatter. Uncontrollable short circuits between the electrode and the work should be avoided to help the welder or operator to maintain stability of the process. In the case of the GMAW process, arc instability caused by erratic transfer can generate pressure fluctuations that draw air into the vicinity of the arc.

High speed photography and analysis of oscilloscope photographs are used to study the different types of transfer. Transfer through the arc stream of covered electrodes can be characterized as globular (massive drops) or as a showery spray (large number of small drops). These modes are rarely found alone; generally, metal is transferred in some combination of both. Transfer with the GMAW process varies greatly when used with argon shielding. When the current is above the transition level, the transfer mechanism can best be described as an axial spray and short circuits are nonexistent. When helium or an active gas such as carbon dioxide is used for shielding, the transfer is globular and some short circuiting is unavoidable. The GMAW short circuiting arc process has been adapted to use only short circuits for transfer of the metal to the weld pool.

GLOVES, Welding

A gauntlet or hand covering made of leather or other flexible, heat and flame-resistant materials to protect the welder from arc rays, molten metal spatter, sparks and other possible sources of burns.

GOGGLES

Protective glasses equipped with filter plates set in a frame that fits snugly against the face and used primarily with oxyfuel gas processes. See STANDARD WELDING TERMS.

GOLD

(Chemical symbol: Au). A soft, yellow metallic element which occurs freely in nature. It is ductile, highly malleable, resistant to corrosion and a good conductor of heat; used as plating on electrical and mechanical components. Atomic number, 79; atomic weight, 196.97; melting point 958 °C (1756°F); specific gravity 5.47 at 20°C (68°F).

GOUGING

See STANDARD WELDING TERMS. *See* THERMAL GOUGING.

Electric arc and oxyfuel gas cutting processes can be used for gouging. Gouging is usually done to cut a groove or bevel in a workpiece to prepare it for welding.

In manual air carbon arc gouging, the electrode should be gripped as shown in Figure G-19, so that a maximum of 178 mm (7 in.) extends from the cutting torch. For nonferrous materials, this extension should be reduced to 75 mm (3 in.). The air jet should be turned on before striking the arc, and the cutting torch should be held as shown in Figure G-20. The electrode slopes back from the direction of travel with the air jet behind the electrode. The arc may be struck by lightly touching the electrode to the workpiece. The electrode should not be drawn back once the arc is struck. Under proper operating conditions, the air jet will sweep beneath the electrode end and remove all molten metal. The gouging technique is different from that of arc welding because metal is removed instead of deposited. A short arc should be maintained by progressing in the direction of the cut fast enough to keep up with metal removal. The steadiness of progression controls the smoothness of the resulting cut surface.

When gouging a workpiece in the vertical position, gouging should be done downhill, to let gravity assist in removing the molten metal. Gouging in the horizontal position may be done either to the right or to the left, but always in the forehand direction. In gouging to the left, the cutting torch should be held as shown in Figure G-20. In gouging to the right, the cutting torch will be reversed to locate the air jet behind the electrode. When gouging overhead, the electrode and torch should be held at an angle that will prevent molten metal from falling on the operator.

The depth of the groove produced is controlled by the travel speed. Slow travel speeds produce a deep groove; fast speeds produce a shallow groove. Grooves up to 25 mm (1 in.) may be cut. The width of

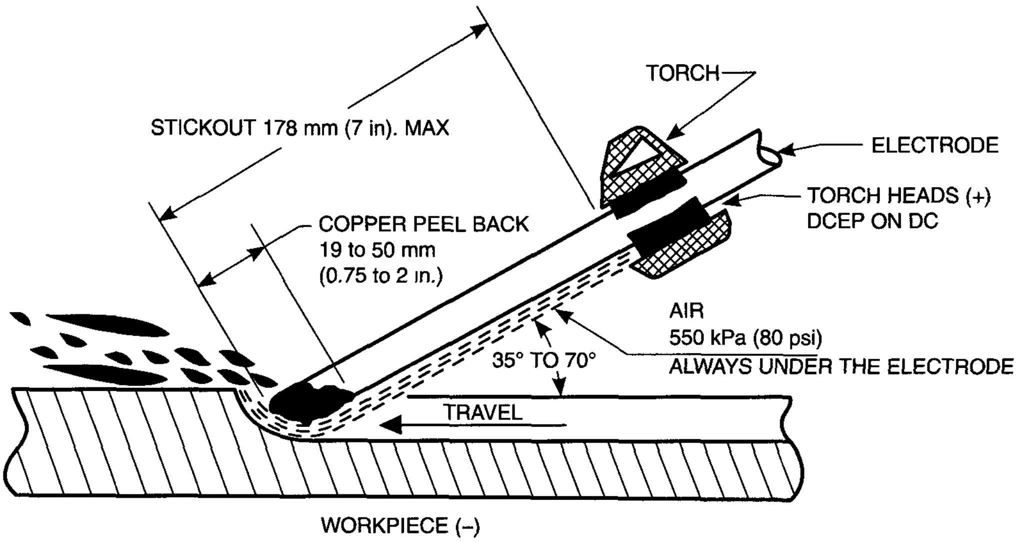


Figure G-19—Typical Operating Procedures for Air Carbon Arc Gouging

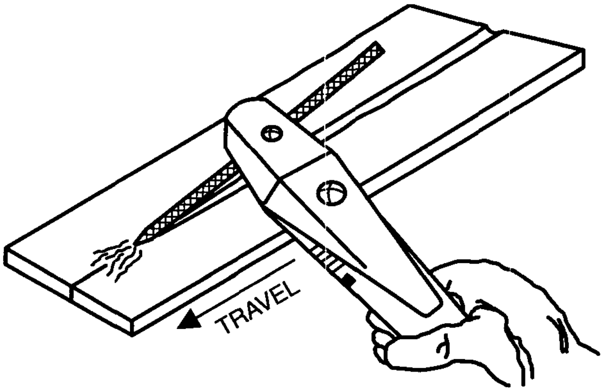


Figure G-20—Manual Air Carbon Arc Gouging Operation in the Flat Position

the groove is determined by the size of the electrode used and is usually about 3.2 mm (1/8 in.) wider than the electrode diameter. A wider groove may be made by oscillating the electrode with a circular or weaving motion.

When gouging, a push angle of 35° from the surface of the workpiece is used for most applications. A steady rest is recommended in gouging to ensure a smoothly gouged surface, particularly in the overhead position. Proper travel speed depends on the size of the electrode, type of base metal, cutting amperage, and air pressure. An indication of proper speed and good gouge quality is a smooth hissing sound in the arc. *See also* ARC GOUGING, BACKGOUGING, OXYGEN GOUGING, PLASMA ARC GOUGING, *and* AIR CARBON ARC CUTTING.

GOVERNING METAL THICKNESS, Resistance Welding

The thickness of the sheet on which the required weld nugget size and depth of fusion is based. See STANDARD WELDING TERMS.

GRADATED THERMAL SPRAY DEPOSIT

A composite thermal spray deposit composed of mixed materials in successive layers that progressively change in composition from the material adjacent to the substrate to the material at the surface of the thermal spray deposit. See STANDARD WELDING TERMS.

GRAIN GROWTH

See METALLURGY.

GRAINS

Groups of crystals present in metal after it has solidified. *See* METALLURGY.

GRAPHITE

An allotrope of carbon. In various forms, graphite has a wide variety of uses in the welding industry. It may appear in the form of plates and rods, and is sometimes used as an electrode in place of a carbon electrode. It is also used as a lubricant, and in putty, coatings and paint. *See* CARBON.

GRAPHITE ARC WELDING

See GRAPHITE, CARBON ARC WELDING, *and* CARBON ELECTRODE.

GRAPHITE ELECTRODE

See CARBON ELECTRODE.

GRAPHITIZATION

A metallurgical change in the microstructure of joints in carbon and certain low-alloy steels subjected to long term service in the temperature range of 450 to 600°C (850 to 1100°F). Graphitization is a breakdown of carbides in the steel to small patches of graphite and iron, caused by the thermal cycle of arc welds. This microstructural change seriously reduces strength. A practical remedy for this problem is to use steels alloyed with chromium or molybdenum, or both. Reference: American Welding Society. G. E. Linnert, Welding Metallurgy, p. 329–31; Vol. 2, Third Edition. Miami, Florida: American Welding Society, 1994.

GRAVITY FEED WELDING

A shielded metal arc welding process variation for making a fillet weld in which a long electrode slides down a tripod-mounted electrode holder as the electrode is consumed. See STANDARD WELDING TERMS.

GRAY CAST IRON

See CAST IRON.

GRINDER

An electric or pneumatic device used for removing excess materials by the action of abrasive wheels or belts on the material. Stationary or portable grinders are used extensively as a means of finishing welds. The abrasives may be emery, silicon carbide, aluminum oxide or a similar hard material.

GRINDING MATERIALS

Abrasive granular materials used alone or compounded, bonded to paper, fabric or tools to wear away a surface by friction.

The earliest industrial grindstones were made of sandstone and were chiefly used for sharpening tools. Sandstone is a natural grinding material because it is composed of particles of quartz held together with a bond of silica. Grinding wheels were difficult to shape because of the irregular size of the quartz grain and the hardness of the stone. Because there was no way to control either grain size or hardness, they could not be considered production tools.

Emery Wheels

Emery wheels, which replaced grindstones, were made of various components, one of which is corundum, a natural aluminum oxide (chemical symbol: Al_2O_3). Another abrasive ingredient of emery is iron oxide. There are other impurities which do not add to the value of emery as an abrasive. Some deposits of emery contain as little as 37% corundum, while others contain as much as 70%. Emery wheels, therefore, while far better than grindstones in their speed and ability to cut metals, were still irregular in their composition and hardness, due to the varying amounts of impurities.

Corundum is almost as hard as the diamond. Grinding wheels made of imperfect diamonds were used on special grinding jobs, but were too expensive for general use. Edward G. Acheson, one of the early experimenters, tried to produce artificial diamonds for grinding wheels by combining clay and carbon at high temperatures. Clay and powdered coke were mixed and heated in a crude electric furnace. Examination of the result revealed a few bright crystals of material, which were hard enough to scratch glass. It was not known what the material was, but it was thought to be a mixture of carbon and corundum. Acheson, therefore, coined the word *"Carborundum,"* and it became the trade name for the new substance. Chemical analysis later showed that it was indeed a new substance, one that does not occur in nature. The substance was silicon carbide (SiC).

Commercial procedures developed for manufacturing silicon carbide and aluminum oxide made it possible to produce, with suitable binders, grinding wheels with uniform particle size and hardness.

GROOVE

The opening provided between two members to be joined by a weld. See STANDARD WELDING TERMS. *See* SCARF GROOVE *and* WELD GROOVE.

GROOVE AND ROTARY ROUGHENING, Thermal Spraying

A method of surface roughening in which grooves are made and the original surface is roughened and spread. See STANDARD WELDING TERMS.

GROOVE ANGLE

The total included angle of the groove between workpieces. See STANDARD WELDING TERMS. *See* Appendix 6.

GROOVE FACE

The surface of a joint member included in the groove. See STANDARD WELDING TERMS. *See* Appendix 6.

GROOVE RADIUS

The radius adjacent to the joint root used to form a J-edge shape. See STANDARD WELDING TERMS. *See* Appendix 6.

GROOVE WELD

A weld made in a groove between the workpieces. See STANDARD WELDING TERMS. *See* Appendix 6.

GROOVE WELD SIZE

The joint penetration of a groove weld. See STANDARD WELDING TERMS. *See* Appendix 12.

GROOVE WELD THROAT

A nonstandard term for GROOVE WELD SIZE.

GROUND CLAMP

A nonstandard and incorrect term for WORKPIECE CONNECTION.

GROUND CONNECTION

An electrical connection of the welding machine frame to the earth for safety. See STANDARD WELDING TERMS. *See* Figure D-5. *See also* WORKPIECE CONNECTION *and* WORKPIECE LEAD.

GROUND LEAD

A nonstandard and incorrect term for WORKPIECE LEAD.

GUIDED BEND TEST

A bending test in which the specimen is placed in a jig and bent to a definite shape. *See* BEND TEST.

GUN

See STANDARD WELDING TERMS. *See also* ARC CUTTING GUN, ARC WELDING GUN, ELECTRON BEAM GUN, RESISTANCE WELDING GUN, SOLDERING GUN, *and* THERMAL SPRAYING GUN.

GUN EXTENSION

The extension tube attached in front of the thermal spraying gun to permit spraying within confined areas or deep recesses. See STANDARD WELDING TERMS.

A typical deck module of an offshore oil drilling installation under construction in Scotland for use in the North Sea. The principal welding processes used in offshore structural fabrication are submerged arc welding (SAW), shielded metal arc welding (SMAW), self-shielded flux cored arc welding (FCAW-SS), and gas shielded flux cored arc welding (FCAW-G).

Photo courtesy of Highlands Fabricators Ltd.

H

HADFIELD STEEL

A manganese steel invented in 1882 by Robert A. Hadfield in Sheffield, England. It has an austenitic structure and an approximate analysis of 12.5% Mn, 1.2% C. Patents granted to Hadfield in 1882–85 covered alloys from 7 to 30% manganese. The steel was first made in the United States in 1892.

Hadfield steel has certain characteristics which make it very useful. For example, it is work hardening. The metal is relatively soft and very tough after quenching in cold water after it is removed from the furnace. Hardness and toughness continue to increase as items made from this steel are impacted by repeated blows during service. *See* MANGANESE STEEL.

HALF-LIFE

The time required for a radioactive substance to decay to half its original value. Radioactive materials are used in radiographic inspection of welds.

HALOGEN CONTAMINATION

The presence of halides, particularly chlorides, has resulted in numerous in-service cracking failures of insulation-covered 18-8 austenitic stainless steels. These failures were first discovered in thermally insulated piping in petrochemical plants which had been built in the 1940s. The elimination of all halide sources during welding and installation, and the prevention of halide contamination during subsequent service, have proven to be extremely difficult. Some failures have been noted even in the presence of very low levels (10 ppm) of chlorides.

These failures have been associated with stress corrosion cracking (SCC), an electrochemical reaction, which produces a fine network of transgranular cracks on the surface of the insulation-covered 18-8 stainless steel. Depending on conditions, failure by SCC may occur in as little as a few days or weeks.

Four conditions are necessary for this SCC to develop:

(1) An 18-8 austenitic stainless steel (such as 304, 304L, 316, 316L, 317, 321, 347.

(2) The presence of halides (particularly the chlorides)

(3) The presence of tensile stresses (elastic or plastic, residual or applied).

(4) The presence of an electrolyte (water).

During SCC, the halide ions dissolve the passive protection layer on the 18-8 stainless steels; localized corrosion cells then become active.

Austenitic stainless steels with higher nickel, chromium, and molybdenum contents have been developed for enhanced resistance to the SCC problem which has plagued the insulation-covered 18-8 stainless steels.

Among the potential trouble-makers are the inks of several types of metal marking pens with high available halogen content, as well as perspiration from the worker's hands. Clean cotton gloves should be worn when working with stainless steel.

HAMMERING, Resistance Spot Welding

Excessive electrode impact on the surface of the workpiece at the start of the welding cycle. See STANDARD WELDING TERMS.

HAMMER WELDING

A nonstandard term for forge welding and cold welding.

HAND SHIELD

A protective device used in arc welding, arc cutting and thermal spraying to shield the eyes, face and neck. It is equipped with a filter glass lens and is designed to be held by hand. See STANDARD WELDING TERMS.

HARD CRACKING

A condition which may develop in the coarse grain structure of the heat-affected zone of alloy steels, but which does not occur in mild steel. It is attributed to the effect of dissolved hydrogen released from austenite as it transforms. It can be avoided in alloy steels by preheating or by using low-hydrogen electrodes, or both.

HARDENABILITY

The relative ability of a steel to form martensite when quenched from a temperature above the upper critical temperature.

Hardenability is commonly measured by the Jominy (end-quench) test, in which the distance is measured from the quenched end to the point where nonmartensitic transformation occurs. *See* JOMINY TEST.

HARDENING

An action which induces hardness. *Hardening* is a term describing the heating and quenching of certain iron-base alloys from a temperature either within or above the critical temperature range.

HARDFACING

A surfacing variation in which surfacing material is deposited to reduce wear. See STANDARD WELDING TERMS. *See also* BUILDUP, BUTTERING, *and* CLADDING.

Hardfacing is the application of a hard, wear-resistant material to the surface of a workpiece by welding or spraying, or allied welding processes, to reduce wear or loss of material by abrasion, impact, erosion, galling and cavitation.

The stipulation that the surface be modified by welding, spraying or allied welding processes excludes the use of heat treatment or surface modification processes such as flame hardening, nitriding, or ion implantation as a hardfacing process.

The stipulation that the surface be applied for the main purpose of reducing wear excludes the application of materials primarily used for prevention or control of corrosion or high-temperature scaling. Corrosion and high-temperature scaling may, however, have a major effect on the wear rate, and for this reason may become a significant factor in selection of materials for hardfacing.

Hardfacing applications for wear control range from very severe abrasive wear service, such as rock crushing and pulverizing, to minute mechanical applications that require minimization of metal-to-metal wear, such as control valves where 0.05 mm (0.002 in.) of wear is intolerable. Hardfacing is used for controlling abrasive wear on mill hammers, digging tools, extrusion screws, cutting shears, parts of earthmoving equipment, ball mills, and crusher parts. It is also used to control wear of unlubricated or poorly lubricated metal-to-metal sliding contacts such as control valves, undercarriage parts of tractors and shovels, and high-performance bearings.

Hardfacing Materials

Hardfacing materials include a wide variety of alloys, ceramics, and combinations of these materials. Conventional hardfacing materials are steels or low-alloy ferrous materials, chromium white irons or high-alloy ferrous materials, carbides, nickel-base alloys, or cobalt-base alloys. A few copper-base alloys are sometimes used for hardfacing applications, but for the most part, hardfacing alloys are either iron, nickel or cobalt base. The microstructure of hardfacing alloys generally consists of hard-phase precipitates such as borides, carbides, or inter-metallics bound in a softer iron, nickel or cobalt-base alloy matrix.

Cobalt-Base Alloys. The alloys listed in Table H-1 that contain 2.5% C have more than 30% by volume total carbides, which results in extremely high abrasion resistance. The microstructure of the Co-30, Cr-12, W-2.5, C alloy, sometimes referred to as Alloy No. 1, has a large volume fraction of carbides. As the carbon content is increased, the volume fraction of the matrix is decreased, and the impact resistance, weldability and machinability are also decreased. Thus, the improvement in abrasive wear resistance is gained at the expense of other properties that may be more desirable.

Nickel-Base Alloys. The commercially available nickel-base hardfacing alloys can be divided into three groups: boride-containing alloys, carbide-containing alloys, and Laves phase-containing alloys. The compositions of some typical nickel-base hardfacing alloys are listed in Table H-2.

The boride-containing nickel-base alloys are commercially produced as spray-and-fuse powders. These alloys are available from most manufacturers of hardfacing products under various trade names and in a variety of forms, such as bare cast rod, tube wires, and powders for plasma spraying. This group of alloys is primarily composed of Ni-Cr-B-Si-C. Usually, the boron content ranges from 1.5% to 3.5%, depending on chromium content, which varies from 0 to 15%. The higher chromium alloys generally contain a large amount of boron, which forms very hard chromium borides with hardness of approximately 1800 DPH (kg/mm^2). Other borides high in nickel and with lower melting points are also present to facilitate fusing. *See* Figure H-1.

The abrasion resistance of these alloys is a function of the amount of hard borides present. Alloys containing large amounts of boron such as Ni-14, Cr-4, Si-3.4, B-0.75, C are extremely resistant to abrasion, but have poor impact resistance. Because most of the boride-containing nickel-base alloys contain only small amounts of solid-solution strengtheners, considerable loss of room-temperature hardness occurs at elevated temperatures.

Table H-1
Composition and Hardness of Selected Cobalt-Base Hard Facing Alloys

		Nominal Macrohardness		Approximate Hardness of Microconstituents		
					Hard Particles	
AWS Designation or Tradename	Nominal Composition	HV	HRC	Matrix, HV	Type	HV
Alloy 21	Co-27Cr-5Mo-2.8Ni-0.2C	255	24–27	250	Eutectic	900
RCoCrA	Co-28Cr-4W-1.1C	424	39–42	370	Eutectic	900(a)
RCoCrB	Co-29Cr-8W-1.35C	471	40–48	420	Eutectic	900(a)
RCoCrC	Co-30Cr-12W-2.5C	577	52–54	510	M_7C_3	900(a)
					M_6C	1540
						1700
Alloy 20	Co-32Cr-17W-2.5C	653	53–55	540	M_7C_3	900
					M_6C	—
Tribaloy T-800	Co-28Mo-17Cr-3Si	653	54–64	800(b)	Laves phase	1100

(a) Matrix and M_7C_3 eutectic.
(b) Matrix and Laves phase eutectic.

Table H-2
Composition and Hardness of Selected Nickel-Base Hard Facing Alloys

		Nominal Macrohardness		Approximate Hardness of Microconstituents		
					Hard Particles	
AWS Designation or Tradename	Nominal Composition	HV	HRC	Matrix, HV	Type	HV
RNiCr-C	Ni-15Cr-4Si-3.5B-0.75C	633	57	420	Primary boride	2300
					Secondary boride	950
					Eutectic	750
					Carbide (M_7C_3)	1700
RNiCr-B	Ni-12Cr-3.5Si-2.5B-0.35C	530	51	410	Primary boride	2300
					Secondary boride	950
					Eutectic phase	750
Hastelloy C	Ni-17Cr-17Mo-0.12C	200	HRB 95	180	M_6C	1700
Haynes 716	Ni-11Co-26Cr-29Fe-3.5W-3Mo-1.1C-0.5B	315	32	215	M_7C_3	1500
Tribaloy T-700	Ni-32Mo-15Cr-3Si	470	45	800(a)	Laves phase	—

(a) Matrix and Laves phase eutectic.

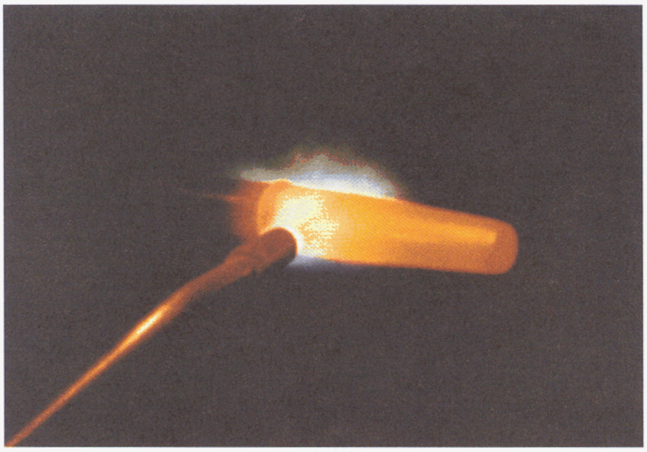


Figure H-1—Fusing a Ni-Cr-B-W Hardfacing Alloy to the Surface of a Thermowell Using an Oxyacetylene Torch. A Thermowell is a Device Used to Protect Thermocouples when Measuring Temperatures Inside Catalytic Crackers, Smokestacks, and Similar Corrosive and Ablative Atmospheres.

Photo courtesy of Wall Colmonoy Corporation

Iron-Base Alloys. Iron-base hardfacing alloys are more widely used than both cobalt-base or nickel-base hardfacing alloys, and constitute the largest volume use of hardfacing alloys. Iron-base hardfacing alloys produce a broad range of desirable properties at low cost. Most equipment that undergoes severe wear, such as crushing and grinding equipment and earthmoving equipment, is usually very large and rugged, and is often subject to contamination. Parts subjected to wear usually require downtime for repair. For this reason, there is a general inclination to hardface them with the materials that are most readily available at the lowest cost. As a result, literally hundreds of iron-base hardfacing alloys are available.

Due to the great number of alloys involved, iron-base hardfacing alloys are best classified by their suitability for different types of wear and their general microstructure rather than by chemical composition. Most iron-base hardfacing alloys can be divided into the following classes: pearlitic steels, austenitic steels, martensitic steels, and high-alloy irons. *See* Table H-3.

Table H-3
Composition and Hardness of Selected Iron-Base Hard Facing Alloys

Nominal Composition	Nominal Hardness HV	Nominal Hardness HRC	Unlubricated Sliding Wear (a), mm^3	Abrasive Wear (b), mm^3	Density, lb/in.^{3}
Pearlitic Steels					
Fe-2Cr-1Mn-0.2C	318	32	0.5	55	0.28
Fe-1.7Cr-1.8Mn-0.1C	372	38	0.6	67	0.27
Austenitic Steels					
Fe-14Mn-2Ni-2.5Cr-0.6C	188 RHB	88 RHB	0.4	86	0.28
Fe-15Cr-15Mn-1.5Ni-0.2C	230	18	0.3	113	0.28
Martensitic Steels					
Fe-5.4Cr-3Mn-0.4C	544	52	0.4	54	0.27
Fe-12Cr-2Mn-0.3C	577	54	0.3	60	0.27
High-Alloy Irons					
Fe-16Cr-4C	595	55	0.3	13	0.27
Fe-30Cr-4.6C	560	53	0.2	15	0.26
Fe-36Cr-5.7C	633	57	0.1	12	0.27

(a) Wear measured from tests conducted on Dow-Corning LFW-1 against 4620 steel ring at 80 rpm for 2000 revolutions varying the applied loads.

(b) Wear measured from dry sand rubber wheel abrasion tests. Tested for 2000 revolutions at a load of 30 lb using a 9-in. diameter rubber wheel and AFS test sand.

Carbides. The quantity of carbides used for hardfacing applications is small compared with iron-base hardfacing alloys, but carbides are extremely important for severe conditions presented by some abrasion and cutting applications. Historically, tungsten-base carbides were used exclusively for hardfacing applications. Recently, however, carbides of other elements, such as titanium, molybdenum, tantalum, vanadium and chromium have proven to be useful in many hardfacing applications.

The widespread use of carbides for hardfacing is primarily based on the general belief that all carbides, due to their high hardness, resist fracture and fragmentation as well as abrasion, especially under high-stress applications. In reality, the resistance of carbide composites is a function of the abrasion resistance of the matrix. While the various carbides have high hardness values, they unfortunately do not have resistance to crushing force, i.e., fracture and fragmentation. Carbides should not be selected based solely on hardness value. For comparison, Table H-4 lists the hardness of various carbides and other selected materials.

Table H-4
Approximate Hardness of Selected Materials

	Hardness		
Material	HV	HK	Mohs
Diamond	...	8000	10
SiC	3200	2750	9.2
W_2C	3000	2550	+9
VC	2800		+9
TiC	2800	2750	+9
Cr_3C_2	2700		
Alumina	...	2100	9
WC	2400	1980	+9
Cr_7C_3	2100	...	...
$Cr_{23}C_6$	1650	...	...
Mo_2C	1570	...	8
Zircon	...	1340	...
Fe_3C	1300		...
Quartz	1000	800	7
Lime	...	560	...
Glass	...	500–600	...

Copper-Base Alloys. The copper-base hardfacing alloys are similar to bronzes and are used in applications where copper-base bearing materials are normally employed as homogeneous parts. It is often more economical to apply copper-base hardfacing alloys as overlays on less expensive base metals such as low-carbon steels.

The properties of copper-base hardfacing alloys are similar to the properties of corresponding bronzes. Copper-base hardfacing alloys are used for applications where resistance to corrosion, cavitation erosion and metal-to-metal wear is required, as in bearing materials. Copper-base hardfacing alloys have poor resistance to corrosion by sulfur compounds, abrasive wear and elevated-temperature creep. They are not as hard as all the classes of alloys previously discussed, and are not easily welded.

Hardfacing Alloy Selection

Hardfacing alloy selection is guided primarily by wear and cost considerations. However, other manufacturing and environmental factors must also be considered, such as base metal, deposition process, and impact, corrosion, oxidation and thermal requirements. Usually, the hardfacing process dictates the hardfacing or filler-metal product form.

Hardfacing alloys are usually available as bare rod, flux-coated rod, spooled solid wires, spooled tube wires (with and without flux), or powders. Table H-5 lists various welding processes, heat sources, and the proper forms of consumables for each process. In general, the impact resistance of hardfacing alloys decreases as the carbide content increases. As a result, in situations where a combination of impact and abrasion resistance is desired, a compromise between the two must be made. Where impact resistance is extremely important, austenitic manganese steels are used to build up worn parts.

Hardfacing Process Selection

Hardfacing process selection, like hardfacing alloy selection, depends on the engineering application or service performance requirements. Other technical factors involved in hardfacing process selection include (but are not limited to) hardfacing property and quality requirements, physical characteristics of the workpiece, metallurgical properties of the base metal, form and composition of the hardfacing alloy, and welder skill. Cost considerations are often the determining factor in the final process selection.

Traditionally, hardfacing has been limited, by definition, to welding processes. However, this definition has been expanded to include thermal spraying (THSP) as a hardfacing process. Frequently the first consideration in hardfacing process selection is to determine if welding processes or THSP processes are

Table H-5
Hard Facing Processing

Process	Heat Source	Mode of Application	Hardfacing Alloy Form
Oxyfuel gas welding	Oxyfuel gas	Manual or automatic	Bare cast rods or powder
Shielded metal arc welding	Electric arc	Manual	Flux coated rods
Open arc welding	Electric arc	Semiautomatic	Flux cored tube wire
Gas tungsten arc welding	Inert gas shielded electric arc	Manual or automatic	Bare rods or wire
Submerged arc welding	Flux covered electric arc	Semiautomatic	Bare solid or tubular wire
Plasma transferred welding	Inert gas shielded plasma arc	Automatic	Powder, hot wire
Plasma arc welding	Inert gas shielded plasma arc	Manual or automatic	Same as GTAW
Spray and fuse	Oxyfuel gas	Manual	Powder
Plasma spray	Plasma arc	Manual or automatic	Powder
Detonation gun	Oxyacetylene detonation	Automatic	Powder

preferred or required. As a rule, welding processes are preferred for hardfacing applications requiring dense, relatively thick coatings with high bond strengths between the hardfacing and the workpiece. Thermal spraying processes, on the other hand, are preferred for hardfacing applications requiring thin, hard coatings applied with minimum thermal distortion of the workpiece.

Source: ASM International; Metals Handbook, Desk Edition; ASM International. 1985.

HARDNESS

The resistance of a material to plastic flow, most often measured by indentation by a penetrator under an impressed load. Additionally, hardness may refer to the resistance to machining, abrasion, or scratching. *See* HARDNESS TESTING.

HARDNESS TESTING

Hardness tests are used to evaluate welds, either alone or to complement information from other test results. The Rockwell, Brinell, Vickers, and Knoop tests are indentation hardness tests that measure the area or depth of indentation under load to determine the hardness. The indentations are made with testing machines selected on the basis of specimen size, form, and purpose of the hardness measurement. Indentation hardness testing is a complex measurement because of the different degrees of work hardening that occur in metals and the influence of the indenter used.

In the Brinell, Vickers, and Knoop tests, the area of the indentation is measured to determine hardness. Rockwell hardness testing relates hardness to the depth of indentation under load.

Rockwell Hardness (HR). The Rockwell hardness test has become the most widely used method for determining hardness because it provides scales that can accommodate specimens of a wide variety of metals in a wide variety of sizes and shapes. The Rockwell hardness test is simple to perform; the hardness number is conveniently read directly on the testing machine, and the testing can be automated if required.

The procedure involves initial application of a minor seating load to the indenter to establish a zero datum position. A diamond-tipped indenter with a sphero-conical shape is used for hard metals, and a small hardened steel ball of prescribed size is used for softer metals. Both the minor load and the major load can be selected, depending on specimen requirements. More than a dozen scales of hardness numbers have been tabulated; each is designated by a letter of the alphabet. These basic scales are supplemented by additional scales that provide modified conditions to compensate for specimen form (e.g., curvature) and approximate level of hardness. Rockwell hardness numbers should always be quoted with a scale symbol, which indicates the kind of indenter, major load, and other testing conditions.

Three Rockwell scales are most commonly used for measuring the hardness of steels:

(1) C Scale, which uses a sphero-conical indenter which applies a 150 kg major load

(2) B Scale, which uses a ball indenter (usually 1.588 mm [1/16 in.] diameter) and a major load of 100 kg (these conditions can be adjusted by an established correction factor)

(3) N Scale, which encompasses many established conditions for superficial hardness testing.

ASTM E18, *Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials* provides standard test methods.

Brinell Hardness (HB). The Brinell method for testing hardness, like the Rockwell scale, has a long history of applications and is commonly used in many metal working plants. The Brinell test is used to monitor mechanical properties in metal articles of substantial size, such as bars, beams, or plates. The Brinell scale is based on the impression made in a flat surface by a hardened steel ball 10 mm (.39 in.) in diameter, when driven into the metal at a force of 3000 kg (6600 lb.). The 30-second test time ensures that plastic flow of the metal surrounding the indentation has ceased. A standard procedure is used to measure the diameter of the indentation and to compute the Brinell hardness (HB) number, using an equation that relates load applied, ball diameter, and indentation diameter to the hardness number. (Computation is seldom needed, since most test results are available in tabular form).

Standards for testing are set forth in ASTM E10, *Brinell Hardness of Metallic Materials,* and ASTM E 370, *Mechanical Testing of Steel Products.*

Vickers Hardness Test (HV). The indenter, a square-based diamond pyramid with a 136° included angle, is used with a variety of loads from 1 kg (2.2 lb) to 120 kg (264 lb). In this microhardness test, impressions can be closely spaced and depth of penetration can be very small.

A standard method for this test is provided in ASTM E92, *Vickers Hardness of Metallic Materials.*

Knoop Hardness Test (HK). A very small indenter, a rhombohedral-based diamond with edge angles of 172°30' and 130°, is used with a variety of loads, usually under 1 kg (2.2 lb). The impression has one long and one short diagonal. Impressions can be very closely spaced and the depth of penetration can be extremely small.

Microhardness Testing

Microhardness tests can be performed with a number of instruments that use a very small indenter and a very light, precise load to make an indentation in a polished surface. The resulting indentation is measured by microscope. A polished and etched metallographic specimen is frequently used to allow hardness determinations on individual phases or constituents in the microstructure. By using an indenter with a test load in the range of 1 to 1000 g, the indentation can be confined to a single grain in the microstructure. Standards for microhardness testing using the Knoop and the Vickers instruments are covered in ASTM E384, *Microhardness of Materials.*

Scleroscope Testing Equipment

The Shore Scleroscope is a hardness testing machine which consists of a vertical glass tube in which a small cylinder, or hammer, with a very hard point slides freely. This hammer weighs 2.5 grams, and is allowed to fall on the sample to be tested from a height of 25 cm. The distance which it rebounds, measured on a scale on the glass tube, constitutes the hardness.

The scale is divided into 140 parts, each part representing a degree of hardness. As examples of this scale, the hardness of glass is 130; the hardest steel is 110; mild steel is from 26 to 30, and cast gray iron is 39.

Comparison of Scales

The relationship among the several hardness scales is presented in Table H-6, showing the appropriate equivalent hardness values for steels.

Brinell Tensile Strength

The Brinell hardness of steel will give a fairly accurate indication of the tensile strength of the material. It has been found that by correlating the Brinell hardness numbers and the tensile strength of various steels in lb/in.^{2}, the tensile strength of a given steel is approximately 500 times its Brinell hardness number. In determining the tensile strength by the use of this rough check it has been found that as a rule, the tensile strength will be slightly low for hardness below 200 HB and above 400 HB. Between the two figures the indicated tensile strength is slightly above the actual strength.

HARD SETTING

A nonstandard term for the application of diamond-substitute inserts to wearing surfaces, using the oxyacetylene process with a welding rod of a softer material. *See* HARDFACING.

HARD SOLDER

A nonstandard term for brazing filler metal. *See* BRAZING.

HARD SPOTS IN CAST IRON

See CAST IRON, Hard Spots.

Table H-6
Approximate Equivalent Hardness Numbers for Steels

HRC (Rockwell C)	HRB (Rockwell B)	HV (Vickers)	HB (Brinell)	Scleroscope
69		1004		
68		940		97
67		900		95
66		865		92
65		832		91
64		800		88
63		772		87
62		746		85
61		720		83
60		697	654	81
59		674	634	80
58		653	615	78
57		633	595	76
56		613	577	75
55		595	560	74
54		577	543	72
53		560	525	71
52		544	512	69
51		528	496	68
50		513	481	67
49		498	469	66
48		484	455	64
47		471	443	63
46		458	432	62
43		446	421	60
44		434	409	58
43		423	400	57
42		412	390	56
41		402	381	55
40		392	371	54
39		382	362	52
38		372	353	51
37		363	344	50
36		354	336	49
35		345	327	48
34		336	319	47
33		327	311	46
32		318	301	44
31		310	294	43
30		302	286	42
29		294	274	41
28		286	271	40
27		279	264	39
26		272	258	38
25		266	253	38
24		260	247	37
23	100	254	243	36
22	99	248	237	35
21	98.5	243	231	35
19.9	98	228	228	34
	97	222	222	33
	96	216	216	32
	95	210	210	31.5
	94	205	205	31
	93	200	200	30
	92	195	195	
	91	190	190	29
	90	185	185	28
	89	180	180	27
	88	176	176	
	87	172	172	26
	86	169	169	26
	85	165	165	25
	84	162	162	
	83	159	159	24
	82	156	156	24
	81	153	153	
	80	150	150	23
	79	147	147	
	78	144	144	22

Note: For HB values <460, measurements are made with a 10 mm diameter hardened steel ball; for HB values >460, measurements are made with a 10 mm diameter tungsten carbide ball.

HARD SURFACING

A nonstandard term for HARDFACING.

HARTFORD TEST

The Hartford test involves an inspection of welds for insurance purposes. It is primarily a procedure qualification test in which sample welds are made using the same material, same equipment and same type of welding wire which are to be used on the job under construction. Even when this combination has been tested and approved, it is necessary before actual work can be started to satisfy the Hartford inspector that the welding operator who is to do the work is capable of producing welds equal in quality to those obtained in the procedure qualification test.

This qualification test remains valid for the individual welder only as long as he continues to work in the same shop with the same equipment and the same welding wire. If the manufacturer should wish to change any of the details of the welding procedure, the welder may be required to repeat the entire qualification program.

HEALTH, SAFETY IN WELDING

See ANSI/ASC Z49.1, latest edition, *Safety in Welding, Cutting and Allied Processes,* published by the American Welding Society. *See* Appendix 13.

HEAT-AFFECTED ZONE (HAZ)

The portion of the base metal whose microstructure or mechanical properties have been altered by the heat of welding, brazing, soldering or thermal cutting. See STANDARD WELDING TERMS. *See* Figure H-2. *See also* METALLURGY.

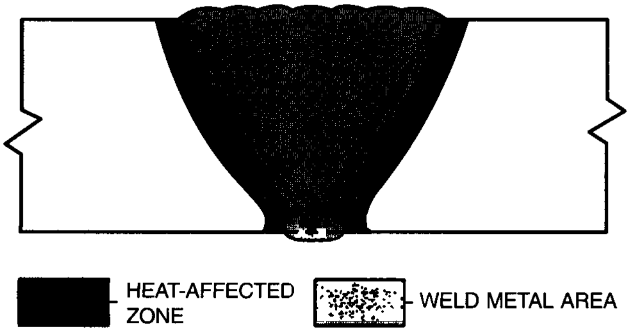


Figure H-2—View of a Heat-Affected Zone

HEAT-AFFECTED ZONE CRACK

A crack in the heat-affected zone of the weldment. See STANDARD WELDING TERMS. *See* Appendix 9.

HEAT BALANCE

The various material, joint, and welding conditions that determine the welding heat pattern in the joint. See STANDARD WELDING TERMS.

HEAT CONDUCTIVITY

See THERMAL CONDUCTIVITY.

HEATING GATE

The opening in the thermite mold through which the parts to be welded are preheated. See STANDARD WELDING TERMS. *See also* THERMITE WELDING.

HEAT INPUT

The energy supplied by the welding arc to the work piece. See STANDARD WELDING TERMS.

HEATING TORCH

A device for directing the heating flame produced by the controlled combustion of fuel gases. See STANDARD WELDING TERMS.

HEAT OF FUSION

The heat given off during the freezing (cooling and solidification) of a metal or alloy, or absorbed during the melting; sometimes called the *heat of solidification.* It is expressed in calories per gram. In the case of alloys, the processes of melting and freezing are complex and usually occur over a range of temperatures rather than at a single temperature. *See* METALLURGY.

HEAT TIME

The duration of each current impulse in multiple impulse welding, resistance seam welding or projection welding. See STANDARD WELDING TERMS. *See also* Figure H-3.

HEAT TREATMENT

The post-welding introduction of heat to the weldment, to remove or improve conditions brought about by the heat of welding. Reduction in grain size, surface hardening, annealing or normalizing, or stress relief are all within the capability of correct heat treatment.

In most shops, post weld heat treat (PWHT) is accomplished in a heat treat furnace with controlled temperature modes allowing for temperature increase, hold-at-soaking temperature, and controlled cooling

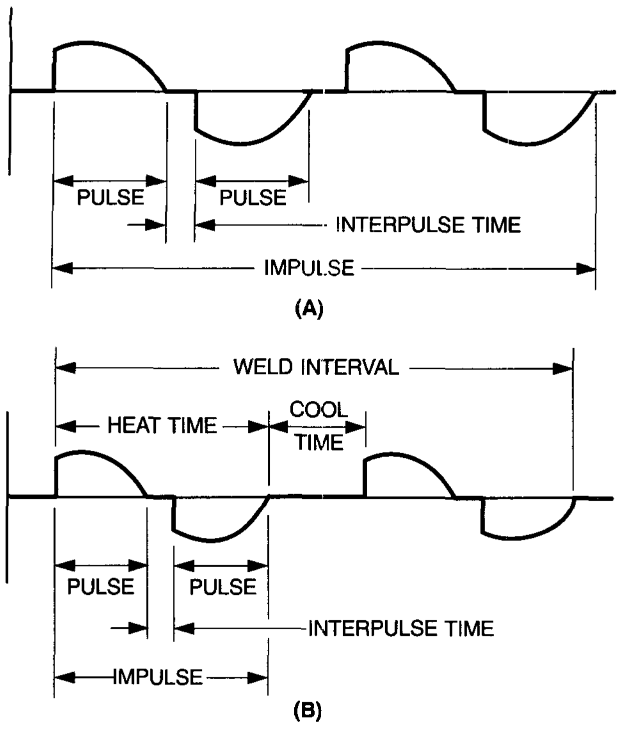


Figure H-3—Resistance Welding Current Characteristics

rate. For small weldments made by oxyacetylene welding, the torch flame can be used for heat treating. For field projects, two heating processes are available: exothermic and electrical resistance. Each method has advantages as well as limitations for use as a heat treating process.

Exothermic. Exothermic materials are special combustible materials which burn under controlled conditions. They are commercially available in molded shapes and flexible lengths that can be stored and cut to fit as needed. The exothermic material is wrapped around the weldment, such as a pipe joint, and wired in place. Then a flame is applied to the material and it burns rapidly, giving off large quantities of heat. When the temperature reaches a predetermined point, determined by experimentation, the exothermic material is completely consumed. Cooling of the joint is controlled by the thickness of the insulation backing on the form. After cooling, the wrapping wires are cut and the material is removed from the joint. In recent years, however, the use of exothermics for PWHT has fallen off sharply due to environmental and thermal control considerations.

Electrical Resistance. Post weld heat treatment using resistance heating involves wrapping the joint with a number of resistance heaters. Advanced electrical resistance systems with automatic controllers make it possible to heat treat several weldments simultaneously.

HELIARC WELDING PROCESS

See GAS TUNGSTEN ARC WELDING.

HELIUM

(Chemical Symbol: He). An inert gas used as a shielding gas in various arc welding processes to protect the weld from atmospheric contamination. Helium has an atomic weight of 4.00; boiling point -269°C (-425°F), and specific gravity of 0.137 as compared to air. Helium can be liquefied and solidified.

HELIUM ARC WELDING

See GAS TUNGSTEN ARC WELDING.

HELIX

A coil of wire; a solenoid.

HELMET

See WELDING HELMET, EYE PROTECTION *and* GOGGLES.

HENRY (H)

The electrical unit of inductance. One henry equals the self-inductance of a circuit in which the variation of one ampere per second results in an induced electromotive force of one volt.

HERTZ (Hz)

The unit of electrical frequency. One hertz is one cycle per second.

HIGH-CARBON STEEL

See STEEL, HIGH CARBON.

HIGH FREQUENCY, Gas Tungsten Arc Welding

An alternating current in the frequency range of 2 MHz used for arc starting and stabilization.

HIGH-FREQUENCY HEATING

A process in which the heating effect is produced electrostatically. The chief objective of the process is to obtain uniform heating throughout a mass of material which is a non-conductor of electricity, and hence a non-conductor of heat.

To achieve this objective, the non-conducting material to be heated is used to form the dielectric of a condenser, with the electrodes consisting of conductive surfaces, one on each face of the material. Several thousand volts and a frequency in the range of 1.5 to 10 MHz are employed. The heat is generated by the agitation of the molecules when subjected to the high-frequency field, unlike the hysteresis effect occurring in induction heating. The energy of agitation is converted into heat, which is uniformly distributed throughout the mass of the material.

HIGH-FREQUENCY RESISTANCE WELDING (HFRW)

A group of resistance welding process variations that use high frequency welding current to concentrate the welding heat at the desired location. See STANDARD WELDING TERMS. *See* Figure H-4. *See also* HIGH-FREQUENCY SEAM WELDING *and* UPSET WELDING.

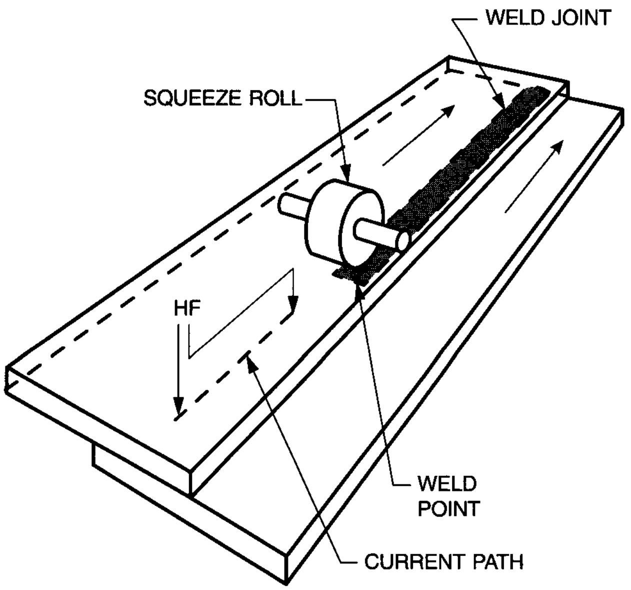


Figure H-4—Lap Joint Made by High-Frequency Seam Welding

High-frequency resistance welding is a forge welding process in which the faying surface is heated to plastic welding temperatures by using power in the range of 400 to 450 kHz. Power is introduced to the weldment through small contacts sliding or rolling directly on the metal to be welded. The process is continuous, and produces a strong forge weld when the heated parts are passed in line through squeeze rolls.

The process is particularly suited for continuous production of large volumes of tubular and similar products. Welds can be made without filler metal, at speeds to 300 m/min (1000 ft/min) in ferrous, non-ferrous, exotic and dissimilar metals, in thicknesses of 0.1 to 16 mm (0.0045 to 0.625 in.). Users are able to achieve high production rates with a variety of metals, and are able to weld many of the high-strength alloys that often prove troublesome when other welding processes are used.

HIGH-FREQUENCY SEAM WELDING (RSEW-HF)

A resistance seam welding process variation in which the high-frequency welding current is supplied through electrodes into the workpieces. See STANDARD WELDING TERMS. *See also* Figure H-4. *See also* HIGH-FREQUENCY RESISTANCE WELDING *and* INDUCTION SEAM WELDING.

HIGH-FREQUENCY SYSTEMS

Welding machines and welding processes operating in the 50 kHz to 3 MHz frequency range. High-frequency power sources are used for arc initiation, arc stabilization and gas ionization with the gas tungsten arc welding (GTAW) process.

Arc Initiation. By ionizing a gas path between the electrode and the workpiece, high-frequency power helps bridge the physical distance for making non-touch starts. Non-touch starts are preferable in GTAW, since they minimize the possibility of electrode contamination, as well as weld metal contamination, which would result from touching the tungsten electrode to the workpiece. High-frequency voltage is considered relatively safe for the operator to use in making non-touch starts. While the voltage is high, the current is in milliamperes.

Arc Stabilization. Arc stabilization is considered the most important function of high-frequency power in welding. When welding with an a-c welding power source connected to a 60 Hz power system, there is an arc outage each 1/120 of a second. The time of the arc outage will depend somewhat on the re-initiation characteristics of the welding machine. When high frequency is a part of the welding circuitry system, it provides the stable re-initiation effect necessary to maintain a steady arc.

Gas Ionization. In GTAW, the open circuit voltage of the welding machine is insufficient to ionize the shielding gases; consequently, a direct arc path is not readily established. This can be overcome by imposing high-frequency voltage on the arc voltage, producing a high-frequency voltage in the range of 20 000 volts at the electrode tip. Since the ionization potentials of the two commonly used shielding gases, argon and helium, are relatively low, the high-frequency voltage creates an ionized path for the welding current to follow.

HIGH-FREQUENCY UPSET WELDING (UW-HF)

An upset welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces. See STANDARD WELDING TERMS. *See* Figure H-5. *See also* HIGH-FREQUENCY RESISTANCE WELDING *and* INDUCTION UPSET WELDING.

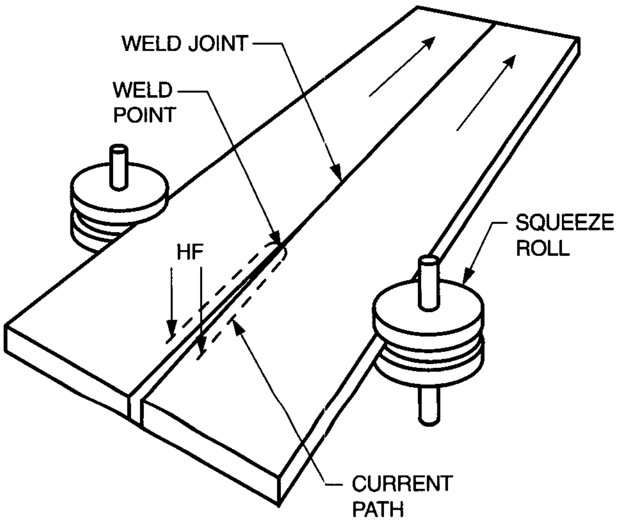


Figure H-5—Butt Joint Made by High-Frequency Upset Welding

HIGH-LOW

A nonstandard term for WELD JOINT MISMATCH.

HIGH PULSE CURRENT, Pulsed Power Welding

The current during the high pulse time that produces the high heat level. See STANDARD WELDING TERMS. *See also* Appendix 19.

HIGH PULSE TIME, Pulsed Power Welding

The duration of the high pulse current. See STANDARD WELDING TERMS. *See also* Appendix 19.

HIGH-SPEED STEEL

See STEEL, HIGH SPEED *and* TOOL WELDING.

HIGH TENSION

A term referring to high electric voltage.

HIGH VACUUM ELECTRON BEAM WELDING (EBW-HV)

An electron beam welding process variation in which welding is accomplished at a pressure of 10^{-4} *to* 10^{-1} *pascals (approximately* 10^{-6} *to* 10^{-3} *torr). See* STANDARD WELDING TERMS.

High vacuum electron beam welding is done inside a vacuum chamber. The chamber is evacuated to create a "high purity" environment (high vacuum) to avoid contamination by oxygen or nitrogen. This environment results in minimum heat effects and maximum reproducibility, and is required for high precision welding applications. Products include nuclear fuel elements, special alloy jet engine components, pressure vessels for rocket propulsion systems, and hermetically sealed vacuum devices. *See* ELECTRON BEAM WELDING.

HOLD TIME

The duration of force application at the point of welding after the last pulse ceases. See STANDARD WELDING TERMS. *See also* Figure H-6.

In brazing or soldering, the amount of time a joint is held within a specified temperature range.

HOLDING TIME

In brazing or soldering, the amount of time a joint is held within a specified temperature range.

HOLLOW BEAD

A nonstandard term when used for ELONGATED POROSITY.

HOLOGRAPHIC NONDESTRUCTIVE TESTING

A holographic process for testing, utilizing the coherent light of the laser, in which the specimen is not damaged. Holographic nondestructive testing systems usually incorporate holography (lens-less, three-dimensional laser photography), interferometry, and an appropriate means of stressing the test specimen. Mild stressing is sometimes accomplished with a hot air gun, a quartz heater, or even amplified sound.

Inspection consists of optical comparison of a test specimen in two or more (unstressed and stressed) states. Performance characteristics of the test object can then be evaluated directly by observing the resulting holographic interferometric fringe pattern. Lines in the hologram that show abrupt bends indicate defects. Where a defect exists, the surface under stress will move more. Lines with sharp angular bends are one indication of a defect; rings or spread lines are other possible indications. Besides being relatively fast, the process permits scan-testing of fairly sizeable weldments.

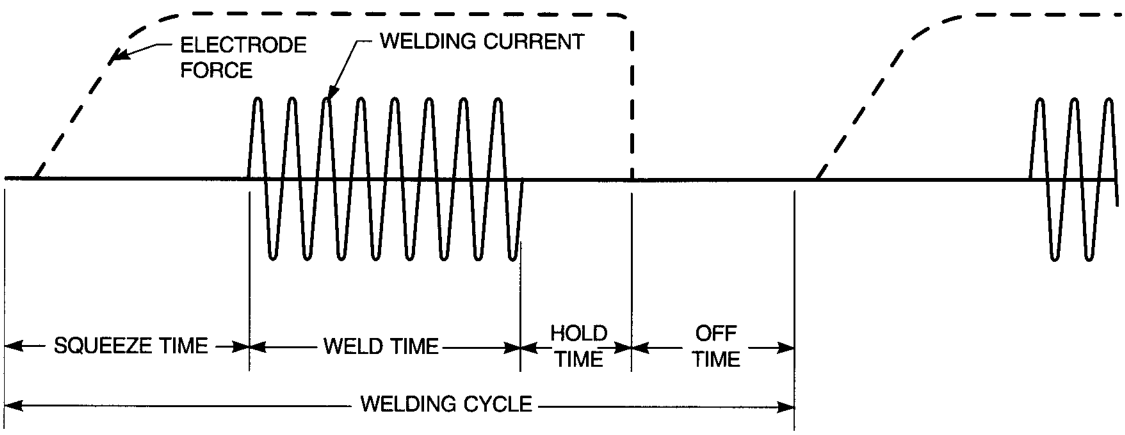


Figure H-6—Single-Impulse Resistance Spot Welding Schedule

HOOD

A non-standard term for WELDING HELMET. *See also* EYE PROTECTION.

HOOKE'S LAW

A statement of a natural law that in an elastic material, strain is proportional to stress. The value of stress at which a material ceases to obey Hooke's Law is known as the proportional limit. *See* ELASTICITY.

HORIZONTAL FIXED POSITION

A nonstandard term for 5G. *See also* Appendix 4, Welding Test Positions

HORIZONTAL POSITION

See HORIZONTAL WELDING POSITION.

HORIZONTAL ROLLED position

A nonstandard term for 1G. *See* Appendix 4, Welding Test Positions.

HORIZONTAL WELDING POSITION, Fillet Weld

The welding position in which the weld is on the upper side of an approximately horizontal surface and against an approximately vertical surface. See STANDARD WELDING TERMS. *See also* Appendix 4, Welding Test Positions.

HORIZONTAL WELDING POSITION, Groove Weld

The welding position in which the weld face lies in an approximately vertical plane and the weld axis at the point of welding is approximately horizontal. See STANDARD WELDING TERMS. *See also* Appendix 4, Welding Test Positions.

HORN

An extension of the arm of a resistance welding machine that transmits the electrode force, usually conducts the welding current, and may support the workpiece. See STANDARD WELDING TERMS.

HORN SPACING

A nonstandard term for THROAT HEIGHT on a resistance welding machine.

HORSEPOWER (Hp)

A unit of power, numerically equivalent to a rate of 33 000 foot-pounds of work per minute, or 550 ft-lb per second. An electrical hp is equal to 746 watts.

HOSE CONNECTION STANDARDS

During the early years of welding and cutting apparatus development, there was no uniformity among manufacturers of torches, hose connections and regulators. In order to use one manufacturer's torch with another manufacturer's regulator, an adaptor had to be inserted to make the connection, or hose connections had to be changed entirely. In a cooperative effort, the equipment manufacturers developed a set of standards which were approved by the Gas Products Association (no longer in existence) and the International Acetylene Association. These standards have been in use since 1926. They were also adopted by the National Screw Thread Commission of the Bureau of Standards (now the National Institute of Standards and Technology), Washington D.C., as Standard No.107.

Threads for the hose connections for small torches are 3/8 in. O.D., 24 threads per in., left hand for acetylene and other fuel gases, and right hand for oxygen.

Threads for ordinary size torches and for regulators are 9/16 in. O.D., 18 threads per in., left hand for acetylene and other fuel gases, and right hand for oxygen.

HOSE REEL

A frame that turns on an axis on which welding hose is wound; it is frequently spring-loaded to automatically retract excess hose.

HOSE, Welding

The flexible tubing used to supply gases to the welding or cutting torch. This hose must be sturdy enough to resist the pressure of the gases and stand up under the constant flexing and twisting of welding operations. Hose specifically manufactured for welding in accordance with *Specification 1-P-7 for Rubber Welding Hose*, published by the Compressed Gas Association and the Rubber Manufacturers Association, should be used. Lesser grades may disintegrate inside, and the resulting particles can clog the torch valves and contaminate the weld.

To prevent error in connecting apparatus for oxyfuel gas welding, two colors of hose are used: red for fuel gas and green for oxygen. Hose connections must be checked for tightness to avoid gas leakage. When parallel lengths are strapped together for convenience, no more than 100 mm (4 in.) of any 400 mm (12 in.) section of hose should be covered by the strapping. Ferrules and clamps made specifically for welding hoses should be used to secure hose to fittings.

Long runs of hose should be avoided. Excess hose should be coiled to prevent kinks and tangles, but should not be wrapped around cylinders or cylinder carts while in use. Twin hose lines, with two hose lines molded into a single casing of rubber, are convenient and prevent twisting and kinking. Welding hose will be much safer and have longer service life if it is kept away from flames, sparks or molten metal. Before starting to weld, the operator should also see that hose is not left where it can be walked on or run over by vehicles while the operator is concentrating on the weld. This is likely to happen if very long lengths of hose are used.

A backfire which reaches back into the hose ruins it completely, and if it is used for any length of time after such an accident the gas passages in the torch will become clogged with fine particles of the burned lining. Contact with grease or oil is unsafe with oxygen use. Leaky hose is dangerous (and wasteful); hose should be tested at regular intervals by immersing it in water while under pressure. When leaks are found, they should not be repaired with tape. The section with the leak should be cut out and a union inserted, fastened securely with clamps.

HOT CONDUCTOR

A term sometimes used for a conductor or wire carrying current or voltage.

HOT CRACK

A crack formed at temperatures near the completion of solidification. See STANDARD WELDING TERMS.

HOT GAS WELDING

A manual or semiautomatic process used to weld polymeric composites. A heated gas is blown over a welding rod and the joint surfaces. The molten rod is used to fill in the joint and weld the two parts. Hot-gas welding is suitable for small weld areas, but is slow even for small areas, with welding rates of 0.8 to 5 mm/s (2 to 12 in./min).

Hot gas welding is used primarily for low-cost composite matrices with lower melting temperatures for small-volume production of parts with many varying geometries. Hot gas welded joints cannot be used in high-strength applications because the joint area is small (on the order of the part thickness) and it cannot compensate for discontinuity in the reinforcement across the joint.

HOT PLATE WELDING

A technique for welding polymer matrices with low melting temperature, in which the parts are brought into contact with a hot plate. The plate surfaces are usually coated with polytetrafluorethelyne (PTFE) to keep the parts from sticking to the hot plate. For high-temperature polymeric matrices, special bronze alloys may be used to reduce sticking. In some cases, non-contact welding is used, in which the parts are brought very close to the hot plate without actually touching it. In this case, the hot plate is elevated to very high temperatures and the composite surfaces are heated by convection and radiation. This technique is especially good for mass production of small parts. It is tolerant of variations in material properties and welding conditions and is widely used for welding thermoplastics. This technique is not flexible and is not often used in small production of parts with varying geometries. Because heating and pressing are done at different times, this technique is difficult to use for composites with high thermal conductive reinforcements; the surfaces cool and resolidify before the parts can be aligned and pressed together.

HOT ISOSTATIC PRESSURE WELDING

A diffusion welding process variation that produces coalescence of metals by heating and applying hot inert gas under pressure. See STANDARD WELDING TERMS.

HOT PRESSURE WELDING (HPW)

A solid-state welding process that produces a weld with heat and application of pressure sufficient to produce macro deformation of the workpieces. See STANDARD WELDING TERMS. *See* COLD WELDING; DIFFUSION WELDING *and* FORGE WELDING.

HOT RODS

A term sometimes used in referring to E6020 and E6030 electrodes. They are called "hot rods" because when depositing weld metal in flat or horizontal positions with these electrodes, high current may be used while holding a very short arc. As a result, a high rate of deposition is obtained. There is also a significant increase in penetration beyond the root of the weld, which measurably increases the strength of the weld. Because of the deeper penetration obtained, much of the weld metal is derived from the base metal of the part being joined, therefore the process is economical because less electrode is consumed. *See* DEEP WELDING.

HOT SHORT

The condition of metal when it proves to be very brittle and unbendable at red heat but can be bent without showing signs of brittleness when cold or at white heat. This condition is often a result of a high sulphur and phosphorus content.

HOT START CURRENT

A very brief current pulse at arc initiation to stabilize the arc quickly. See STANDARD WELDING TERMS.

HOT WIRE WELDING

A variation of a fusion welding process in which a filler metal wire is resistance heated by current flowing through the wire as it is fed into the weld pool. See STANDARD WELDING TERMS. *See also* GAS TUNGSTEN ARC WELDING.

Hp

Abbreviation for horsepower.

HUBERENIUM

A non-toxic lead alloy coating for protecting iron and steel against corrosion. It is produced by alloying lead with 8% tin and 1% bismuth. The alloy has a density of 10.7 g/cm^3.

HUEY TEST

A laboratory test to determine the corrosion-resisting qualities of welded stainless steel. This test is carried out by subjecting welding samples to the action of boiling 65% nitric acid for five 48-hour periods. After each test the specimen is washed in water but is not polished or scraped. It is then dried, weighed and immersed in fresh acid. Four observations are made for each period: weight loss, overall penetration, appearance of weld and base metal, and the relative attack on the heat-affected zone.

The specimens are exposed to the boiling acid in a glass apparatus with condensers to prevent loss of acid by evaporation. The test is used to determine metal quality and also to show intergranular sensitivity caused by large weight losses.

HYDRATED LIME

Hydrated lime, often called dry slaked lime, is very useful in a welding shop to slow the cooling of castings after they have been welded. Small castings which can be handled after welding are placed, while hot, in a box and covered with fine powdered lime. This protects them from oxygen in the air and slows the rate of cooling, ensuring soft welds.

HYDRAULIC

Pertaining to water or fluids in motion.

HYDRAULIC BACK PRESSURE VALVE

See VALVE, HYDRAULIC BACK PRESSURE.

HYDROABRASIVE MACHINING

See WATER JET CUTTING.

HYDROGEN

(Chemical symbol: H). Hydrogen is a chemical element that occurs in free state in the gases of certain volcanos. In combination with other elements it is found in most organic compounds and many inorganic compounds. Water is a chemical compound of hydrogen and oxygen, in which approximately 11% by weight is hydrogen.

Hydrogen is the lightest element known; it has an atomic weight of 1.008, compared with 16 for oxygen. The density as compared with air is .0695. In gas form, hydrogen is colorless, odorless, and tasteless. When liquefied, it is a clear and colorless liquid. Under atmospheric pressure the boiling point of hydrogen is –252.5°C (–422.5°F).

Hydrogen combines readily with oxygen in the presence of heat, and forms water. Hydrogen and oxygen burn together with an almost colorless flame.

They produce a very hot flame that can be utilized for various purposes, such as lead burning, brazing, and for welding aluminum. The principal objection to the oxyhydrogen flame is that it is very difficult to determine whether the flame is neutral or not, because of the absence of a definite inner cone in the flame.

Hydrogen can be manufactured either by steam reformation of hydrocarbons, partial oxidation of coal or hydrocarbons, or electrolysis of water. The most widely used commercial method is steam reformation of natural gas or an alternate feedstock such as propane or refinery gases. In this process the hydrocarbon source is reacted with superheated steam in the presence of a nickel catalyst to produce hydrogen plus some other gaseous by-products. The gas stream is then passed through an absorption bed to purify the product and produce pure hydrogen.

Where steam reformation is uneconomical, hydrogen is manufactured by partial oxidation of hydrocarbons. With this method combustion takes place in special burners that oxidize the input material in an oxygen deficient atmosphere in the presence of water vapor. Purification is accomplished in a manner similar to that used in steam reformation.

Hydrogen is supplied to users in seamless, drawn-steel cylinders, charged to a pressure of 13.8 MPa at 21°C (2000 psi at 70°F). The size of the hydrogen cylinder standardized by the gas industry has a capacity of about 5.4 m^3 (191 cu. ft).

HYDROGEN ARC WELDING

See ATOMIC HYDROGEN WELDING.

HYDROGEN BRAZING

A nonstandard term for any brazing process that takes place in a hydrogen or hydrogen-containing atmosphere.

HYDROGEN CUTTING

See OXYFUEL GAS CUTTING, Underwater Cutting; *and* PLASMA ARC CUTTING.

HYDROGEN EMBRITTLEMENT

Hydrogen embrittlement is a condition that causes a loss of ductility and which exists in weld metal due to hydrogen absorption. In some metals the loss of ductility induces cracking. Underbead cracking may also be caused by hydrogen embrittlement of the weld. Metals that are subject to hydrogen embrittlement will have reduced impact values and lower mechanical properties.

HYDROMATIC WELDING

A nonstandard term for PRESSURE CONTROLLED WELDING.

HYDROSTATIC TEST

A test in which the soundness of tanks, closed containers or pressure vessels is determined by applying internal pressure. It may be nondestructive or destructive, as required. The pressure is applied hydrostatically, and in this method of testing there is little tendency for the container to disintegrate explosively in case of rupture and sudden release of pressure. The equipment required for hydrostatic testing consists of a pump, pressure gauge, and the pipe necessary to connect to the device being tested.

To conduct a hydrostatic test, the vessel to be tested is completely filled with water and all air bubbles are allowed to escape. After all outlets have been closed, the pump is operated until the desired pressure is obtained. Pressures up to 41 MPa (6000 psi) may be easily obtained.

In some instances specifications call for a hammer test of the pressure vessel while under twice the working pressure. In this case the weight of the hammer in pounds is equal to the shell thickness in tenths of an inch. Blows are struck at 15 cm (6 in.) intervals at both sides of the weld for the full length of the seam. A thorough visual inspection follows; then the pressure is increased to three times the working pressure and the seam is again inspected. *See* TUBE TESTING.

HYSTERESIS (Magnetic)

The tendency of magnetism to lag behind the current that produces it. It is the resistance of magnetic particles of a material to seek polar orientation when subjected to a magnetic field. Hysteresis losses occur in transformer core material when there is a molecular resistance to the changing of polarity that occurs each half cycle in an alternating current.

Hz

Abbreviation for Hertz.

References

Metals Handbook, Desk Edition, ASM
Standard Welding Terms and Definitions, ANSI/AWS A3.0
Welding Handbook, Vol. 1
Welding Handbook, Vol. 2
Welding Handbook, Vol. 2
Welding Metallurgy

I

I-BEAM

A steel beam, the cross section of which resembles the capital letter, I. *See* STRUCTURAL WELDING.

IMAGE QUALITY INDICATOR

See PENETRAMETER.

IMPACT TEST

A destructive test in which one or more blows are forcefully applied to a specimen to evaluate fracture toughness or other characteristics. The results are expressed in terms of energy absorbed or the number of blows of a specific intensity required to break the specimen. *See* CHARPY TEST *and* IZOD TEST.

IMPEDANCE

A measure of the opposition to current flow in an alternating current circuit; a combination of resistance and reactance. It is designated by "Z" in electrical drawings. The unit of impedance is the ohm.

IMPEDANCE COIL

A reactance choke coil, used to limit the flow of alternating current.

IMPULSE, Resistance Welding

A sudden change, such as an increase or decrease in voltage or current. In resistance welding, an impulse of welding current consisting of a single pulse, or a series of pulses separated only by an interpulse time. See STANDARD WELDING TERMS. *See* Figures H-6 and I-1.

INADEQUATE JOINT PENETRATION

A nonstandard term describing joint penetration which is less than that specified.

INCANDESCENT

Emitting light as a result of heating; for example, a metal glowing or white with heat. The resistance welding process was once known as *incandescent welding* because the metals are momentarily incandescent at the moment of welding.

INCLINED POSITION

A nonstandard term for the 6G welding position. *See* Appendix 4, WELDING TEST POSITIONS.

INCLINED POSITION, with Restriction Ring

A nonstandard term for the 6 GR welding position. *See* 6G. *See also* Appendix 4, WELDING TEST POSITIONS.

INCLUDED ANGLE

A nonstandard term for GROOVE ANGLE.

INCLUSION

Entrapped particles of solid material, such as slag, flux, tungsten, or oxide occurring in metal or welds. See STANDARD WELDING TERMS.

INCOMPLETE FUSION (IF)

A weld discontinuity in which fusion did not occur between weld metal and fusion faces or adjoining weld beads. See STANDARD WELDING TERMS. *See* Figure I-2. *See also* COMPLETE FUSION.

INCOMPLETE JOINT PENETRATION (IJP)

A joint root condition in a groove weld in which weld metal does not extend through the joint thickness. See STANDARD WELDING TERMS. See Figure I-3. *See also* COMPLETE JOINT PENETRATION, COMPLETE JOINT PENETRATION WELD, PARTIAL JOINT PENETRATION WELD, *and* JOINT PENETRATION.

Incomplete Penetration. Among the causes of incomplete penetration are improper joint preparation; using an electrode that is too large, using insufficient welding current, and excessive welding speed.

To correct incomplete penetration: allow proper opening at bottom of weld; use electrodes of appropriate diameter in narrow groove; use sufficient welding current and proper welding speed; use a backup bar; chip or cut out the back of the joint and deposit a bead.

INDENTATION

In a spot, seam, or projection weld, the depression on the exterior surface or surfaces of the base metal. See STANDARD WELDING TERMS.

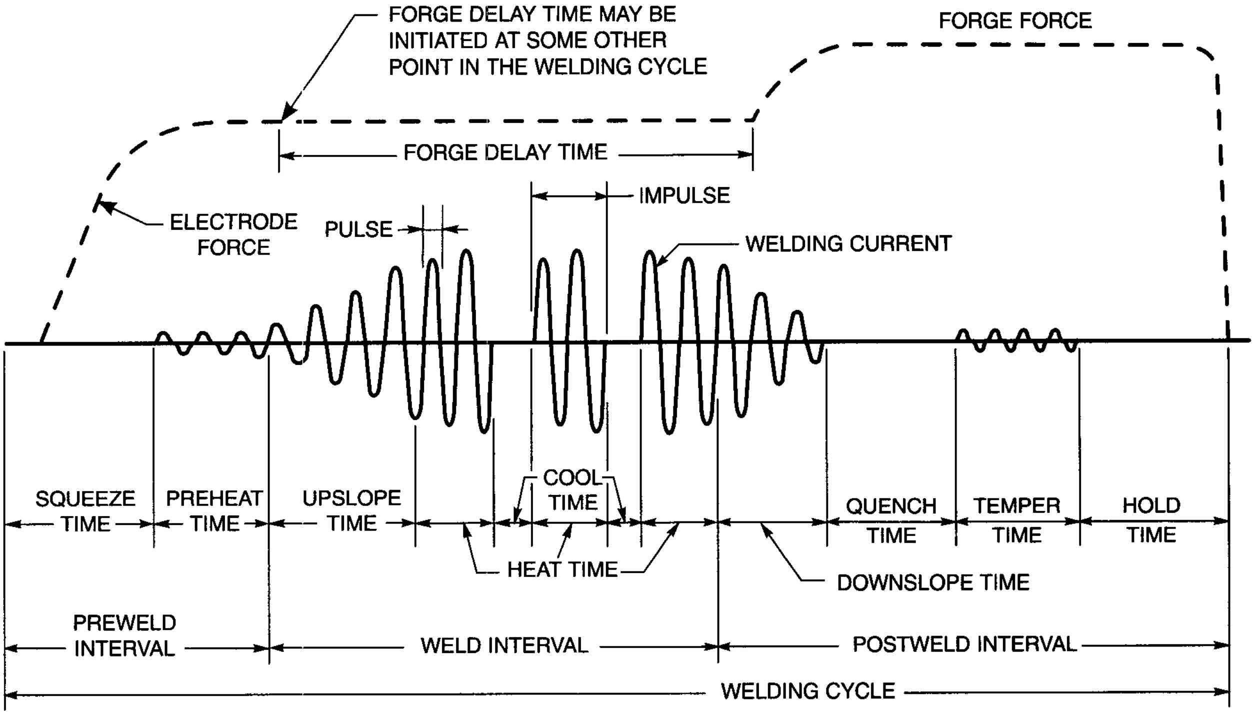


Figure I-1—Multiple-Impulse Resistance Spot Welding Schedule

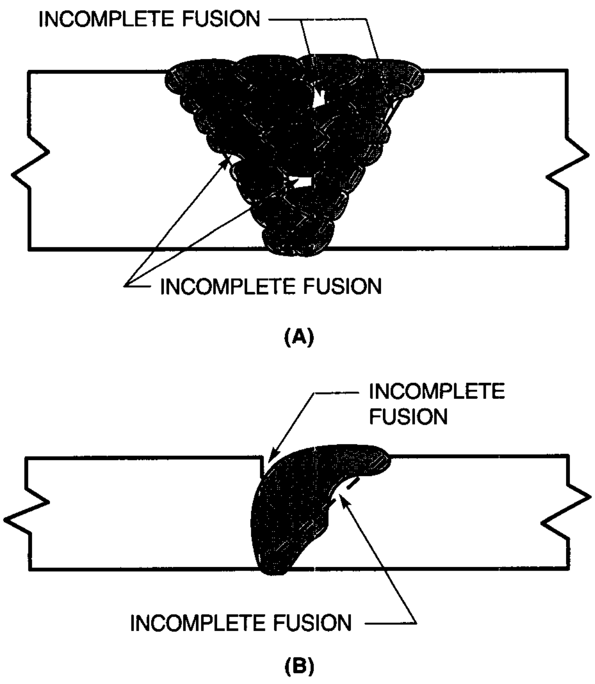


Figure I-2—Examples of Incomplete Fusion

INDIRECT WELDING

A resistance welding secondary circuit variation in which the welding current flows through the workpieces in locations away from, as well as at, the welds for resistance spot, seam, or projection welding. See STANDARD WELDING TERMS. *See* Figure I-4.

INDUCED CURRENT

Current in an electric circuit that is produced by inductance from another circuit.

INDUCED E.M.F. (Electromotive Force)

Voltage in an electric circuit that is produced by induction from another circuit.

INDUCED MAGNETISM

Magnetism that is produced by electric current or by the action of other magnetism.

INDUCED VOLTAGE

Voltage or pressure in an electric circuit produced by induction.

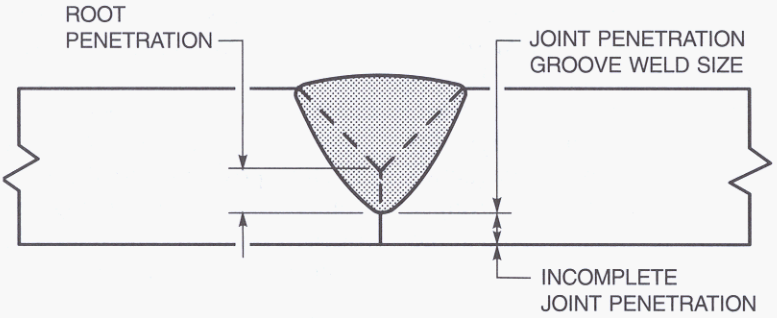


Figure I-3—Examples of Joint Penetration, Root Penetration, and Incomplete Joint Penetration

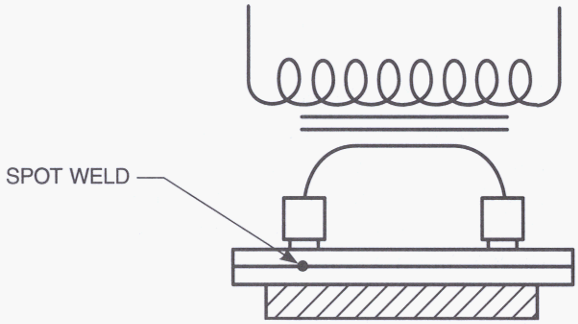


Figure I-4—Example of a Resistance Spot Weld Made with Indirect Welding

INDUCTANCE

The ability of a conducting coil to generate electromotive force by induction within itself.

INDUCTION

The process of generating electromotive force in a closed circuit by varying a magnetic flux through the circuit.

INDUCTION BRAZING (IB)

A brazing process that uses heat from the resistance of the workpieces to induced electric current. See STANDARD WELDING TERMS.

Induction brazing uses a non-ferrous filler metal with a melting point above 425°C (800°F), but below that of the base metals. The filler metal is distributed in the joint by capillary action.

Brazing by induction heating is accomplished by placing the joint to be brazed in an alternating magnetic field. Either magnetic or non-magnetic materials may be induction-brazed.

Induction brazing of hydraulic fittings is shown in Figure I-5. The fittings are placed in a reversing magnetic field generated in the copper bracket to the left of center. Parts are prefluxed and preformed filler material is placed prior to heating.

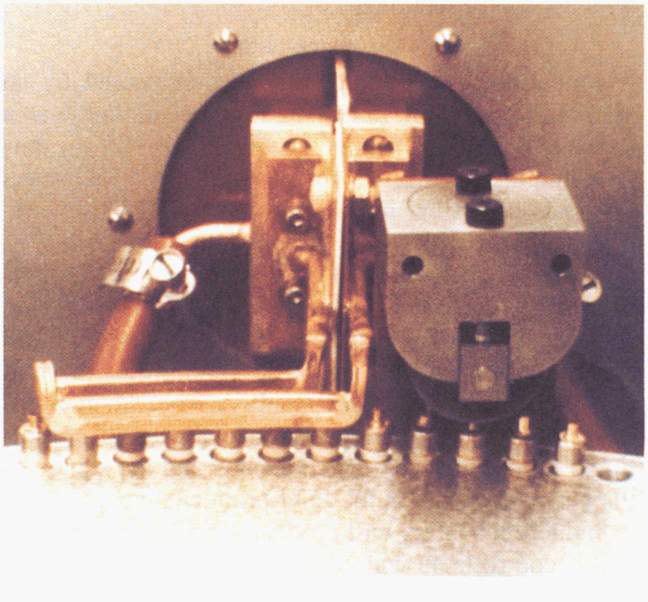


Figure I-5—Induction Brazing of Hydraulic Fittings

Photo courtesy of Pillar Industries

The heating of non-magnetic material depends solely on eddy current losses. Eddy current losses are a function of the frequency of current reversal of the magnetic field, which in turn is determined by the frequency of the current reversals in the conductor. Because the resistance of non-ferrous (non-magnetic) metals is usually less than that of ferrous (magnetic) metals, this loss is comparatively small, so a stronger magnetic field must be used to obtain comparable heating results. It is necessary, therefore, to go to high frequencies in order to increase the heating effect. *See* INDUCTION HEATING.

INDUCTION FURNACE

See FURNACE.

INDUCTION GENERATOR

A rotating device, i.e., a motor, or a solid state electronic device based on an oscillator which may be used to change the frequency of the a-c field, which produces electric current for use in induction heating applications. The device produces a varying magnetic field which induces current into the workpiece.

INDUCTION HEATING

Heating a material from within by causing an electric current to flow through the material by electromagnetic induction. It is essential that the material being heated is not a part of any closed electric circuit supplied from a source of electric energy, as is the case with resistance welding.

Fundamentals

Induction heating is a phenomenon caused by an alternating magnetic field. The field occurs in the area surrounding a conductor carrying an alternating current, and the reversals of the magnetic field follow the reversals of current in the conductor. Magnetic material, if placed within this field, is heated by both hysteresis and eddy current losses. Hysteresis loss is caused by molecular friction within the material, and the magnitude of this loss is directly proportional to the frequency of the magnetic field. Eddy current losses are resistance losses resulting from small circulating currents within the material. This loss is proportional to the square of the frequency and the square of the current flowing in the field-producing conductor.

Induction heating will produce a fast, localized heat that is controllable within close limitations to a predetermined temperature; these qualities make this heating process adaptable to many mass production manufacturing applications.

Wear resistance of pinion gears, splines and journals on shafts can be improved by selective hardening. A system for hardening a small pinion gear of AISI 4140 steel provides a case extending 0.50 to 0.75 mm (0.020 to 0.030 in.) below the roots of the gear teeth. As shown in Figure I-6, the gear is moved from the loading position into the induction coil on a pop-up rotary spindle. After being heated, it is lowered to the quench position. The unit is serviced by a 60-kW/150 to 400 kHz induction generator.

Skin Effect. The higher the frequency of the induction heater power supply, the more the induced voltage tends to concentrate in the outer layers (skin effect) of the workpiece. Thus, the induction heater can produce a hardened outer surface of the workpiece while leaving the inner surface relatively unchanged.

INDUCTION HYSTERESIS

See INDUCTION HEATING.

INDUCTION SEAM WELDING (RSEW-I)

A resistance seam welding process variation in which high-frequency welding current is induced in the workpieces. See STANDARD WELDING TERMS. *See* HIGH FREQUENCY RESISTANCE WELDING *and* HIGH-FREQUENCY SEAM WELDING.

INDUCTION SOLDERING (IS)

A soldering process in which the heat required is obtained from the resistance of the workpieces to induced electric current. See STANDARD WELDING TERMS.

INDUCTION UPSET WELDING (UW-I)

An upset welding process variation in which high-frequency welding current is induced in the workpieces. See STANDARD WELDING TERMS. *See* Figure I-7. *See also* HIGH FREQUENCY RESISTANCE WELDING *and* UPSET WELDING.

INDUCTION WELDING (IW)

A welding process that produces coalescence of metals by the heat obtained from the resistance of the workpieces to the flow of induced high-frequency welding current with or without the application of pressure. The effect of the high-frequency welding current is to concentrate the welding heat at the desired location. See STANDARD WELDING TERMS. *See* Figure I-7.

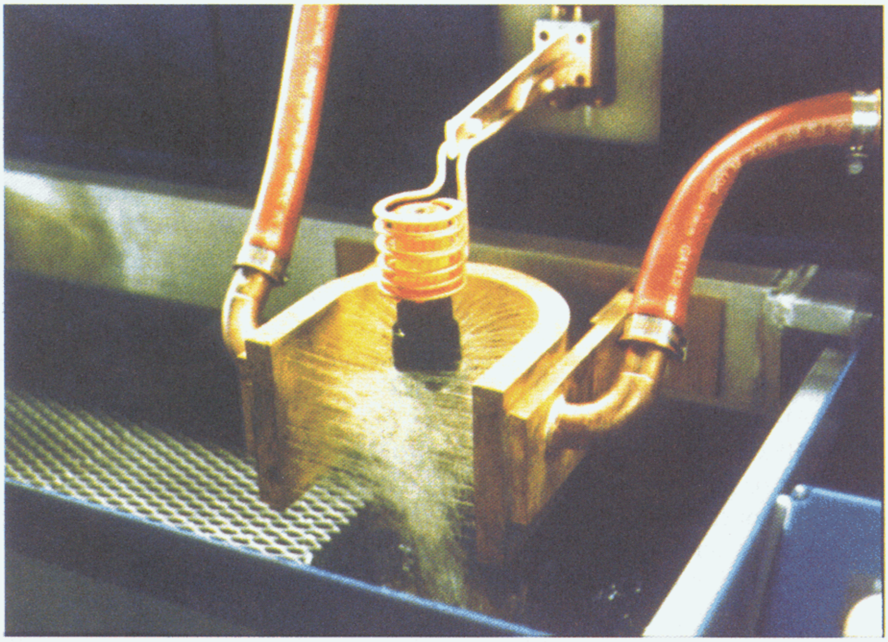


Figure I-6—Induction Heating Coil Used to Case Harden a 4140 Steel Pinion Gear

Photo courtesy of the Lepel Corporation

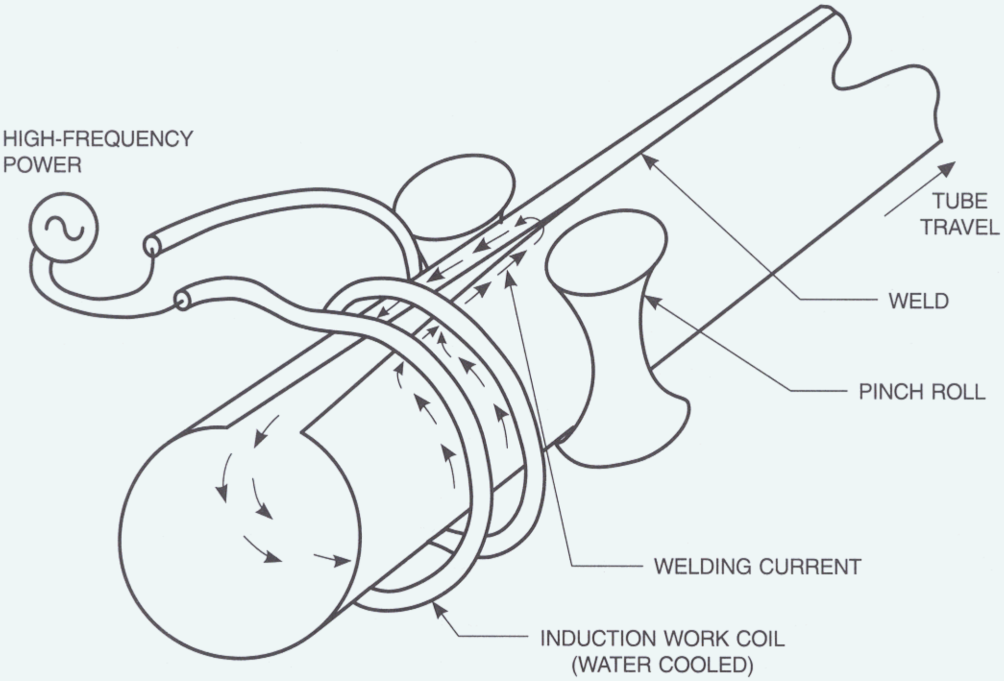


Figure I-7—Induction Upset Welding of Tube Showing Induction Work Coil

INDUCTION WORK COIL

The inductor used when welding, brazing, or soldering with induction heating equipment. See STANDARD WELDING TERMS. *See* Figure I-7.

INDUSTRIAL WELDING MACHINES

Arc welding machines with a 60% or higher duty cycle generally used for industrial production. They can be transformer, motor-drive, engine-drive or solid state machines. They may be either ac, dc or a combination of both.

INERT GAS

A gas that does not normally combine chemically with materials. See STANDARD WELDING TERMS. *See also* PROTECTIVE ATMOSPHERE.

Inert gases such as argon or helium may be used as shielding gases in welding operations because they will not react with the materials being welded and they prevent atmospheric contamination of the puddle and the electrode.

Nitrogen is sometimes considered to be an inert gas; however, under certain conditions it will react to produce nitrides, which are undesirable. *See* ARGON, HELIUM, GAS METAL ARC WELDING, *and* GAS TUNGSTEN ARC WELDING.

INERT GAS CARBON ARC WELDING

An obsolete, rarely-used arc welding process in which joining is produced by heating with an electric arc between a carbon electrode and the work. Shielding is obtained from an inert gas, such as helium or argon. Pressure and filler metal may or may not be used.

INERT GAS METAL ARC WELDING

A nonstandard term for GAS METAL ARC WELDING (GMAW). *See* GAS METAL ARC WELDING.

The GMAW process is popularly called *MIG* (metal inert gas); also *CO_2 welding*. The terms *MIG* and *CO_2 welding* are in general use in the industry, although for technical reasons they are not listed among the standard terms of the American Welding Society. *See* STANDARD WELDING TERMS.

INERT GAS SHIELDED ARC WELDING

A nonstandard term for GAS TUNGSTEN ARC WELDING (GTAW).

The GTAW process is popularly called *TIG*; this term is in general use in the welding industry, although for technical reasons it is not listed as a standard term by the American Welding Society. *See* STANDARD WELDING TERMS. *See also* GAS TUNGSTEN ARC WELDING.

INERT GAS TUNGSTEN ARC WELDING

A nonstandard term for GAS TUNGSTEN ARC WELDING (GTAW). *See* GAS TUNGSTEN ARC WELDING. *See also* STANDARD WELDING TERMS.

INERTIA FRICTION WELDING

A variation of friction welding in which the energy required to make the weld is supplied primarily by the stored rotational kinetic energy of the welding machine. See STANDARD WELDING TERMS. *See* Figure I-8.

INFRARED BRAZING (IRB)

A brazing process that uses heat from infrared radiation. See STANDARD WELDING TERMS.

INFRARED RADIATION

Electromagnetic energy with wave lengths from 770 to 12 000 nanometers. See STANDARD WELDING TERMS.

INFRARED RAYS

Part of the light spectrum produced by arc welding, which can have harmful effects on the eyes. *See* EYE PROTECTION.

INFRARED SOLDERING (IRS)

A soldering process in which the heat required is furnished by infrared radiation. See STANDARD WELDING TERMS.

INFRARED WELDING, Plastics

Heating by infrared lamps has been developed as a method for heating large polymeric structures. In infrared welding, infrared lamps scan the joining surface to melt the polymer. When a suitable temperature is reached, as controlled by sensors, the infrared lamps are withdrawn and the parts are joined or pressed together.

INGOT IRON

An open hearth iron very low in manganese, carbon and other impurities.

INITIAL CURRENT

The current after starting the arc but before establishment of welding current. See STANDARD WELDING TERMS. *See also* Appendix 19.

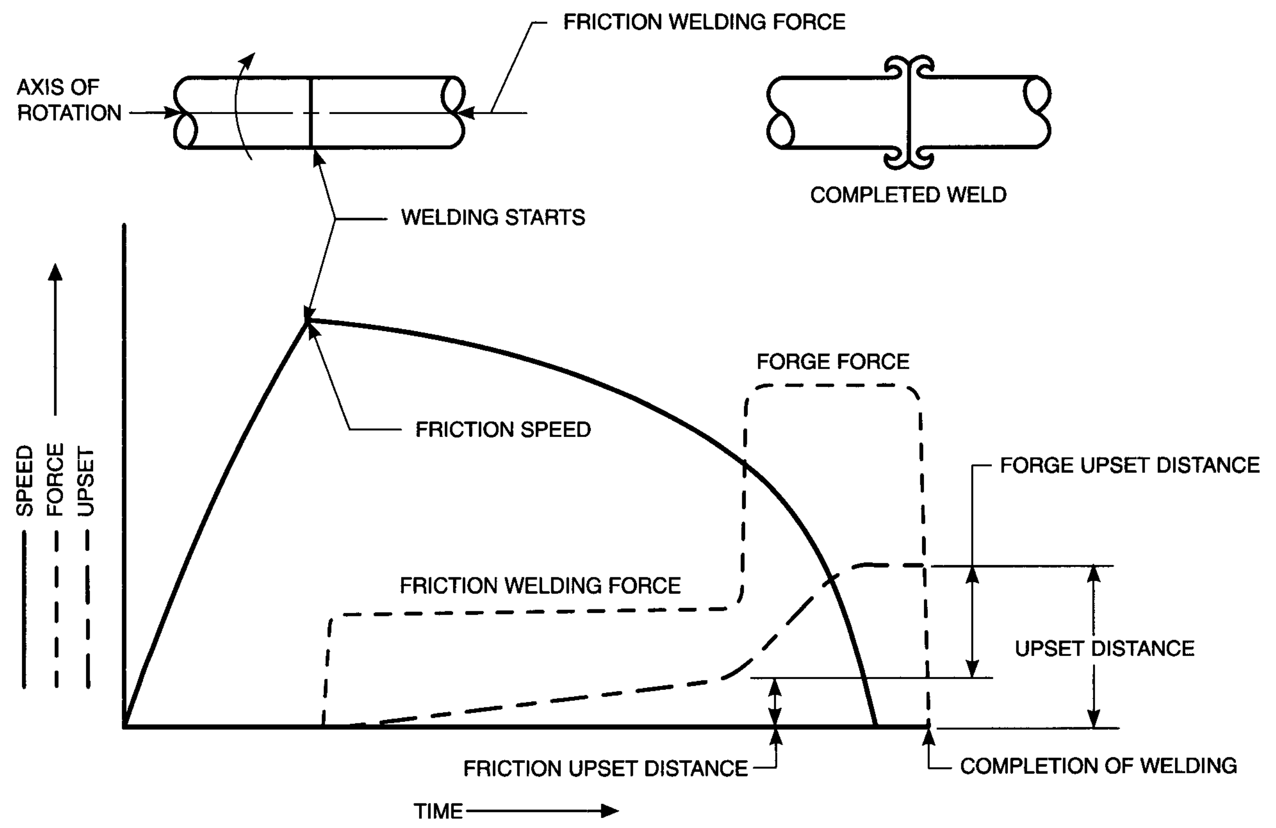


Figure I-8—Generalized Diagram of Inertia Friction Welding

INJECTOR PRINCIPLE

See TORCH, Injector.

INNER CONE

The brilliant, short part of an oxyacetylene flame immediately adjacent to the orifice of the torch tip.

INSPECTION OF WELDS

See NONDESTRUCTIVE EXAMINATION, TESTING, DYE PENETRANT INSPECTION, RADIOGRAPHIC EXAMINATION, *and* MAGNETIC PARTICLE INSPECTION.

INTERFACE

See BRAZE INTERFACE, SOLDER INTERFACE, THERMAL SPRAY DEPOSIT INTERFACE, *and* WELD INTERFACE.

INTERGRANULAR PENETRATION

The penetration of a filler metal along the grain boundaries of a base metal. See STANDARD WELDING TERMS.

INTERMEDIATE FLUX

A soldering flux with a residue that generally does not attack the base metal. The original composition may be corrosive. See STANDARD WELDING TERMS.

INTERMITTENT WELD

A weld in which the continuity is broken by recurring unwelded spaces. See STANDARD WELDING TERMS. *See* Figure C-3.

Chain Intermittent Fillet Welds

Two lines of intermittent fillet welding in a T- or lap joint, in which the increments of welding in one line are approximately opposite to those in the other line.

Staggered Intermittent Fillet Welds

Two lines of intermittent fillet welding in a T- or lap joint, in which the increments of welding in one line are staggered with respect to those in the other line. *See also* SKIP WELDING.

INTERPASS TEMPERATURE, Thermal Spraying

In multipass thermal spraying, the temperature of the thermal spray area between thermal spray passes. See STANDARD WELDING TERMS.

INTERPASS TEMPERATURE, Welding

In a multipass weld, the temperature of the weld between weld passes. See STANDARD WELDING TERMS.

INTERPULSE TIME, Resistance Welding

The time between successive pulses of current within the same impulse. See STANDARD WELDING TERMS. *See* Figure H-3.

INTERRUPTED SPOT WELDING

A nonstandard term for MULTI-IMPULSE WELDING.

INTERNATIONAL ACETYLENE ASSOCIATION

An organization of manufacturers and users of acetylene and oxygen, and equipment using these gases, which was formed in 1898 and disbanded in 1963. The Compressed Gas Association assumed the activities of this organization.

INVERTER POWER SUPPLY

A welding power supply that utilizes solid-state components to change the incoming 60 Hz power to a higher frequency, nominally 18 to 100 kHz. Changing the frequency results in greatly reduced size and weight of the transformer. Inverters can be used with all of the arc welding processes.

ION

An atom, or group of atoms, of matter which has gained or lost one or more outer shell electrons, and which therefore carries an electrical charge. Positive ions, or cations, are deficient in outer shell electrons. Negative ions, or anions, have an excess of outer shell electrons. The ion or charged atom provides an electrical conductor for the arc welding current to follow from the electrode to the workpiece.

IONIC BOND

A primary bond arising from the electrostatic attraction between two oppositely charged ions. See STANDARD WELDING TERMS.

IONIZATION POTENTIAL

The energy necessary to remove from or add one or more electrons to an atom, thereby making it an ion. The potential energy requirement varies, depending on the material involved. The term *ionization potential* is generally used when referring to shielding gases with the GMAW or GTAW welding processes. *See* ION.

I^2R LOSS

The power loss due to current flowing through a conductor which has resistance. This loss is converted into heat; its units are watts.

IRON

(Chemical symbol: Fe). The most abundant of metallic elements, known and used since very early times. Pure iron, which is practically unknown in industry, is silver-white, very ductile, malleable, and magnetic. It is the basis for many important alloyed structural materials. It has a specific gravity of 7.87; atomic weight, 55.84; melting point, 1536°C (2797°F); boiling point, 3000°C (5432°F).

Iron ores occur in large deposits in many parts of the world in the form of various iron oxides. The ore is heated in a blast furnace with limestone and coke to produce molten pig iron, and with further treatment, is converted into steel.

IRON CARBON DIAGRAM

See FLAME HARDENING *and* METALLURGY.

IRON LOSS

The hysteresis and eddy current losses in the iron cores of electrical machinery.

IRON, PIG

See CAST IRON.

IRON POWDER ELECTRODES

See CONTACT ARC WELDING *and* ELECTRODE CLASSIFICATION.

IRON SOLDERING (INS)

A soldering process in which the heat required is obtained from a soldering iron. See STANDARD WELDING TERMS.

IRON, WROUGHT

See WROUGHT IRON.

ISOTHERMAL TRANSFORMATION DIAGRAM

A diagram which graphically describes the time delay and the reaction rate of austenite transformation to pearlite, bainite or martensite. It also shows the temperature at which these transformations take place.

ISOTOPES

Atoms of the same element which are identical in their chemical behavior but different from one another in the number of neutrons contained in their nuclei, and thus have different atomic weights. In common usage, isotopes that are radioactive are known as radioisotopes.

Isotopes have an important role in industry as production aids, serving in three basic fields: (1) as tracers and gauges, "super-detectives" for monitoring and controlling a wide variety of industrial operations; (2) in place of X-ray machines, as cameras for spotting machinery faults and wear; and (3) as catalysts or active agents in creating and modifying materials.

Isotopes also act as flow tracers for detecting leaks in buried or inaccessible equipment. In a typical case, a leak was suspected in the copper tubing of a heating system buried in the concrete floor of a factory. A small amount of a radioisotope (iodine-131) was added to the water of the heating system. A Geiger counter quickly located the increased radioactivity at the leak; the break was repaired by removing a section of flooring only 15 cm (6 in.) long.

ISOTOPE RADIOGRAPHY

The production of radiographs using an isotope as a source of radiation.

Radioactive isotopes have largely replaced radium and X-ray machines for inspecting welds, castings, and finished products for voids and cavities. Isotopes such as cobalt-60, cesium-137, and iridium-192 are used in radiographic testing of lead, steel, and iron castings.

Procedures using isotopes are similar to the techniques used with X-ray machines. A radiation source is placed on one side of the material to be tested, and photographic film on the other. After exposure, the film is developed and interpreted.

Isotope radiography has proven safe, reliable, and versatile. Inspection of complicated machinery can be made without dismantling. Radiation sources can be of any desired shape or size, and they offer high radioactivity at relatively low cost.

IZOD TEST

An impact test performed on a specimen of a metallic material to evaluate resistance to failure at a discontinuity and to evaluate the resistance of a comparatively brittle material during extension of a crack.

In an Izod test, a small bar of round or square cross section is held as a cantilevered beam in the gripping anvil of a pendulum machine. The specimen is broken by a single overload of the swinging pendulum, and the energy absorbed in breaking the specimen is recorded by a stop pointer moved by the pendulum. The Izod specimen can be tested as an unnotched bar, or it can be prepared with a 45° V-notch in the face struck by the pendulum. The energy absorbed in breaking Izod specimens is reported in joules (1 joule = .0737 ft/lb). Standard methods for impact testing can be found in ASTM E23, *Notched Bar Impact Testing of Metallic Materials.*

The Izod test of the notched specimen is particularly useful for detecting the presence of embrittling constituents, which might be caused by nitrides that take form during aging or in slow cooling after annealing, and for locating the brittle zone. This test does not reflect the tensile properties of the weld or the parent metal. *See* CHARPY TEST. *See* Figure C-4.

This high-speed X-2000 train from ABB Traction, Inc. is weld-fabricated in Sweden from the Type 300 series of stainless steels

J

JAWS, Electrode Holder

The part of an electrode holder which grips the welding electrode. The electrode holder jaws are usually made of a hard copper alloy.

J-EDGE SHAPE

An edge shape formed by the combination of a bevel with a bevel radius. *See* STANDARD WELDING TERMS. *See* Appendix 6, Section 3.

J-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6, Sections 4 and 5. *See also* GROOVE WELD.

JIG

The terms *jig* and *fixture* have essentially the same meaning. Jigs, or fixtures, are designed to hold pieces of an assembly in correct relationship during welding, and to expedite removal of the completed parts after welding. Sometimes simple jigs, toggle clamps, C-clamps or wedges are sufficient to hold the alignment. In a manufacturing setting, elaborate jigs designed to hold large sheet or plate metal might be required.

In industrial production of welded parts, close dimensional control and correct alignment are critical when planning for high rates of production. Specifications must be precisely followed to produce parts that are interchangeable and readily assembled.

In repair work it is particularly necessary to hold the parts in alignment to bring the broken item to its original shape, especially if it is part of an assembly.

Jig design requires mechanical ingenuity and a knowledge of the laws of expansion and contraction of metal. When steel is heated to a welding temperature, it has very little strength and ductility. For this reason a crack or tear is very easily started by any stress due to warping contraction. In using a jig, the several parts required for a welded assembly are cut to length and fitted so that there is only a small clearance between the abutting members. This clearance should be as uniform as possible, for example, when a truss member is welded into the sidewall of a tube, the end of the member should be milled to fit the contour of the tube.

For arc or oxyfuel gas welding of thin sheet metal ranging from, for example, 10 gauge (3.6 mm [0.141 in.]) and thinner sections, the need to use a jig is more critical than when welding the heavier plate metals. As a general rule, the thinner the sheet metal, the greater the need for a jig. Greater changes occur in the edge contours of thin sheets matched up for butt welding than in heavier sheet or plate metal. The jig must provide a means to control warping and edge movements by absorbing heat or forcibly restraining the parts to some degree.

Some welding jigs are designed to hold the parts in a level position convenient for welding, with capability of rotation in a horizontal or vertical plane.

Tack-welding jigs are used in laying transmission pipelines to assure concentricity of the adjoining pipe ends and good alignment. They are essentially welding jigs, which are removed immediately after the tack-welds have been made. The fact that the pipe ends no longer require the support of the jig during the welding operation means that the function of the jig has been transferred to the tack-welds.

Jig Design

Simplicity should be the first consideration in the design and construction of the shop-made fixture. Sometimes the design can accommodate set-up and welding in the same fixture.

Convenience in reaching the welded surface and visibility are two important factors. For arc welding, the design usually includes copper backing bars with machined grooves to permit complete penetration of the weld metal. The grooves should be extremely shallow (0. 4 to 0.8 mm [0.015 to 0.030 in.]), and comparatively narrow (4.5 to 6.4 mm [0.18 to 0.25 in.]), and should not be square cornered.

Allowances for heat control must be made to prevent misalignment, buckling or overlapping of the parts. The jig should be constructed so that it carries heat away from the weld. Clamping pressures will largely depend on the type of structure being welded.

See also FIXTURE *and* POSITIONER.

JOINT

The junction of members or the edges of members that are to be joined or have been joined. See STANDARD WELDING TERMS. *See* Appendix 5.

Of the many types of joints, the most common are edge, butt, lap and tee.

JOINT BRAZING PROCEDURE

The materials, detailed methods, and practices employed in the brazing of a particular joint. See STANDARD WELDING TERMS.

JOINT BUILDUP SEQUENCE

A nonstandard term for CROSS-SECTIONAL SEQUENCE.

JOINT CLEARANCE, Brazing and Soldering

The distance between the faying surfaces of a joint. See STANDARD WELDING TERMS.

In brazing, this distance is referred to as that which is present before brazing, at the brazing temperature, or after brazing is completed.

JOINT DESIGN

The shape, dimensions, and configuration of the joint. See STANDARD WELDING TERMS.

JOINT EFFICIENCY

The ratio of strength of a joint to the strength of the base metal, expressed in percent. See STANDARD WELDING TERMS.

JOINT FILLER

A metal plate inserted between the splice member and thinner joint member to accommodate joint members of dissimilar thickness in a spliced butt joint. See STANDARD WELDING TERMS. *See* Figure J-1.

JOINT GEOMETRY

The shape and dimensions of a joint in cross section prior to welding. See STANDARD WELDING TERMS.

JOINT OPENING

A nonstandard term for ROOT OPENING.

JOINT PENETRATION

The distance the weld metal extends from the weld face into a joint, exclusive of weld reinforcement. See STANDARD WELDING TERMS. *See* Appendix 12. *See also* GROOVE WELD SIZE.

Joint penetration is the depth of fusion of a weld from the original surface of the base metal to the point where fusion ends.

For the weld to be acceptable it is necessary that the base metal and filler metal be completely fused

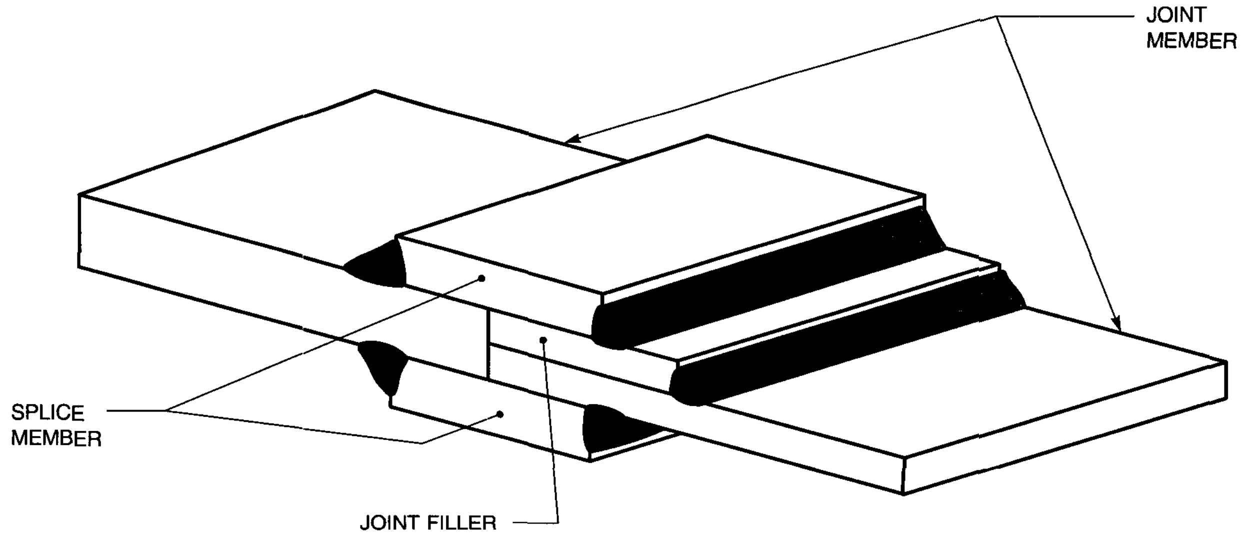


Figure J-1—Double-Spliced Butt Joint with Joint Filler together to that point. A weld may be made with partial penetration, where a gap or notch exists at the root of the weld, or complete penetration where fusion is complete from top to bottom.

Complete joint penetration is normally required in welds and when it cannot be obtained from one side in one pass, several passes are used with grooved joint preparation or weld passes are made from the root surface, or both.

In a square butt joint, joint penetration and root penetration are the same. In a groove weld, root penetration is the distance from the bottom of the groove to the point where fusion ends.

Through penetration and complete fusion and bonding of the metal are essential for successful sound welds. Through penetration is not easily accomplished in square butt joints over 6 mm (1/4 inch) thickness by most arc welding processes. A groove or bevel joint preparation is used to achieve complete penetration. A gap between two plates with square edges may help attain penetration but oxides formed on the edges could prevent complete metallurgical bonding near the root of the joint. Full penetration can be attained in square butt joints in thicker plates by the electron beam, laser and plasma arc processes.

JOINT PREPARATION

See EDGE PREPARATION.

JOINT RECOGNITION

A function of an adaptive control that determines changes in the joint geometry during welding and directs the welding equipment to take appropriate action. See STANDARD WELDING TERMS. *See* JOINT TRACKING *and* WELD RECOGNITION.

JOINT ROOT

That portion of a joint to be welded where the members approach closest to each other. In cross section, the joint root may be either a point, a line, or an area. See STANDARD WELDING TERMS. *See* Figure J-2.

JOINT SPACER

A metal part, such as strip, bar, or ring, inserted in the joint root to serve as a backing and to maintain the root opening during welding. See STANDARD WELDING TERMS. *See* Figure J-3.

JOINT TRACKING

A function of an adaptive control that determines changes in joint location during welding and directs

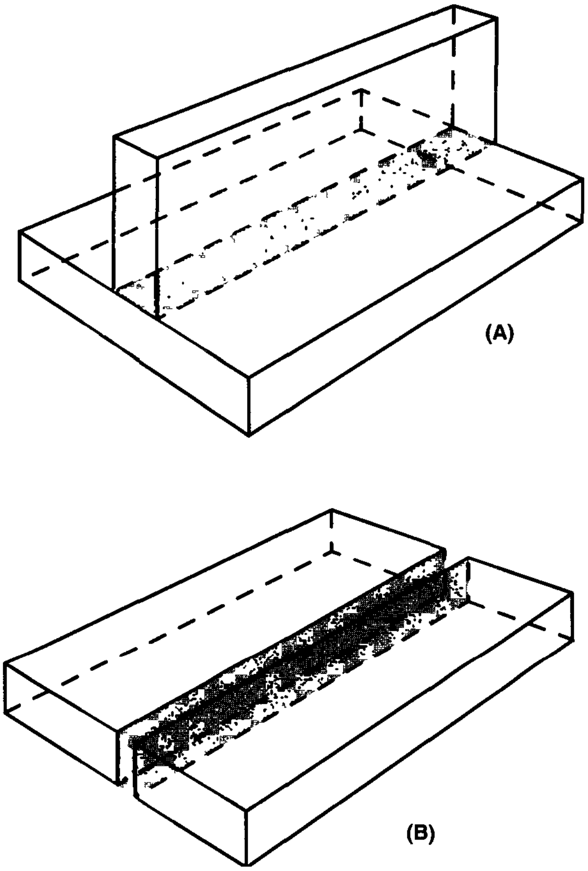


Figure J-2—Typical Joint Roots
(The joint root is the shaded area.)

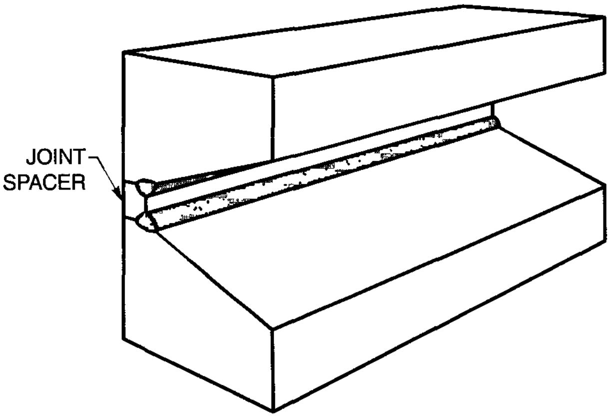


Figure J-3—Illustration of a Joint Spacer

the welding machine to take appropriate action. See STANDARD WELDING TERMS. *See* JOINT RECOGNITION *and* WELD RECOGNITION.

JOINT TYPE

A weld joint classification based on five basic joint configurations such as a butt joint, corner joint, edge joint, lap joint and T-joint. See STANDARD WELDING TERMS. *See* Appendix 5.

JOINT WELDING SEQUENCE

See STANDARD WELDING TERMS. *See* WELDING SEQUENCE.

JOMINY TEST

A laboratory test procedure developed by W. Jominy in 1938 for determining the hardenability of steels and other ferrous alloys. The test, usually called the *End Quench Test* (ASTM A255), is the most common method of determining hardenability, the relative ability of a steel to form martensite when quenched from a temperature above the upper critical temperature.

In the test procedure, a sample of a particular steel is heated to the correct quenching temperature, assuring that the surface is protected from oxidation. After heating, the sample is quenched. The quenching water jet impinges on the end of the sample and this area is cooled very rapidly. Since the heat must travel by conduction from the sample to the quenched end, the top portion of the sample will cool very slowly. Different rates of cooling, therefore, will occur all along the sample.

The hardness of the steel at different rates of cooling is indicated by Rockwell C (HRC) hardness readings, starting at 1.6 mm (1/16 in.) from the hardened end and at 1.6 mm (1/16 in.) intervals for a distance of 50 mm (2 in.).

The sample consists of a piece 10 cm (4 in.) in length. It is 25 mm (1 in.) round for a distance of 9.8 cm (3.875 in.), with a flange approximately 2.8 cm (1.125 in.) in diameter and 0.4 mm (0.015 in.) thick on one end. After the sample has been quenched, the next step is to grind a flat about 0.4 mm (0.015 in.) deep along the entire length of the sample to remove the carburized surface. It is on this flat area that the Rockwell C hardness readings are taken. The data are normally plotted as hardness (HRC) versus distance from the quenched end at which a certain hardness (such as HRC 50) is observed that may be used as an indication of hardenability.

If the hardness in the coarse-grained region of the heat-affected zone (HAZ) of a weld in a steel is matched with the same hardness on a Jominy bar of the same steel, then the cooling rates at these two positions (one in the HAZ and the other on the Jominy bar) are the same. The cooling rates at various positions along the Jominy bar are measured and tabulated. Further, the HAZ cooling rates for various welding conditions (plate thickness, joint design, initial plate temperature, current, voltage and travel speed) are measured and tabulated. Thus it is possible to select conditions that avoid the formation of brittle martensite during the arc welding of a particular steel.

Additionally, in lower-carbon quenched-and-tempered steels, conditions can be selected so that a tougher martensite forms in the heat-affected zone.

JOULE

A unit of electrical work. It is a current of one ampere flowing through a resistance of one ohm for one second, i.e., one joule is equal to one watt.

K

KERF

The width of the cut produced during a cutting process. See STANDARD WELDING TERMS. *See* Figure C-11.

KEYHOLE WELDING

A technique in which a concentrated heat source penetrates partially or completely through a workpiece, forming a hole (keyhole) at the leading edge of the weld pool. As the heat source progresses, the molten metal fills in behind the hole to form the weld bead. See STANDARD WELDING TERMS. *See* PLASMA ARC WELDING.

KEYING

A nonstandard term for MECHANICAL BOND.

KICKING COIL

A reactance or choke coil.

KILLED STEEL

Molten steel which has been held in a ladle, furnace, or crucible (and usually treated with manganese, silicon or aluminum) until no more gas is evolved and the metal is perfectly quiet.

KILO

A unit equal to 1000; a prefix placed before a word to indicate 1000 times that word.

KILOAMPERE

One thousand amperes.

KILOVOLT

One thousand volts.

KILOVOLT-AMPERE

(Abbreviation: kVA.) A measure of apparent electrical power made up of two components, an energy component and a watt-less or induction component. Primarily considered as apparent power. Kilovolt-ampere and kilowatt are the same when the current and voltage are in phase, i.e., when the power factor is one.

$$\text{kVA} = \frac{\text{voltage} \times \text{amperes}}{1000}$$

KILOWATT

(Abbreviation: kW). One thousand watts. A watt is a unit of measure of electrical power available for work. This is real power as indicated by a wattmeter. One kilowatt is about equal to 1-1/3 mechanical horsepower. kW = kVA × power factor.

KILOWATT-HOUR

(Abbreviation: kWh). Volume of work equivalent to the consumption of one kilowatt for one hour. Electric power is measured and sold by the kilowatt hour.

KLEINSCHMIDT PROCESS

A form of resistance spot welding, similar to projection welding, patented in 1898. A common application of the Kleinschmidt Process is in joining large pieces of thin metal. The sheets are prepared with raised sections, or projections, to localize the flow of current, and pointed copper electrodes are used. Machines used in this type of application must provide for the exertion of heavy pressure on the electrodes after the metal is heated to the welding point. *See* RESISTANCE WELDING.

KNEE

The supporting structure of the lower arm in a resistance welding machine. See STANDARD WELDING TERMS.

KNURLING, Thermal Spraying

See STANDARD WELDING TERMS. *See* GROOVE AND ROTARY ROUGHENING; ROTARY ROUGHENING, *and* THREADING AND KNURLING, Thermal Spraying.

KSI

A term which indicates 1000 psi in describing tensile strength: 10 ksi = 10 000 psi.

kW

Abbreviation for kilowatt.

kWh

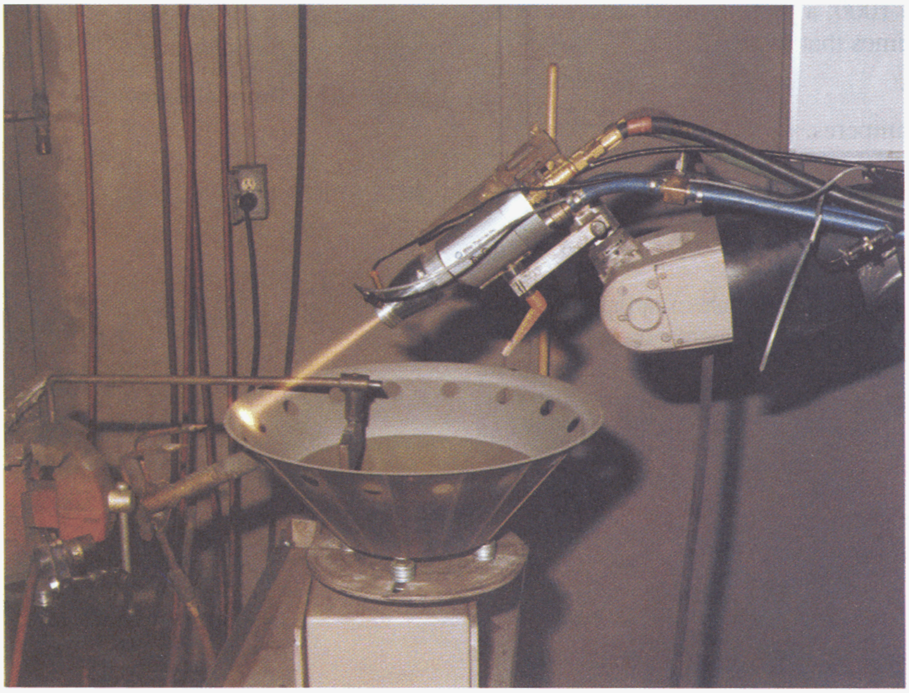
Abbreviation for kilowatt hour.

kVA

Abbreviation for kilovolt-ampere.

A welder uses the gas tungsten arc welding (GTAW) process to fabricate a hopper used in the food processing industry

Photo courtesy of O. H. Hendricks Company



A typical setup for an arc spray system includes a power source, spray gun, and wire feed unit

L

LACK OF FUSION

A nonstandard term for INCOMPLETE FUSION.

LACK OF JOINT PENETRATION

A nonstandard term for INCOMPLETE JOINT PENETRATION. *See* Figure I-3.

LAG

A nonstandard term for DRAG, Thermal Cutting.

LAMELLAR TEAR

A subsurface terrace and step-like crack in the base metal with a basic orientation parallel to the wrought surface caused by tensile stresses in the through-thickness direction of the base metal weakened by the presence of small dispersed, planar shaped, nonmetallic inclusions parallel to the metal surface. See STANDARD WELDING TERMS. *See* Appendix 9.

Lamellar tearing is a cracking phenomenon that occurs in welds joining rolled steel products. Lamellar cracks or tears occur most often during fabrication where weld shrinkage strains exceed the strength of the base metal in the through-thickness direction of the steel.

All steels contain nonmetallic inclusions in varying amounts. Hot-rolled steels may contain other internal imperfections such as porosity, seams, or laminations. When the steel is rolled to the desired shape for fabrication, these inclusions and imperfections are elongated in the direction of rolling. Internal seams and tears may or may not be "healed" (welded together by the rolling action). These defects are likely to occur in thick sections where the mechanical deformation of the internal seams or tears may not be sufficiently worked to "heal" the defects. The specified strength of these steels is always measured in the direction of rolling. The strength of rolled steels in the through-thickness direction (perpendicular to the direction of rolling) is considerably less than the strength obtained in the direction of rolling.

The contraction or shrinkage of deposited weld metal during cooling sets up localized strains in the base metal. These strains may exceed the strength of the base metal in the through-thickness direction, resulting in lamellar tearing. Welds that require the deposition of large amounts of filler metal tend to degrade the tensile properties of the base metal and contribute to lamellar tearing. Highly restrained joints are also susceptible to lamellar tearing and should be welded with caution.

The design of welded joints must take into account the direction of rolling. Welding to members in the through-thickness direction must be avoided, if possible.

Where this is unavoidable, the joint should be detailed to reduce the possibility of lamellar tearing resulting from welding. Figure L-1 illustrates susceptible joint details.

Recognizing lamellar tearing may be difficult since the tearing is internal, like underbead cracking. Corner joints and T-joints are the most susceptible to lamellar tearing, but joint details can be modified to minimize it. If there is any question that subsurface tearing exists, then nondestructive methods should be used to examine the base metal.

For more detailed information on lamellar tearing see American Welding Society, *Welding Handbook*, Vol. 1, 8th Ed. 137–138. Miami, Florida. American Welding Society, 1987.

LAMINATE

A laminate is the composite metal product of two or more layers joined, usually by welding, to form a structural product.

LAMINATION

A type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal. See STANDARD WELDING TERMS.

Metal defects with separation weaknesses are generally aligned parallel to the rolled direction of the fabricated section. These defects may result from elongated pipe, seams, or inclusions in the metal that are made directional during the mechanical working of the metal.

LANCE

See OXYGEN LANCE *and* OXYGEN LANCE CUTTING.

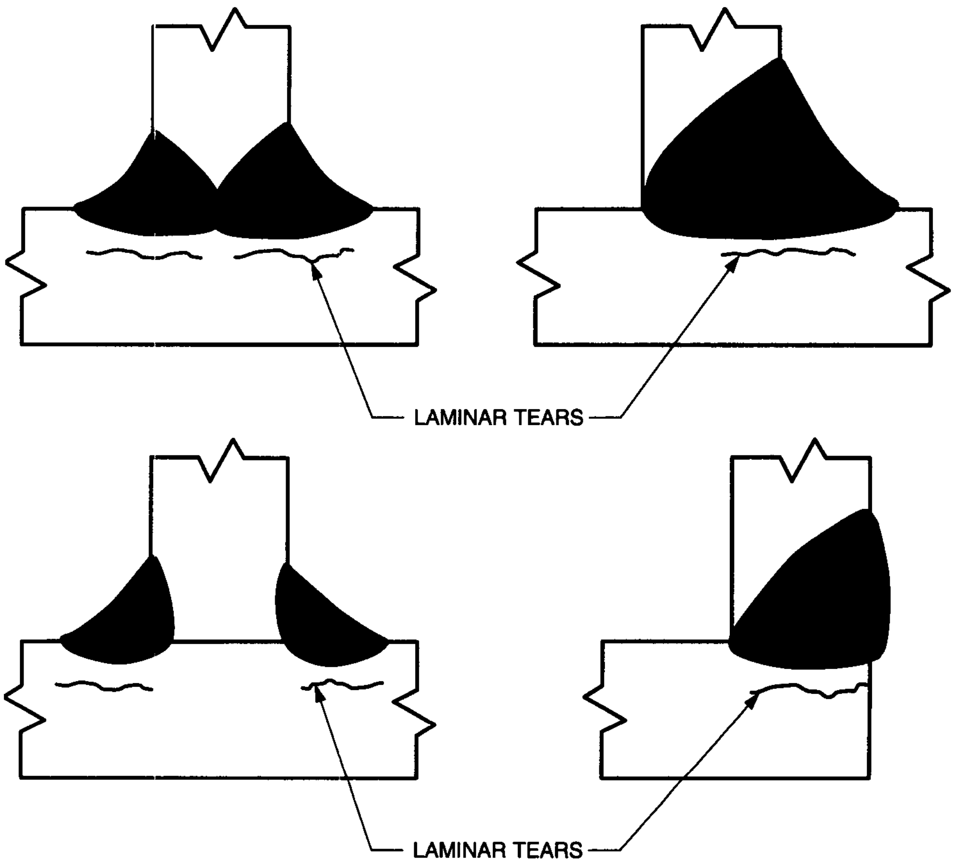


Figure L-1—Weld Joint Designs in Steel Plate that are Prone to Lamellar Tearing and the Likely Location of Tears

LAND

A nonstandard term for ROOT FACE.

LAP

A base metal surface defect (not caused by welding), appearing as a seam in the base metal, caused by folding over hot metal, fins, or sharp corners and then rolling or forging them into the surface.

LAP JOINT

A joint between two overlapping members in parallel planes. See STANDARD WELDING TERMS. *See* Appendix 5.

LAP SEAM WELD

See SEAM WELD.

LAP WELD

See LAP JOINT.

LASER

A device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for light amplification by stimulated emission of radiation. See STANDARD WELDING TERMS.

The laser beam is a focused, high-power, coherent, monochromatic light beam. The laser was independently invented in 1960 by two scientists, one at Bell Laboratories and the other at Hughes Aircraft. Most of the early application development was conducted by Bell Laboratories. The original laser device consisted of a ruby rod surrounded by a xenon flash lamp that excited the chromium atoms in the ruby to higher energy states. Simultaneously stimulated and returning to the ground state, the atoms emit an intense amplified light beam. *See* Figure L-2 for a schematic diagram of a ruby laser.

The rapid flashing of the xenon lamp produced a seemingly steady state of emitted light. Only a focused, monochromatic light beam was permitted to leave the device. Initial application was limited to the low power of the ruby laser.

The three basic types of laser include solid state, gas discharge, and semi-conductor injection types. High power, pulsed outputs in the megawatt range are provided by solid state lasers. Gas discharge lasers use helium, neon, krypton, or xenon to provide low power output frequencies that are continuous. Semi-conductor injection lasers have limited power output, are dependent on liquid nitrogen operating temperatures, and do not need a flashlamp for exciting the atoms since they convert electricity directly into light.

Early laser metal working applications were limited, but with the advent of higher-powered lasers, applications include welding, brazing, cutting, micro perforation, and metal removal. High-powered lasers can cut steel up to 25 mm (1 in.) thick.

LASER BEAM AIR CUTTING (LBC-A)

A laser beam cutting process variation that melts the workpiece and uses an air jet to remove molten and vaporized material. See STANDARD WELDING TERMS.

LASER BEAM BRAZE WELDING (LBBW)

A braze welding process variation that uses a laser beam as the heat source. See STANDARD WELDING TERMS.

LASER BEAM CUTTING (LBC)

A thermal cutting process that severs metal by locally melting or vaporizing with the heat from a laser beam. The process is used with or without assist gas to aid the removal of molten and vaporized material. See STANDARD WELDING TERMS. *See* LASER BEAM AIR CUTTING, LASER BEAM EVAPORATIVE CUTTING, LASER BEAM INERT GAS CUTTING, *and* LASER BEAM OXYGEN CUTTING.

The source of heat for laser beam cutting is a concentrated coherent light beam that impinges on the workpiece to be cut. A combination of melting and evaporation provides the mechanism for removal of material from the kerf. High-power lasers have unique advantages for cutting applications, including capability to cut any metal and producing a narrow kerf and heat-affected zone. High cutting speeds are achieved, and the equipment is adaptable to computer control.

A laser is a heat source with some unique characteristics. Relatively modest amounts of laser energy can

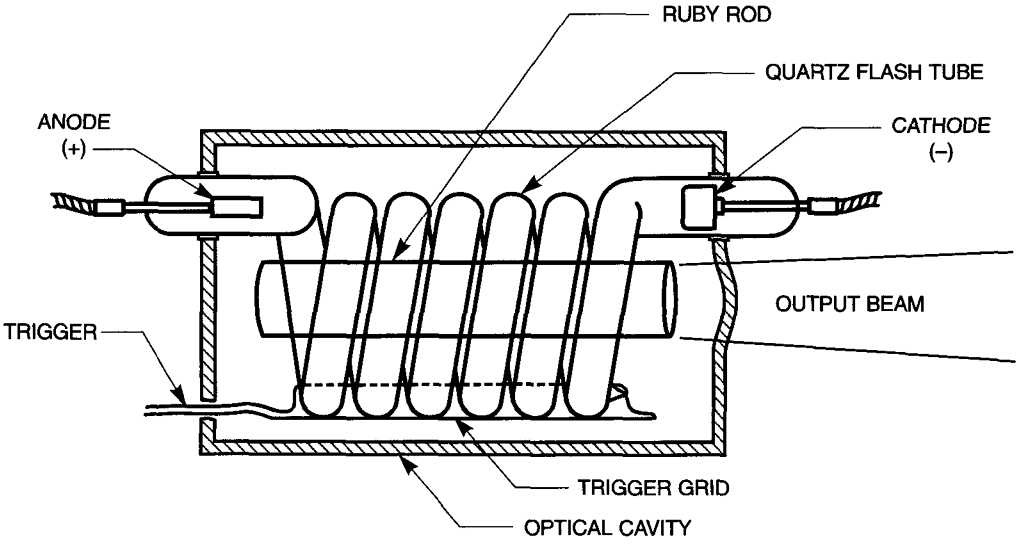


Figure L-2—Schematic Diagram of a Ruby Laser

be focused to very small spot sizes, resulting in high power densities. In cutting and drilling, these power densities are in the range of 10^4 to 10^6 W/mm^2 (6.5×10^6 to 6.5×10^8 W/in.^{2}). Such high concentrations of energy cause melting and vaporization of the workpiece material, and material removal is enhanced by a jet of gas. Depending on the material, a jet of reactive gas such as oxygen can be applied coaxially with the beam, improving process speed and cut edge quality.

Among laser material processing applications, cutting is the most common process; its use has quickly grown worldwide. The first laser material processing application was drilling diamonds for wire drawing dies. Today, laser cutting and the related processes of drilling, trimming, and scribing account for more than 50% of the international industrial laser installations.

A high-power CO_2 laser can cut up to 25 mm (1 in.) thick carbon steel. However, good quality cuts on steel are typically made on metal thinner than 9.5 mm (0.375 in.), because of the limited depth of focus of the laser beam. CO_2 lasers in the range of 400 to 1500 W dominate the cutting area. Neodymium-doped, yttrium aluminum garnet (Nd:YAG) lasers are also used.

Laser cutting has the advantages of high speeds, narrow kerf widths, high-quality edges, low-heat input, and minimal workpiece distortion. It is an easily automated process that can cut most materials. The cut geometry can be changed without the major rework required with mechanical tools; there is no tool wear involved, and finishing operations are not usually required. Within its thickness range, it is an alternative to punching or blanking, and to oxyfuel gas and plasma arc cutting. Laser cutting is especially advantageous for prototyping studies and for short production runs. Compared to most conventional processes, noise, vibration, and fume levels involved in laser cutting are quite low.

Metals which can be cut by the laser beam process include carbon steel, alloy steel, stainless steel, aluminum, copper and copper alloys, nickel base alloys, and titanium and its alloys. Nonmetals such as alumina and quartz can also be cut, along with organic materials, such as cloth and the spectrum of plastics. Some types of composite materials with organic matrices can be cut. Lasers have been successfully used to cut several types of metal-matrix composites.

Figure L-3 shows a CO_2 laser cutting holes in 6 mm (0.25 in.) thick 4130 steel.

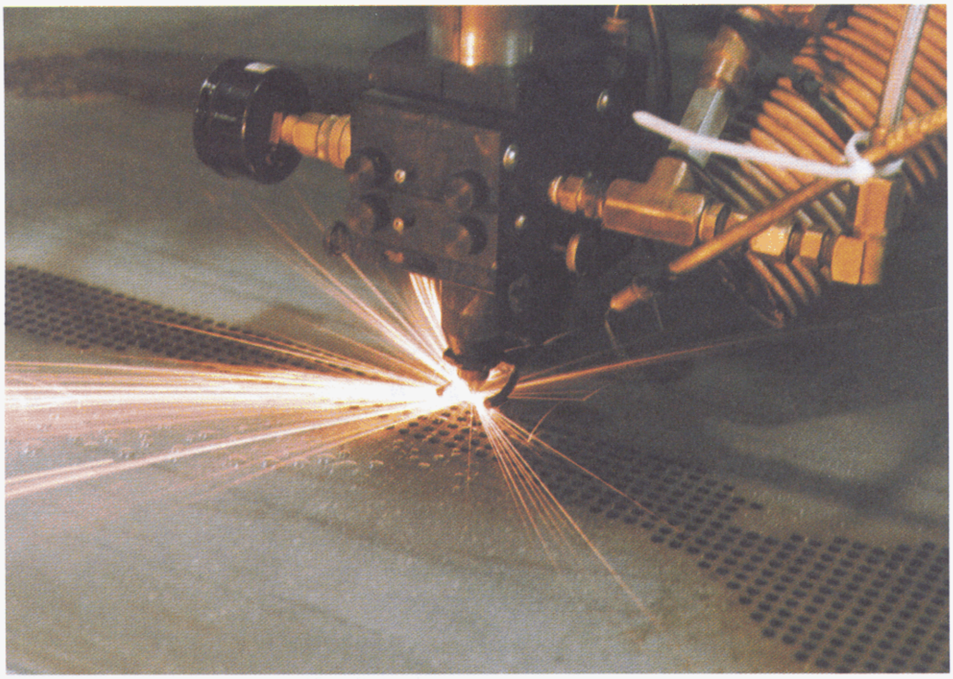


Figure L-3—Photograph of a CO_2 Laser Cutting 6 mm (0.25 in.) Thick 4130 Steel

Photo courtesy of Laser Machining, Inc., Somerset, WI

Laser Drilling. Hole diameters produced by laser beam drilling typically range from about 0.0025 to 1.5 mm (0.0001 to 0.060 in.). Depths achieved are usually less than 25 mm (1 in.) because of beam focusing limitations. Examples of laser drilling on a jet engine compressor blade and a rotor component are shown in Figure L-4.

The process produces clean holes with very small recast layers. When large holes are required, a trepanning technique is used where the beam cuts a circle with the required diameter.

Drilling with a laser is a pulsed operation involving higher power densities and shorter dwell times than laser cutting. Holes are produced by single or multiple pulses. Laser drilling is a cost-effective alternative to mechanical drilling, electro-chemical machining, and electrical-discharge machining for making holes of relatively shallow depths.

Laser drilling shares most of the advantages found in laser cutting. It is especially advantageous when the required hole diameters are less than 0.5 mm (0.020 in.) and when holes are to be made in areas inaccessible to conventional tools. Beam-entry angles can be very close to zero, a situation where mechanical tools are susceptible to breakage. The industrial laser drilling area is dominated by Nd:YAG lasers.

Reference: American Welding Society, *Welding Handbook,* Vol.2, 8th Edition; Miami Florida: American Welding Society, 1991.

LASER BEAM CUTTING OPERATOR

See STANDARD WELDING TERMS. *See* THERMAL CUTTING OPERATOR.

LASER BEAM DIAMETER

The diameter of a laser beam circular cross section at a specified location along the laser beam axis. See STANDARD WELDING TERMS.

LASER BEAM EVAPORATIVE CUTTING (LBC-EV)

A laser beam cutting process variation that vaporizes the workpiece, with or without an assist gas (typically inert gas), to aid the removal of vaporized material. See STANDARD WELDING TERMS.

LASER BEAM EXPANDER

A combination of optical elements that will increase the diameter of a laser beam. See STANDARD WELDING TERMS.

LASER BEAM INERT GAS CUTTING (LBC-IG)

A laser beam cutting process variation that melts the workpiece and uses an inert assist gas to remove

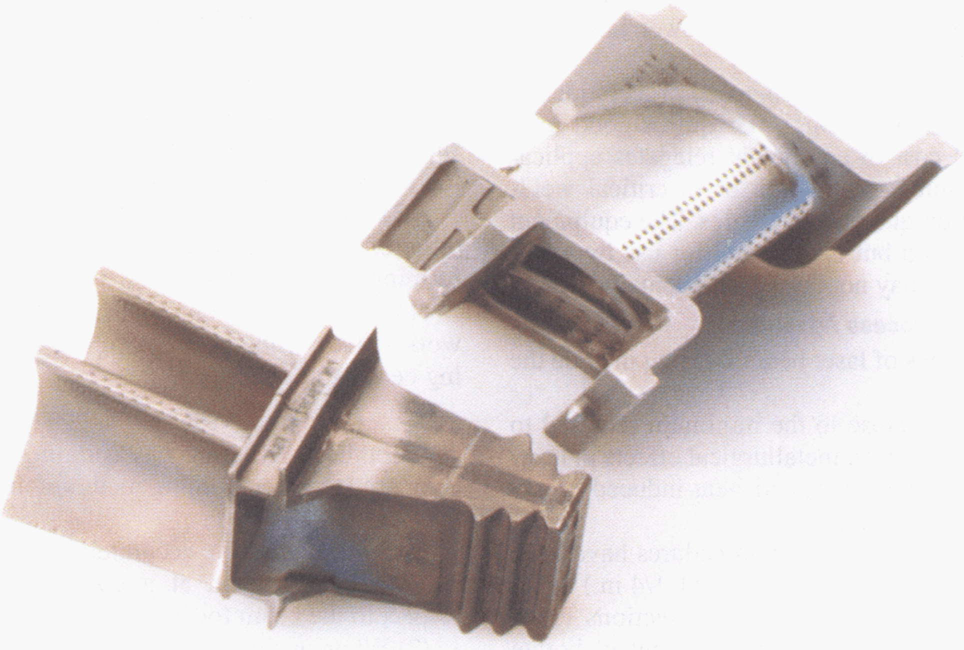


Figure L-4—Jet Engine Turbine Blade Showing Laser Drilled Holes *molten and vaporized material. See* STANDARD WELDING TERMS.

LASER BEAM OXYGEN CUTTING (LBC-O)

A laser beam cutting process variation that uses the heat from the chemical reaction between oxygen and the base metal at elevated temperatures. The necessary reaction temperature is maintained with a laser beam. See STANDARD WELDING TERMS.

LASER BEAM SPLITTER

An optical device that uses controlled reflection to produce two beams from a single incident beam. See STANDARD WELDING TERMS.

LASER BEAM WELDING (LBW)

A welding process that produces coalescence with the heat from a laser beam impinging on the joint. The process is used without a shielding gas and without the application of pressure. See STANDARD WELDING TERMS.

The focused, high power coherent monochromatic light beam used in laser beam welding causes the metal at the point of focus to vaporize, producing a deep penetrating column of vapor extending into the base metal. Yttrium aluminum garnet (YAG) lasers are used for spot and seam welding of thin materials. For welding thicker materials, multi-kilowatt carbon dioxide gas laser systems are available. Such systems provide power densities of 10 kW/mm^2 (6.5 $MW/in.^2$). Continuous power provides a high power laser with deep penetration welding capability.

Laser beam welding is a high-speed process ideally suited to automation, although it requires good joint fit-up. The high cost of equipment relegates applications to high-volume production or to critical weldments requiring unique characteristics. The equipment is very sophisticated but is designed for use by welding operators who may not be skilled manual welders.

Process Advantages

Major advantages of laser beam welding include the following:

(1) Heat input is close to the minimum required to fuse the weld metal; thus, metallurgical effects in heat-affected zones are reduced, and heat-induced workpiece distortion is minimized.

(2) Single pass laser welding procedures have been qualified in materials of up to 32 mm (1-1/4 in.) thick, thus allowing the time to weld thick sections to be reduced and the need for filler wire (and elaborate joint preparation) to be eliminated.

(3) No electrodes are required; welding is performed with freedom from electrode contamination, indentation, or damage from high resistance welding currents. Because LBW is a non-contact process, distortion is minimized and tool wear is essentially eliminated.

(4) Laser beams are readily focused, aligned, and directed by optical elements. Thus the laser can be located at a convenient distance from the workpiece, and redirected around tooling and obstacles in the workpiece. This permits welding in areas not easily accessible with other means of welding.

(5) The workpiece can be located and hermetically welded in an enclosure that is evacuated or that contains a controlled atmosphere.

(6) The laser beam can be focused on a small area, permitting the joining of small, closely spaced components with tiny welds.

(7) A wide variety of materials can be welded, including various combinations of different type materials.

(8) The laser can be readily mechanized for automated, high-speed welding, including numerical and computer control.

(9) Welds in thin material and on small diameter wires are less susceptible to burn-back than is the case with arc welding.

(10) Laser welds are not influenced by the presence of magnetic fields, as are arc and electron beam welds; they also tend to follow the weld joint through to the root of the workpiece, even when the beam and joint are not perfectly aligned.

(11) Metals with dissimilar physical properties, such as electrical resistance, can be welded.

(12) No vacuum or X-ray shielding is required.

(13) Aspect ratios (i.e., depth-to-width ratios) on the order of 10:1 are attainable when the weld is made by forming a cavity in the metal, as in keyhole welding.

(14) The beam can be transmitted to more than one work station, using beam switching optics, thus allowing beam time sharing.

Process Limitations

Laser beam welding has certain limitations when compared to other welding methods, among which are the following:

(1) Joints must be accurately positioned laterally under the beam and at a controlled position with respect to the beam focal point.

(2) When weld surfaces must be forced together mechanically, the clamping mechanisms must ensure

that the final position of the joint is accurately aligned with the beam impingement point.

(3) The maximum joint thickness that can be laser beam welded is somewhat limited. Thus weld penetrations much greater than 19 mm (0.75 in.) are not presently considered to be practical production LBW applications.

(4) The high reflectivity and high thermal conductivity of some materials, such as aluminum and copper alloys, can affect their weldability with lasers.

(5) When performing moderate-to-high power laser welding, an appropriate plasma control device must be employed to ensure that weld reproducibility is achieved.

(6) Lasers tend to have a fairly low energy conversion efficiency, generally less than 10%.

(7) As a consequence of the rapid solidification characteristic of LBW, some weld porosity and brittleness can be expected.

Weld Processing Modes

There are two distinctly different modes of energy transfer in laser welding which are commonly referred to as *conduction mode welding* and *keyhole mode welding*. It is the power density incident on the material surface, as well as the material properties, which ultimately determine which mode is present for a given weld.

Conduction Mode Welding. In conduction mode welding, the laser beam does not produce sufficient vaporization pressure to displace the weld pool, form a cavity, and allow the beam to emerge directly at the root of the weld. Instead, the incident beam energy on the weld pool surface is transferred to the root of the weld solely by conductive and convective heat flow in the molten metal. For a given weld diameter, conduction limited welding has a maximum penetration value at which no further penetration can be obtained without creating a cavity. The maximum aspect ratio (pool depth divided by pool width) for conduction mode welding is between 0.5 and 1.0.

Conduction mode welding can be obtained either with continuous wave lasers or with pulsed power lasers and with either low or high power. Selection of parameters and focusing optics that result in small vapor plumes and the absence of spatter are necessary to insure conduction mode welding.

Keyhole Mode Welding. Keyhole mode welding occurs when the power density of the beam is about 10^6 W/cm^2 (6.45×10^6 W/in.^{2}) or greater. The material at the interaction point melts and vaporizes. The vapor recoil pressure, surface tension, and other phenomenon create a deep cavity. This cavity is a high-pressure region surrounded by walls of molten metal. As the workpiece moves relative to the beam, the cavity is sustained, and the molten metal flows from the front edge of the cavity around the sides of the cavity in a direction opposite to the travel direction, and solidifies at the trailing edge forming a narrow fusion zone or weld.

Applications

Laser beam welding is being used for an extensive variety of applications such as in the production of automotive transmissions and air conditioner clutch assemblies. In the latter application, laser welding permits the use of a design that could not otherwise be manufactured. The process is also being used in the production of relays and relay containers and for sealing electronic devices and heart pacemaker cases. Other applications include the continuous welding of aluminum tubing for thermal windows and for refrigerator doors.

Successful laser welding applications include welding transmission components (such as synchro gears, drive gears and clutch housings) for the auto industry. These annular and circumferential-type rotary welds need from 3 to 6 kW of beam power, depending on the weld speed being employed, and require penetrations which typically do not exceed 3.2 mm (0.125 in.). Materials welded are either carbon or alloy steels. In some cases, such as the gear teeth, they have been selectively hardened before welding. There are many advantages to laser welding such assemblies. The low heat input provided by the laser does not affect the prehardened zones adjacent to the weld. Also, this low heat input produces a minimal amount of distortion so that precision stampings can often be welded to finished dimensions. Since the ease of automation and high weld-speed capability of the laser process makes it ideal for automotive-type production, a number of these systems have been installed in the automotive industry.

Figure L-5 shows a laser weld in an automotive transmission component. This operation involved welding a threaded annular boss onto a circular ring. Here a 2.5 kW CO_2 laser was used to provide a 4.8 mm (0.181 in.) deep weld at 1.5 m/min (60 in./min), employing helium shielding gas.

Metals Welded

Laser beam welding can be used for joining most metals to themselves as well as dissimilar metals that

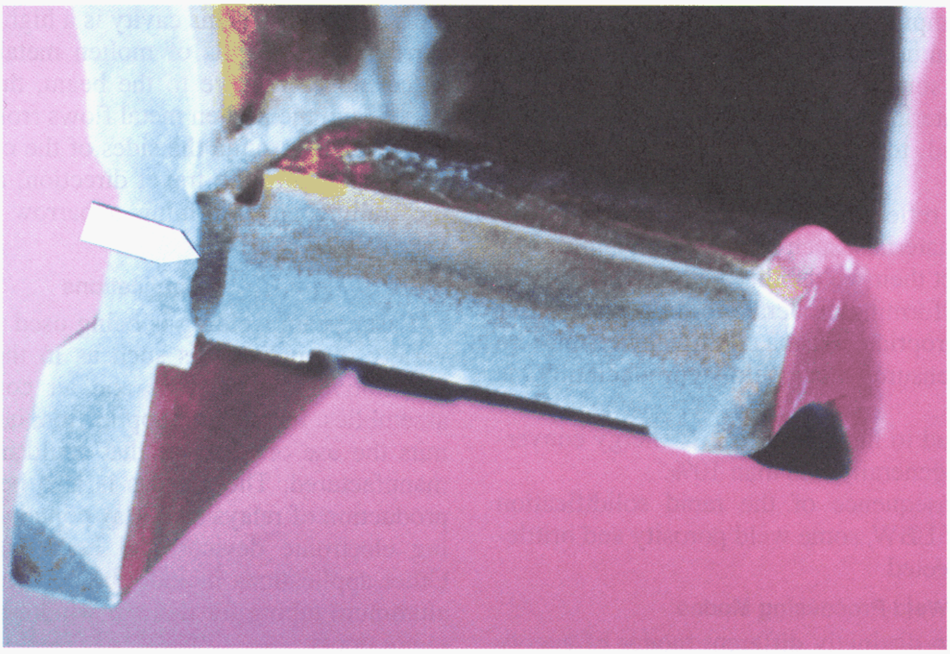


Figure L-5—Cross Section of a Laser Beam Weld Joining a Boss to a Ring. A 2.5 kW CO_2 Laser Produced a Travel Speed of 1500 mm/min (60 in./min). Penetration was 4.8 mm (0.181 in.).

are metallurgically compatible. Low-carbon steels are readily weldable, but when the carbon content exceeds 0.25%, martensitic transformation may cause brittle welds and cracking. Pulsed welding helps minimize the tendency for cracking. Fully killed or semi-killed steels are preferable, especially for structural applications, because welds in rimmed steel may have voids. Steels having high amounts of sulfur and phosphorus may be subject to hot cracking during welding. Also, porosity may occur in free machining steels containing sulfur, selenium, cadmium, or lead.

Most of the 300 series stainless steels, with the exception of free machining Types 303 and 303Se and stabilized Types 321 and 347, are readily weldable. Welds made in some of the 400 series stainless steels can be brittle and may require post weld annealing. Figure L-6 shows the cross section of a 416 stainless steel cap welded onto a 310 stainless steel body, using a 750 W CO2 laser at 114 cm/min (45 in./min) weld speed. Penetration into the body component was 1.27 mm (0.05 in.). Many heat resistant nickel and iron based alloys are being welded successfully with laser beams. Titanium alloys and other refractory alloys can be welded in this way, but an inert atmosphere is always required to prevent oxidation.

Copper and brass are often welded to themselves and other materials with specialized joint designs used for conduction welding. Aluminum and its weldable alloys can be joined for partial penetration assembly welds and are commonly joined by pulsed conduction welds for hermetically sealed electronic packages. Joint designs must retain aluminum in tension.

Refractory metals such as tungsten are often conduction welded in electronic assemblies, but require higher power than other materials. Nickel-plated Kovar is often used in sealing welds for electronic components, but special care is required to ensure that the plating does not contain phosphorous, which is usually found in the electroless nickel plating process commonly used for Kovar parts that are to be resistance welded.

Dissimilar metal joints are commonly encountered in conduction welds where the twisting of conductors forms a mechanical support that minimizes bending of potentially brittle joints. Dissimilar metals having different physical properties (reflectivity, conductivity and melting points) are often joined in the welding of conductors. Special techniques such as adding extra turns of one material to the joint as opposed to the other may be required to balance the melting charac-

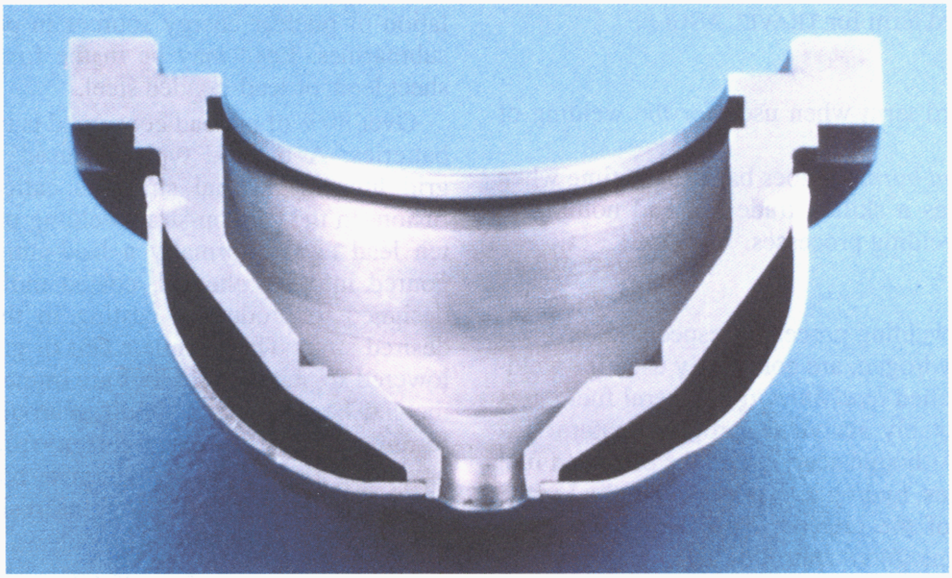


Figure L-6—Cross Section of a Laser Beam Weld Joining a 416 Stainless Steel Cap to a 310 Stainless Steel Body

teristics of the materials. Some of these concepts can also be applied to structural and assembly welds, but the possibilities are much more limited.

For detailed information on LASER BEAM WELDING see American Welding Society, *Welding Handbook,* Vol.2, 8th Ed. Miami, Florida, American Welding Society, 1991.

LASING GAS

A gaseous lasing medium. See STANDARD WELDING TERMS.

LASING MEDIUM

A material that emits coherent radiation by virtue of stimulated electronic or molecular transitions to lower energy. See STANDARD WELDING TERMS.

LAYER

A stratum of weld metal consisting of one or more weld beads. See STANDARD WELDING TERMS. *See* Figure L-7.

LAYER LEVEL WOUND

A nonstandard term for LEVEL WOUND.

LAYER WOUND

A nonstandard term for LEVEL WOUND.

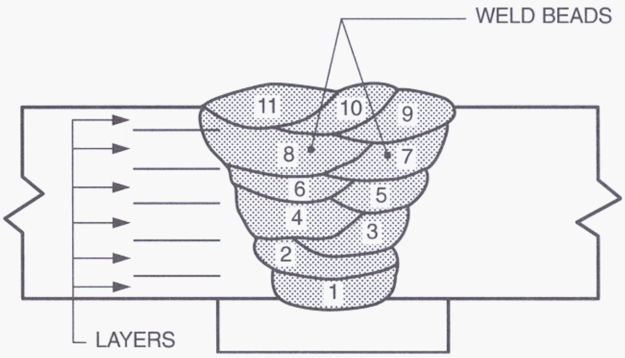


Figure L-7—Cross-Sectional Sequence Showing Layers of Weld Metal

LEAD

(Chemical symbol: Pb). Lead is metallic, bluish-white in color, with a bright luster. It is very soft, highly malleable, ductile and a poor conductor of electricity. Commercially pure lead is used for making pipe and containers for corrosive liquids, and is widely used in storage batteries. Lead as an alloying element is used mainly for manufacturing solders.

Lead has an atomic number 82, an atomic weight 207.20, melting point 327°C (621°F), and specific gravity 11.35 at 20°C (68°F).

LEAD ANGLE

A nonstandard term for TRAVEL ANGLE.

LEAD BURNING

A nonstandard term when used for the welding of lead.

The term, *lead burning*, goes back to the time when lead burning was a skilled trade but had nothing in common with welding processes.

LEAD WELDING

Oxyfuel gas welding processes, especially oxyacetylene and oxyhydrogen, are commonly used for welding lead (also called *lead burning*). Several fuel gases can be used, notably acetylene, propane, natural gas and hydrogen. Although acetylene is the preferred fuel in many countries, hydrogen is preferred in the United states because of the precise flame size that can be obtained, allowing good control of the weld-bead size. With oxyacetylene, the higher pressure needed to obtain a small flame tip disrupts control of the liquid lead pool. Oxyhydrogen and oxyacetylene torches can be used for welding in all positions. Oxynatural gas and oxypropane are limited to the flat position because of the greater difficulty in controlling weld pool size and shape.

In all cases, the proportion of oxygen is adjusted to obtain a neutral flame. Excess oxygen will oxidize the lead surface and inhibit welding. Welding position, flame intensity, and how the torch is manipulated depend on the type of joint which is to be welded. Usually the torch is moved in a semicircular or V-shaped pattern along the joint. The molten lead is controlled and directed with the flame to produce a circular or herringbone appearance.

Applications

The widespread use of lead in the chemical industries is a direct result of the ease with which lead can be welded, as well as its exceptional resistance to corrosion caused by a wide variety of chemicals. Lead welding is used for lining tanks, conveyors, ducts and other equipment used to store or mix chemical solutions and is used extensively in chemical processing plants when acid resistance is a specification. Welded lead sheet is used worldwide as a waterproof membrane to protect underground parking garages and other structures. Lead welding is used extensively in the preparation of lead-shielded components for gamma-ray attenuation. A specific use is in mobile power reactor equipment such as that used on naval ships, where the use of lead instead of iron may result in a weight saving of 30%. It is also used in the installation of nuclear energy sources in power plants and submarines. Lead may be in the form of cast slabs, sheet lead, or lead-bonded steel.

Over 80% of all lead consumed is used in lead-acid batteries. A method typically used to weld battery grid lugs to internal straps is called *cast-on-strap* fusion. In the cast-on-strap welding process, the molten lead alloy (normally a lead-antimony alloy), is poured into a preheated, coated mold. The mold is designed to produce a casting in the shape of the desired strap. The complete cell or group of plates is lowered so that the grid lugs are immersed in the strap metal. The strap metal solidifies around the grid lugs, forming a strap to collect current from each lug and providing a complete metallurgical bond between the lug and strap to give a corrosion-resistant joint with low electrical resistance.

Base Metal

Two grades of lead primarily used in industry are chemical lead (commercially pure lead) and antimonial lead (lead alloyed with antimony). The fact that lead has both low tensile strength and low creep strength must always be considered for commercial applications; adequate support for lead products must always be considered.

Filler Metal and Surface Preparation

Filler metal is usually added in the form of a rod of convenient size. Its composition should be similar to that of the base metal to be welded. Strips of the base metal can be sheared from sheet material, or filler metal can be cast in a suitable mold.

Proper surface preparation, as in all joining, is necessary for making sound welds. The joint area should be cleaned with a suitable, safe solvent to remove all dirt, oil, and grease from the surfaces to be joined. The surface to be joined, adjacent surfaces, and filler metal should be cleaned of surface oxides by wire brushing or mechanical shaving. When pipe is to be welded, the interior of the pipe should also be prepared.

Joint Design

Joint designs commonly used in welding lead sheet or plate are shown in Figure L-8. For vertical and overhead welding, the lap joint should be used. An edge flange joint is used only under special conditions.

Lap joints are generally designed with one part overlapping the other about 12 to 50 mm (0.5 to 2 in.), depending on the lead thickness. The thicker the lead sheet or plate, the greater the overlap required.

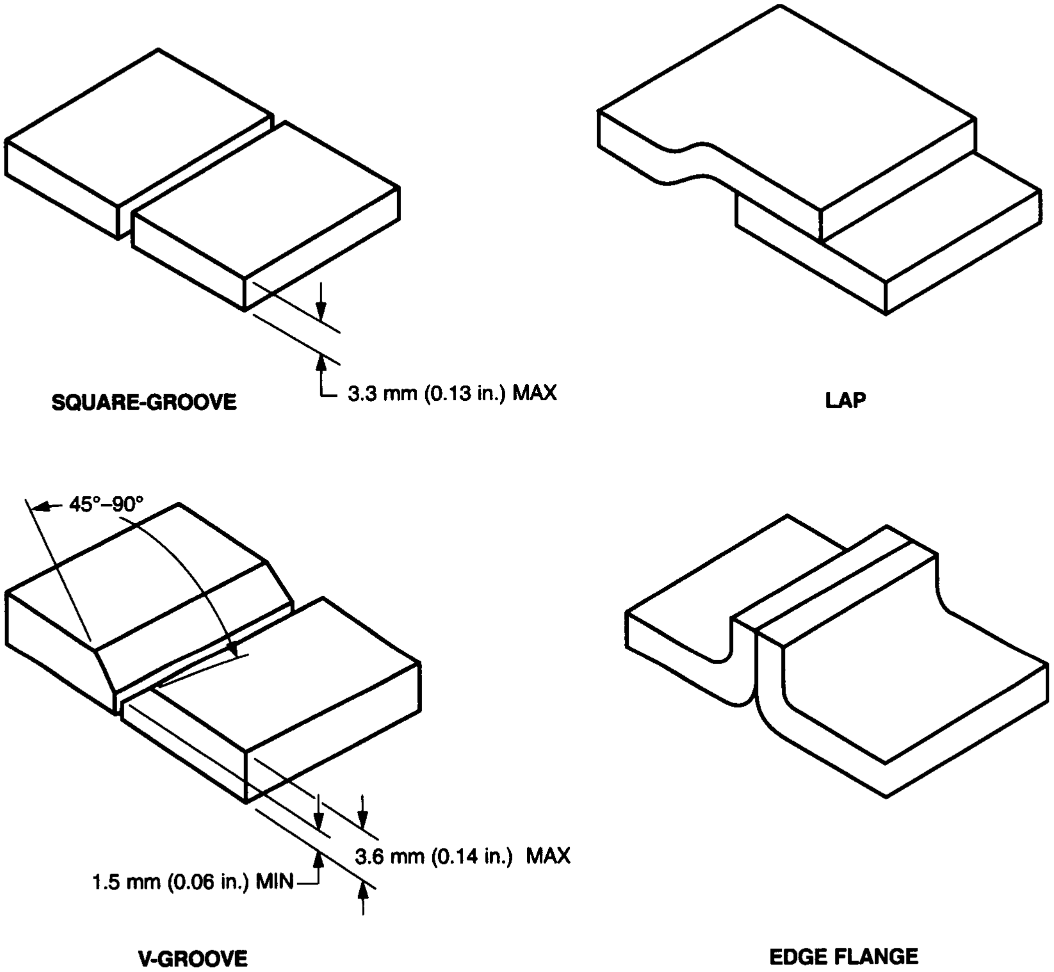


Figure L-8—Joint Designs for Welding Lead Sheet

For butt joints in sheet thicknesses of 3.2 mm (0.125 in.) or less, a square-groove butt joint is required. V-groove designs should be used for sections over 4 mm (0.15 in.) thick.

An edge-flange joint, for use with thin sheet, is prepared by flanging the edge of each sheet to be joined to a right angle. The flange width should be 1.5 times the sheet thickness.

A butt joint is usually preferred for the welding of lead pipe. However, a lap or cup joint may be appropriate for wall thicknesses of 4 mm (0.15 in.) or under. The cup design is shown in Figure L-9. A sleeve is often used on large diameter pipe joints. The sleeve is slipped over the joint and welded to both pipes with fillet welds.

Sheet Welding

Flat Position. Butt joints are usually used in welding sheet in the flat position, although a flange joint is preferred for welding thin sheet. Filler metal is generally not added to the first weld pass.

Vertical Position. Lap joints are used almost exclusively when welding in the vertical position. Welding should be uphill beginning at the bottom of the joint, with a backing used to support the initial weld metal. Butt joints may be used in special cases, but for this type of joint a mold must be used to contain the weld metal.

Overhead Position. This position is the most difficult for lead welding and should be avoided whenever possible.

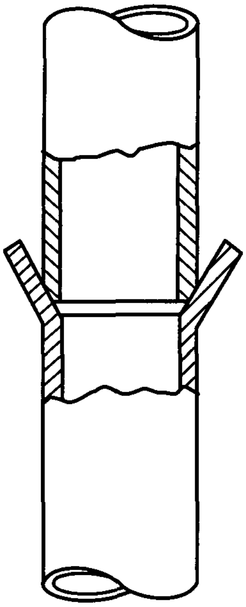


Figure L-9—Cup Joint Design for Welding Lead Pipe in the Vertical Position

Horizontal Joints. A lap joint is used for both the overhand and underhand techniques for welding horizontal joints.

Safe Practices

Fumes from molten lead and its compounds are toxic. Exposure to these materials can be a serious health hazard if precautions are not taken to keep fumes at a safe level. Exposure to lead fumes can occur in a variety of situations where cleaning and welding are performed on lead and lead products. Specifically, exposure results when workers must handle and weld lead sheets or pipes, or when lead surfaces are cleaned with abrasive.

Fume concentrations within the breathing zone of the welding or cutting operator can be controlled by either of two ventilation methods. Fumes can be dispersed by diluting fume-laden air with uncontaminated air, or can be captured by a collector hood connected to an exhaust system. Dilution ventilation can be provided either naturally or mechanically. Local exhaust ventilation is a practical means of controlling exposure of welding and cutting operators to fumes produced while working. Under some circumstances, approved respirators may be necessary to adequately protect operators from unsafe concentrations of lead within the breathing zone.

For detailed information on LEAD WELDING see American Welding Society, *Welding Handbook,* Vol.3, 8th Ed., Miami, Florida, American Welding Society 1996. Additional information may be obtained from ANSI Z49.1, *Safety in Welding and Cutting,* The American Welding Society, Miami, Florida, or the Lead Industries Association, 292 Madison Avenue, New York N.Y. 10017.

LEADS

A nonstandard term for WELDING LEADS.

LEG OF A FILLET WELD

See FILLET WELD LEG. *See* STANDARD WELDING TERMS.

LENGTH OF WELD

See EFFECTIVE LENGTH OF WELD.

LENS

See STANDARD WELDING TERMS. *See* FILTER PLATE.

LEVEL WOUND

Spooled or coiled filler metal that has been wound in distinct layers so that adjacent turns touch. See STANDARD WELDING TERMS. *See* RANDOM WOUND.

LIGHT-GAUGE WELDING

The welding of sheet metal or strip metal, including cold-formed members 5 mm (0.18 in.) or less in thickness. When welding is for structural purposes, refer to ANSI/AWS D1.3, *Structural Welding Code—Sheet Steel.* When welding sheet metal for non-structural applications, refer to ANSI/AWS D9.1, *Sheet Metal Welding. See* SHEET METAL WELDING.

LIGHTER

A device used to ignite the gases flowing from a welding torch.

The spark lighter, probably the safest, simplest and most commonly used lighter, consists of a piece of flint and a short steel file mounted at opposite ends of a U-shaped piece of spring wire. The spring action causes the flint to scratch over the file, creating a spark which ignites the gas flowing from the torch.

When using a lighter of any type, the torch must be directed away from the operator, other personnel, and flammable material.

LIGHTLY COATED ELECTRODE

A filler metal electrode consisting of a metal wire with a light coating applied subsequent to the drawing *operation, primarily for stabilizing the arc. See* STANDARD WELDING TERMS. *See* COVERED ELECTRODE *and* FILLER METAL.

LIME

A solid, white (when pure), highly infusible caustic, a constituent of the chemical calcium oxide (CaO), made by calcining limestone, shells, or other sources of calcium carbonate. Lime is a byproduct of acetylene, generated by dropping calcium carbonate into water. The chemical reaction is:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$$

See QUICKLIME.

The temperature of acetylene generation often causes a quantity of carbide lime to be carried by the gas. This lime dust passes freely through water; the quantity is small and can be easily removed by a chemical purifier. Its effect on welds seems negligible, although there have been incidental reports that the narrow passages of some regulators or torches are affected.

LIMIT OF ELASTICITY

See ELASTIC LIMIT.

LIMITED DUTY WELDING MACHINES

Alternating current arc welding machines rated at 300 amperes or lower with duty cycles less than 50% are usually referred to as limited duty welding machines. These welding machines have a National Electrical Manufacturers Association (NEMA) Class II classification.

LIMITED INPUT WELDING MACHINES

Limited input welding machines are classed as utility or farm welding machines. There is a limit on the allowable primary current and a limit on the rated output load of the welding machine. Limited input welding machines are usually classified as 130 ampere for a 3 kva power circuit, or 180 amperes for a 5 kva power circuit, and usually have a 20% duty cycle.

LINEAR DISCONTINUITY

A discontinuity with a length that is substantially greater than its width. See STANDARD WELDING TERMS.

LINEAR INDICATION

A test result in which a discontinuity in the material being tested is displayed as a linear or aligned array. See STANDARD WELDING TERMS.

LINEAR POROSITY

A nonstandard term when used for ALIGNED POROSITY.

LINE DROP

The loss of voltage along the conductors (electrode and workpiece leads) in a circuit, due to the resistance of the conductors when current is flowing.

LIQUID PENETRANT TESTING

A non-destructive testing process in which a penetrating agent is used to detect weld defects and other possible flaws in non-magnetic materials. Liquid penetrant inspection is accomplished in a three-step method for preparation and testing. First, a cleaner is sprayed on the part to be tested and all dirt and grease removed; the penetrant is applied and the excess removed; then the developer is sprayed on. The developer, on drying, draws the penetrant to the surface and the flaws will show up in natural light. Many of the dye penetrants are packaged in spray cans for convenient use.

A variation of the dye penetrant method of inspection is the fluorescent penetrant method. This system requires ultraviolet light (black light) to reveal defects. If there are defects, they appear in sharp glowing contrast to the surrounding flaw-free surface.

The fluorescent penetrant is an oil-base agent with suspended fluorescent particles capable of penetrating every surface defect. It is applied by dipping, spraying or brushing on the piece to be inspected. After it has entered any of the seams, cracks and pinholes, the surface excess is washed away with a water spray. When it has dried, a dry powder of water-suspension developer is applied to create a dry powder film on the surface. This draws the penetrant up from the defect. The inspection is done under a black light in a darkened booth. *See* MAGNETIC PARTICLE INSPECTION.

LIQUATION

The partial melting of compositional heterogeneities such as banding or inclusion stringers in heated base metal or heat-affected zones. See STANDARD WELDING TERMS.

Liquation is the separation of a low melting constituent of an alloy from the remaining constituents, usually apparent in alloys having a wide melting range.

LIQUEFACTION

Reduction of a gas to the liquid state by compression or refrigeration or a combination of the two. *See* OXYGEN PRODUCTION.

LIQUID AIR PROCESS

A method of separating oxygen, nitrogen, argon and other gases present in air. The liquid air process liquefies air by repeated cycles of cooling, compression, and expansion.

The process makes use of the differences in the boiling points of the major elements in liquid air to separate these components. The boiling point for oxygen is –183°C (–297°F) and for nitrogen, –196°C (–320.4°F). These low temperatures are reached partly by refrigeration and partly by the Joule-Thomson effect, whereby rapidly expanding gas is cooled by expansion.

See CRYOGENICS *and* OXYGEN PRODUCTION.

LIQUID ARGON

Argon below its boiling point, –186°C (–302.3°F), is in the liquid state. In the liquid state, 4.0 L (1.06 gallons) of argon is equivalent to 25 m^3 (890 ft^3) of gas at 21°C (70°F) and 101.4 kPa (14.7 psia). Argon is more convenient to handle and store in its liquid state and is used extensively in welding and other industries because it is inert.

LIQUID NITROGEN

Nitrogen is liquid at below its boiling point of –196°C (–320.4°F). In the liquid state, 4.0 L (1.06 gallons) of nitrogen will produce 20 m^3 (706 ft^3) of nitrogen gas at 21°C (70°F) and 101.4 kPa (14.7 psia). Liquid nitrogen is used extensively for metallurgical purposes. For example, metal parts such as pins, shafts and similar pieces are cooled in liquid nitrogen to effect shrink-fitting of assemblies. *See* CRYOGENICS.

LIQUID OXYGEN

Oxygen as a gaseous element forms 21% (by volume) of the earth's atmosphere. Oxygen is a liquid below its boiling point of –183°C (–297°F). Liquid oxygen is obtained by the liquefaction of air. It is separated from the other liquid atmospheric elements by fractional distillation.

The development of satisfactory containers for storage of cryogenic liquids at very low temperatures has enabled air liquefaction products to be transported and stored on the premises of the ultimate user. As a liquid, 4.0 L (1.06 gallons) of oxygen will produce 25.2 m^3 (890 ft^3) of gaseous oxygen at 21°C (70°F) and 101.4 kPa (14.7 psia).

Liquid oxygen is converted to a gas at the job site, providing a source of high purity oxygen for welding, cutting, and other operations in which large volumes of gases are used. In addition to welding and industrial uses, liquid oxygen has an important role as a fuel for rocket engines in the United States space program. High purity oxygen is extensively used for oxygen therapy in hospitals and medical service organizations. *See* OXYGEN PRODUCTION; LIQUID AIR PROCESS, *and* CRYOGENICS.

LIQUIDUS

The lowest temperature at which a metal or an alloy is completely liquid. See STANDARD WELDING TERMS.

In a constitution or equilibrium diagram (phase diagram), the liquidus is the locus of points representing the temperatures at which the various chemical compositions in the system begin to freeze on cooling or to finish melting on heating, under equilibrium conditions. *See* METALLURGY.

LITHARGE

Lead oxide (PbO); a yellow, crystalline substance that forms on the surface of molten lead.

LOAD VOLTAGE

The voltage at the output terminals of the power supply when current is flowing.

LOCAL PREHEATING

Preheating a specific portion of a structure. See STANDARD WELDING TERMS.

The preheat temperature of the workpiece must be sufficiently high to prevent cracking on cooling. For groove welding, it is generally accepted that the base metal of the workpieces must be at the minimum specified preheat for a distance of not less than 75 mm (3 in.) in all directions from the point of welding. *See* PREHEAT.

LOCAL STRESS-RELIEF HEAT TREATMENT

Stress relief heat treatment of a specific portion of a structure. See STANDARD WELDING TERMS.

The usual purpose of a postweld heat treatment (PWHT) is to stress-relieve the weld and the heat-affected zone (HAZ). Stress relieving heat treatment is also used when necessary to maintain dimensional stability during subsequent machining operations. Consideration must be given to possible distortion of the structure due to localized stress relief. *See* STRESS-RELIEF HEAT TREATMENT *and* HEAT TREATMENT.

LOCKED-UP STRESS

A nonstandard term for RESIDUAL STRESS.

LONGITUDINAL BEND SPECIMEN

See LONGITUDINAL WELD TEST SPECIMEN. *See also* STANDARD WELDING TERMS.

LONGITUDINAL CRACK

A crack with its major axis orientation approximately parallel to the weld axis. See STANDARD WELDING TERMS. *See* Appendix 9.

LONGITUDINAL SEAM

Usually refers to pipe or tubular products that have a joint parallel to the axis of the product. The base metal may be joined by welding or mechanical methods. *See* PIPE WELDING *and* TUBULAR JOINT.

LONGITUDINAL SEAM WELDING

Longitudinal seam welding produces a resistance seam weld at the faying surface of overlapped parts progressively along the length of the joint. *See* Figure H-4. *See also* RESISTANCE SEAM WELDING.

LONGITUDINAL SEQUENCE

The order in which the weld passes of a continuous weld are made with respect to its length. See STANDARD WELDING TERMS. *See* BACKSTEP SEQUENCE, BLOCK SEQUENCE, CASCADE SEQUENCE, CONTINUOUS SEQUENCE, *and* RANDOM SEQUENCE.

LONGITUDINAL TENSION SPECIMEN

See LONGITUDINAL WELD TEST SPECIMEN.

LONGITUDINAL WELD TEST SPECIMEN

A weld test specimen with its major axis parallel to the weld axis. See STANDARD WELDING TERMS. *See* TRANSVERSE WELD TEST SPECIMEN.

LOW ALLOY HIGH STRENGTH STEEL

See STEEL, High Strength Low Alloy.

LOW-CARBON STEEL

See STEEL, Low-carbon.

LOW HYDROGEN

Hydrogen has a critical effect on the quality of weld deposits in steels. Under certain conditions, the presence of hydrogen results in cracking. Hydrogen-induced cracking is also called underbead cracking, cold cracking, or delayed cracking. Cracking generally occurs at a temperature below 93°C (200°F) immediately on cooling or after a period of several hours. The time depends on the type of steel, the magnitude of welding stresses, and the hydrogen content of the steel weld and heat-affected zones (HAZ). Diffusion of hydrogen into the heat-affected zone from the weld metal during welding contributes to cracking in the HAZ.

To eliminate this problem, a low-hydrogen electrode was developed for shielded metal arc welding.

The main source of hydrogen in welding is from moisture, either from the base metal, the electrode coating, or from the shielding gases used in gas tungsten arc welding, gas metal arc welding, and flux cored arc welding. The elimination of moisture from these sources is necessary to prevent the formation of underbead or delayed cracking. *See* LOW-HYDROGEN ELECTRODES.

LOW-HYDROGEN ELECTRODES

Low-hydrogen electrodes for shielded metal arc welding were developed to control the contamination of the weld and weld metal from hydrogen absorption during welding. The moisture content of the electrode covering is maintained within specification limits, usually less than 0.15% moisture. Low-hydrogen (EXX15 and EXX16) and low-hydrogen, iron powder (EXX18, EXX24, and EXX28) electrodes were designed and developed to contain the minimum amount of moisture in the coverings.

To maintain this low moisture level in the covering, the filler metal manufacturer furnishes these electrodes in hermetically sealed containers. When the sealed container is opened, electrodes not used immediately should be stored in a holding oven at 120°C (250°F). Electrodes should not exceed the moisture limits prescribed by the appropriate specification. Electrodes which have been exposed to the atmosphere for time beyond that permitted by the specification, or have been exposed to moisture, should either be discarded or reconditioned by re-baking. If not specified, information on the appropriate time and temperature for reconditioning should be requested from the manufacturer. Wet electrodes should be discarded. *See* FILLER METAL *and* SHIELDED METAL ARC WELDING.

LOW MELTING, Non-Fusion Welding

A term sometimes used for BRAZE WELDING.

LOW-PRESSURE TORCH

A type of oxyfuel gas torch used for welding. *See* TORCH *and* OXYFUEL GAS WELDING.

LOW PULSE CURRENT, Pulsed Power Welding

The current during the low pulse time that produces the low heat level. See STANDARD WELDING TERMS. *See* Appendix 19.

LOW PULSE TIME, Pulsed Power Welding

The duration of the low current pulse. See STANDARD WELDING TERMS. *See* Appendix 19.

LOW SPOTS

Weld defects appearing as excessive concavity or cratering. These defects are caused by moving the torch or electrode too rapidly or unevenly.

LOW-TEMPERATURE STRESS RELIEF

The residual stresses induced in weldments during welding may be relieved by applying heat at temperatures much lower than ordinarily used for stress relieving. The most satisfactory method for relieving stresses in carbon and low alloy steels is to treat the entire weldment in a furnace at a temperature between 540 to 650°C (1000 to 1200°F). Where the structure is too large to make this method practical, stresses due to welding have been satisfactorily relieved by applying low-temperature heat to the weldment, the heat-affected zone, and adjacent base metal.

In carbon and low-alloy steels, low-temperature stress relief is accomplished by heating the weldment and adjacent base metal to not more than 315°C (600°F), although some low-alloy steels should not be heated above 205°C (400°F).

Heating Methods

Various heating methods used to accomplish low-temperature stress relief of weldments include (1) oxyfuel gas torch heating with acetylene, propane, or butane, (2) electric resistance heating; and (3) induction heating. Each method has advantages and limitations.

Torch Heating. For stress relieving, uniform heating can be accomplished with single burner torches to bring the temperature to 315°C (600°F). The "softer" flames produced by propane or butane torches are usually preferred over oxyacetylene torches.

Resistance Heating. Electric resistance heating is a widely used method for low-temperature stress relieving, especially at field erection sites, and also for applications requiring prolonged application of heat, such as weldments in thick sections. Resistance heating is usually accomplished with heating blankets that have nichrome wires in a pattern throughout the blanket. The high-resistance nichrome wires are heated by passing an electric current through them.

Thermocouples are attached to the base metal and the weldment to be heated. The thermocouple wires are connected to control equipment that will automatically control the time-temperature cycle to ensure uniform heating of the weldment and adjacent base metal.

Induction Heating. Induction heating is extensively used at field erection sites for heat treatment of welds, and is particularly suitable for welds in pipes with wall thickness above 50 mm (2 in.), or for structural members on which it is possible to wrap the copper conductors around the weldment and base metal to be heated. Relatively low frequencies, 25, 60, and 400 Hz, are used with 60 Hz input equipment. On thick material, especially heavy-wall pipe, this method has the advantage of providing uniform heat throughout the material with a smaller temperature difference between the outside and inside surfaces of the base metal and weldment. The electric field is usually obtained by wrapping copper conductors around the weldment and adjacent base metal to be heated. Special fixtures are available to facilitate the rapid attachment and removal of the induction heating coils.

Temperature Control

Temperature control in heat treating operations is especially important and frequently influences equipment selection.

For torch heating, temperature-indicating crayons are widely used. They should be free of sulfur and lead. Stress relieving temperatures up to 370°C (700°F) may also be monitored with direct reading, magnetically attached surface thermometers.

In electric resistance heating, surface thermometers or electrically operated pyrometers are used to control the current flow automatically in the heating units.

For induction heating, thermocouples are usually attached to the surfaces of metals to be heated. The thermocouple wires are connected to a pyrometer to control the temperature of the weldment and adjacent base metal during heat treating.

M

M_F TEMPERATURE

The martensite finish temperature. Specifically for steel, the temperature at which the transformation of austenite into martensite is completed.

M_S TEMPERATURE

The martensite start temperature. Specifically for steel, the temperature at which the transformation of austenite into martensite begins.

MACHINE

A nonstandard term when used for MECHANIZED.

MACHINE OXYGEN CUTTING

See OXYGEN CUTTING *and* MECHANIZED THERMAL CUTTING.

MACHINE WELDING

See MECHANIZED WELDING *and* AUTOMATIC WELDING.

MACHINE DESIGN

The advances that have been made in welding and thermal cutting processes have provided the means of shaping and joining large sections of iron and steel. These processes have replaced castings in the production of machine frames, machine bases, and other structures. Correctly designed welded frames are stronger and lighter, but rigidity has not been sacrificed.

Designing for Strength and Rigidity. Machine designs must have sufficient strength so that members will not fail by breaking or yielding when subjected to normal operating loads or reasonable overloads. Strength designs are common in road machinery, motor brackets, farm implements, and like structures.

For weldments in machine tools and other machinery, rigidity as well as strength is important, since excessive deflection under load would result in lack of precision in the product. A design based on rigidity requires the use of design formulas for sizing members. Some parts of a weldment serve their design function without being subjected to loading much greater than their own weight (dead load). Some typical parts are dust shields, safety guards, and cover plates for access holes. Only casual attention is required in sizing such members.

Design Formulas. The design formulas for strength and rigidity always contain terms representing the load, the stress, and the strain or deformation. If two of the three terms are known, the others can be calculated. All problems of design thus resolve into one of the following:

(1) Finding the internal stress or deformation caused by an external load on a given member.

(2) Finding the external load that may be placed on a given member for any allowable stress or deformation

(3) Selecting a member to carry a given load without exceeding the specified stress or deformation.

In designing within allowable limits, the designer should generally select the most efficient material section size and section shape. The properties of the material and those of the section determine the ability of a member to carry a given load.

Sizing of Steel Welds. A weld is sized for its capability to withstand static or cyclic loading. Allowable stresses for welds for various types of loading are normally specified by the construction standards applicable to the job. They are usually based on a percentage of tensile or yield strength of the metal to ensure that a soundly welded joint can support the applied load for the expected service life. Allowable stresses or stress ranges are specified for various types of welds under static and cyclic loads. The allowable stress ranges for welded joints subjected to cyclic loading specified in current standards are based on testing of representative full-size welded joints in actual or mockup structures.

The primary requirement of machine design for a machine and some of its members is rigidity. Such members are often thick sections so that the movement under load can be controlled within close tolerances. Whereas low-carbon steel has an allowable stress in tension of 138 MPa (20 ksi), a welded machine base or frame may have a working stress of only 14 to 28 MPa (2 to 4 ksi). In these cases the weld sizes should be designed for rigidity rather than load conditions.

A practical method is to design the weld size to carry one-third to one-half of the load capacity of the thinner member being joined. This means if the base metal is stressed to one-third to one-half of the normal allowable stress, the weld would be strong enough to carry the load. Most rigid designs are stressed below these values.

Welding Conditions. Designers specifying welding procedures for machinery fabrication should specify the following:

(1) Joint type, groove angle, root opening and root face
(2) Electrode type and size to be used
(3) Current type, polarity and current in amperes
(4) Arc length (arc voltage)
(5) Travel speed
(6) Welding position i.e., flat, horizontal, vertical, overhead
(7) Test procedures for weld metal and joints

MACROETCH

Etching of a metal surface to accentuate the gross structural details and defects for observation by the unaided eye, or at a magnification not exceeding ten diameters.

MACROGRAPH

A graphic reproduction of the surface of a prepared specimen at a magnification not to exceed ten diameters. When photographed, the reproduction is called a photomacrograph.

MACROSCOPIC

Visible at magnifications from one to ten diameters.

MACROSTRUCTURE

The structure of metals as revealed by examination of the etched surface of a polished specimen at a magnification not greater than ten diameters.

MACROETCH TEST

A test in which a specimen is prepared with a fine finish, etched, and examined under low magnification. See STANDARD WELDING TERMS.

MAG

Metal Active Gas; a little-used term for gas metal arc welding in which an active gas such as carbon dioxide is used. *See* GAS METAL ARC WELDING.

MAGNESIUM

(Chemical symbol: Mg). A light, white and fairly tough metal. It tarnishes slightly in air, and when fabricated into ribbon, wire or powder, ignites on heating and burns with a dazzling white flame. Magnesium is one of the most abundant elements; it is eighth in estimated amount in the earth's crust. It is removed commercially from sea water in the form of magnesium chloride (a mineral similar to table salt). Pure magnesium is obtained from molten magnesium chloride by the electrolysis process; the magnesium collects on the cathode. Atomic weight 24.32; atomic number, 12; melting point 651°C (1204°F); boiling point 1110°C (2030°F).

In the pure state, magnesium does not have sufficient strength or other properties to make it suitable for structural purposes. However, it alloys readily with aluminum, zinc, silicon, manganese and tin, to form a variety of structural alloys. The strength of these alloys is comparable to aluminum alloys but they weigh only 65% as much as aluminum. *See* MAGNESIUM ALLOYS.

MAGNESIUM ALLOYS

Magnesium alloys are used in a wide variety of applications where light weight is important. Structural applications include industrial, materials-handling, commercial, and aerospace equipment. In industrial machinery, such as textile and printing machines, magnesium alloys are used for parts that operate at high speeds and must be lightweight to minimize inertial forces. Materials-handling equipment examples are dock boards, grain shovels, and gravity conveyors; commercial applications include such items as luggage and ladders. Good strength and rigidity at both room and elevated temperatures, combined with light weight, make magnesium alloys useful for some aerospace applications.

Alloy Systems

Most magnesium alloys are ternary types. They may be considered in four groups based on the major alloying element: aluminum, zinc, thorium, or rare earths. There are also binary systems employing manganese and zirconium. Magnesium alloys may also be grouped according to service temperature. The magnesium-aluminum and magnesium-zinc alloy groups are suitable only for room-temperature service. Their tensile and creep properties decrease rapidly when the service temperature is above about 150°C (300°F).

The magnesium-thorium and magnesium-rare earth alloys are designed for elevated-temperature service. They have good tensile and creep properties up to 370°C (700°F).

Designation Method. Magnesium alloys are designated by a combination letter-number system composed of four parts. Part 1 indicates the two principal alloying elements by code letters arranged in order of decreasing percentage. The code letters are listed in Table M-1.

Table M-1
Code Letters for Magnesium Alloy Designation System

Letter	Alloying Element
A	Aluminum
E	Rare earths
H	Thorium
K	Zirconium
M	Manganese
Q	Silver
Z	Zinc

Part 2 indicates the percentages of the two principal alloying elements in the same order as the code letters. The percentages are rounded to the nearest whole number. Part 3 is an assigned letter to distinguish different alloys with the same percentages of the two principal alloying elements. Part 4 indicates the condition of temper of the product. It consists of a letter and number similar to those used for aluminum, as shown in Table M-2. They are separated from Part 3 by a hyphen.

An example is alloy AZ63A-T6. The prefix AZ indicates that aluminum and zinc are the two principal alloying elements. The numbers 6 and 3 indicate that the alloy contains nominally 6% aluminum and 3% zinc. The following A indicates that this is the first standardized alloy of this composition. The fourth part, T6, states that the product has been solution heat-treated and artificially aged.

Commercial Alloys. Magnesium alloys are produced in the form of castings and wrought products including forgings, sheet, plate, and extrusions. A majority of the alloys produced in these forms can be welded. Commercial magnesium alloys are designed for either room-temperature or elevated-temperature service. Some of the more important magnesium alloys for room temperature service are listed in Table M-3. Those for elevated temperature service are listed in Table M-4.

Wrought Alloys. Welded construction for room-temperature service is frequently designed with AZ31B alloy. It offers a good combination of strength, ductility, toughness, malleability, and weldability in all wrought product forms. The alloy is strengthened by work hardening. AZ80A and ZK60A alloys can be artificially aged to develop good strength properties for room temperature applications.

Table M-2
Temper Designations for Magnesium Alloys

F	As fabricated
O	Annealed, recrystallized (wrought products only)
H	Strain-hardened
T	Thermally treated to produce stable tempers other than F, O, or H
W	Solution heat-treated (unstable temper)
Subdivisions of H	
H1, plus one or more digits	Strain-hardened only
H2, plus one or more digits	Strain-hardened and then partially annealed
H3, plus one or more digits	Strain-hardened and then stabilized
Subdivisions of T	
T1	Cooled and naturally aged.
T2	Annealed (cast products only)
T3	Solution heat-treated and then cold-worked
T4	Solution heat-treated
T5	Cooled and artificially aged
T6	Solution heat-treated and artificially aged
T7	Solution heat-treated and stabilized
T8	Solution heat-treated, cold-worked, and artificially aged
T9	Solution heat treated, artificially aged, and cold-worked
T10	Cooled, artificially aged, and cold-worked

Weldments made with AZ10A, M1A, and ZK21A alloy are not sensitive to stress-corrosion cracking, so postweld stress relieving is not required for weldments made of these alloys. They are strengthened by work hardening for room-temperature service. HK31A, HM21A, and HM31A alloys are designed for elevated-temperature service. They are strengthened by a combination of work hardening followed by artificial aging.

Cast Alloys. The most widely used casting alloys for room-temperature service are AZ91C and AZ92A. These alloys are more crack-sensitive than the wrought Mg-Al-Zn alloys with lower aluminum content. Consequently, they require preheating prior to fusion welding.

EZ33A alloy has good strength stability for elevated-temperature service and excellent pressure tight-

Table M-3
Commercial Magnesium Alloys for Room-Temperature Service

ASTM Designation	Nominal Composition, % (Remainder Mg) Al	Zn	Mn	RE*	Zr	Th
Sheet and Plate						
AZ31B	3.0	1.0	0.5	—	—	—
M1A	—	—	1.5	—	—	—
Extruded Shapes and Structural Sections						
AZ10A	1.2	0.4	0.5	—	—	—
AZ31B	3.0	1.0	0.5	—	—	—
AZ61A	6.5	1.0	0.2	—	—	—
AZ80A	8.5	0.5	0.2	—	—	—
M1A	—	—	1.5	—	—	—
ZK21A	—	2.3	—	—	0.6	—
ZK60A	—	5.5	—	—	0.6	—
Sand, Permanent Mold, or Investment Castings						
AM100A	10.0	—	0.2	—	—	—
AZ63A	6.0	3.0	0.2	—	—	—
AZ81A	7.6	0.7	0.2	—	—	—
AZ91C	8.7	0.7	0.2	—	—	—
AZ92A	9.0	2.0	0.2	—	—	—
K1A	—	—	—	—	0.6	—
ZE41A	—	4.2	—	1.2	0.7	—
ZH62A	—	5.7	—	—	0.7	1.8
ZK51A	—	4.6	—	—	0.7	—
ZK61A	—	6.0	—	—	0.8	—

*As mischmetal (approximately 52% Ce, 26% La, 19% Nd, 3% Pr).

Table M-4
Commercial Alloys for Elevated-Temperature Service

ASTM Designation	Nominal Composition, % (Remainder Mg) Al	Zn	Mn	RE*	Mn	Ag
Sheet and Plate						
HK31A	3.0	—	0.7	—	—	—
HM21A	2.0	—	—	—	0.5	—
Extruded Shapes and Structural Sections						
HM31A	3.0	—	—	—	1.5	—
Sand, Permanent Mold, or Investment Castings						
EK41A	—	—	0.6	4.0	—	—
EZ33A	—	2.6	0.6	3.2	—	—
HK31A	3.2	—	0.7	—	—	—
HZ32A	3.2	2.1	0.7	—	—	—
QH21A	1.1	—	0.6	1.2	—	2.5

*As mischmetal (approximately 52% Ce, 26% La, 19% Nd, 3% Pr).

ness. HK31A and HZ32A alloys are designed to operate at higher temperatures than is EZ33A. QH21A alloy has excellent strength properties up to 260°C (500°F). All of these alloys require heat treatment to develop optimum properties. They have good welding characteristics.

Mechanical Properties. Typical strength properties at room temperature for magnesium alloys are given in Table M-5. For castings, the compressive yield strength is about the same as the tensile yield strength. However, the yield strength in compression for wrought products is often lower than in tension.

The tensile and creep properties of representative magnesium alloys at a service temperature of 315°C (600°F) are given in Table M-6. The alloys containing thorium (HK, HM, and HZ) have greater resistance to creep at 315°C (600°F) than do the Mg-Al-Zn alloys.

Major Alloying Elements. With most magnesium alloy systems, the solidification range increases as the alloy addition increases. This contributes to a greater tendency for cracking during welding. At the same time, the melting temperature as well as the thermal conductivity and electrical conductivity decrease. Consequently, less heat input is required for fusion welding as the alloy content increases.

Aluminum and zinc show decreasing solubility in solid magnesium with decreasing temperature. These elements will form compounds with magnesium. Consequently, alloys containing sufficient amounts of aluminum and zinc can be strengthened by a precipitation-hardening heat treatment. Other alloying elements also behave similarly in ternary alloy systems. Beryllium, manganese, silver, thorium and zirconium are major alloying elements in magnesium alloys.

Weldability. The relative weldability of magnesium alloys by gas shielded arc and resistance spot welding processes is shown in Table M-7. Castings are not normally resistance welded. The Mg-Al-Zn alloys and alloys that contain rare earths or thorium as the major alloying element have the best weldability. Alloys with zinc as the major alloying element are more difficult to weld. They have a rather wide melting range, which makes them sensitive to hot cracking. With proper joint design and welding conditions, joint efficiencies will range from 60 to 100%, depending on the alloy and temper.

Most wrought alloys can be readily resistance spot welded. Due to short weld cycles and heat transfer characteristics, fusion zones are fine-grained, and

Table M-5
Room-Temperature Mechanical Properties of Magnesium Alloys

ASTM Designation	Tensile Strength		Tensile Yield Strength*		Compressive Yield Strength*		Elongation in 51 mm (2 in.) %
	MPa	ksi	MPa	ksi	MPa	ksi	
Sheet and Plate							
AZ31B-0	255	37	152	22	110	16	21
AZ31B-H24	290	42	221	32	179	26	15
HK31A-H24	228	33	207	30	152	22	9
HM21A-T8	234	34	172	25	131	19	10
M1A-0	234	34	131	19	—	—	18
M1A-H24	269	39	200	29	—	—	10
Extruded Shapes and Structural Sections							
AZ10A-F	241	35	152	22	76	11	10
AZ31B-F	262	38	200	29	97	14	15
AZ61A-F	310	45	228	33	131	19	16
AZ80A-F	338	49	248	36	152	22	11
AZ80A-T5	303	44	262	38	186	27	8
HM31A-T5	303	44	262	38	186	27	8
M1A-F	255	37	179	26	83	12	11
ZK21A-F	290	42	228	33	172	25	10
ZK60A-F	338	49	255	27	193	28	14
ZK60A-T5	358	52	303	44	248	36	11
Sand, Permanent Mold, or Investment Castings							
AM100A-T6	276	40	152	22	152	22	1
AZ63A-F	200	29	97	14	—	—	6
AZ63A-T4	276	40	90	13	—	—	12
AZ63A-T6	276	40	131	19	131	19	5
AZ81A-T4	276	40	83	12	83	12	15
AZ91C-F	165	24	97	14	—	—	2
AZ91C-T4	276	40	83	12	—	—	14
AZ91C-T6	276	40	145	21	145	21	5
AZ92A-F	165	24	97	14	—	—	2
AZ92A-T4	276	40	97	14	—	—	9
AZ92A-T6	276	40	145	21	145	21	2
EK41A-T5	172	25	90	13	—	—	3
EZ33A-T5	159	23	103	15	103	15	3
HK31A-T6	221	32	103	15	103	15	8
HZ32A-T5	186	27	97	14	97	14	4
K1A-F	172	25	48	7	—	—	19
QH21A-T6	276	40	207	30	—	—	4
ZE41A-T5	207	30	138	20	138	20	4
ZH62A-T5	241	35	172	25	172	25	4
ZK51A-T5	206	30	165	24	165	24	4
ZK61A-T6	310	45	193	28	193	28	10

*0.2% offset yield strength.

Table M-6
Elevated-Temperature Properties of Some Representative Magnesium Alloys

	148°C (300°F)						204°C (400°F)						316°C (600°F)					
	Tensile Strength		Tensile Yield Strength		Creep Strength*		Tensile Strength		Tensile Yield Strength		Creep Strength*		Tensile Strength		Tensile Yield Strength		Creep Strength*	
Alloy	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
Sheet and Plate Alloys																		
AZ31B-H24	152	22	90	13	6.9	1.0	90	13	55	8	—	—	41	6	14	2	—	—
HK31A-H24	179	26	165	24	—	—	165	24	145	21	41.4	6.0	83	12	48	7	—	—
HM21A-T8	159	23	145	21	—	—	131	19	124	18	78.6	11.4	103	15	90	13	34.5	5.0
Extrusion Alloys																		
AZ31B-F	172	25	103	15	20.7	3.0	103	15	62	9	—	—	41	6	14	2	—	—
AZ80A-T5	241	35	159	23	24.1	3.5	152	22	103	15	—	—	62	9	21	3	—	—
HM31A-T5	193	28	172	25	—	—	165	24	145	21	75.2	10.9	124	18	103	14	52.4	7.6
ZK60A-T5	172	25	152	22	6.9	1.0	103	15	83	12	—	—	—	—	—	—	—	—
Casting Alloys																		
AZ92A-T6	193	28	117	17	26.2	3.8	117	17	83	12	—	—	55	8	34	5	—	—
AZ63A-T6	165	24	103	15	28.3	4.1	124	18	83	12	—	—	55	8	41	6	—	—
EZ33A-T5	152	22	97	14	—	—	145	21	83	12	55.2	8.0	83	12	55	8	8.3	1.2
HK31A-T6	186	27	103	15	—	—	165	24	97	14	65.5	9.5	138	20	83	12	20.0	2.9
HZ32A-T5	152	22	83	12	—	—	117	17	69	10	53.8	7.8	83	12	55	8	20.7	3.0
QH21A-T6	228	33	200	29	—	—	207	30	186	27	82.7	12	97	14	90	13	—	—

*Creep Strength based on 0.2% total extension in 100 h.

heat-affected zones experience only slight degradation from grain coarsening.

Arc Welding

Applicable Processes. The gas tungsten arc and gas metal arc welding processes are commonly used for joining magnesium alloy components. Inert gas shielding is required with these processes to avoid oxidation and entrapment of oxide in the weld metal. Processes that use a flux covering do not provide adequate oxidation protection for the molten weld pool and the adjacent base metal. Procedures for arc welding magnesium are similar to those used for welding aluminum.

Filler Metals. The weldability of most magnesium alloys is good when the correct filler metal is employed. A filler metal with a lower melting point and a wider freezing range than the base metal will provide good weldability and minimize weld cracking. The recommended filler metals for various magnesium alloys are given in Table M-8.

Casting repairs should be made with a filler metal of the same composition as the base metal when good color match, minimum galvanic effects, or good response to heat treatment is required. For these unusual service requirements, the material supplier should be consulted for additional information. References: American Welding Society, *Welding Handbook*, 8th Edition, Vol. 1, 1987; Vol, 2, 1991; and Vol. 3, 1996; American Welding Society, Miami, Florida.

Safe Practices. The welding fumes from all commercial magnesium alloys, except those containing thorium, are not harmful when the amount of fumes remains below the welding fume limit of 5 mg/m^3. Welders should avoid inhalation of fumes from the thorium-containing alloys because of the presence of alpha radiation in the airborne particles. However, the concentration of thorium in the fumes is sufficiently low so that good ventilation or local exhaust systems will provide adequate protection. The radiation concern, however, is primarily responsible for the decline in use of the thorium-containing alloys. No external

Table M-7
Relative Weldability of Magnesium Alloys

Alloy	Gas Shielded Arc Welding	Resistance Spot Welding
Wrought Alloys		
AZ10A	Excellent	Excellent
AZ31B, AZ31C	Excellent	Excellent
AZ61A	Good	Excellent
AZ80A	Good	Excellent
HK31A	Excellent	Excellent
HM21A	Excellent	Good
HM31A	Excellent	Good
M1A	Excellent	Good
ZK21A	Good	Excellent
ZK60A	Poor	Excellent
Cast Alloys		
AM100A	Good	—
AZ63A	Fair	—
AZ81A	Good	—
AZ91C	Good	—
AZ92A	Fair	—
EK41A	Good	—
EZ33A	Excellent	—
HK31A	Good	—
HZ32A	Good	—
K1A	Excellent	—
QH21A	Good	—
ZE41A	Good	—
ZH62A	Poor	—
ZK51A	Poor	—
ZK61A	Poor	—

Table M-8
Recommended Filler Metals for Arc Welding Magnesium Alloys

	Recommended Filler Metal*				
Alloy	ER AZ61A	ER AZ92A	ER EZ33A	ER AZ101A	Base Metal
Wrought Alloys					
AZ10A	X	X			
AZ31B	X	X			
AZ61A	X	X			
AZ80A	X	X			
ZK21A	X	X			
HK31A			X		
HM21A			X		
HM31A			X		
M1A					X
Cast Alloys					
AM100A		X		X	X
AZ63A		X		X	X
AZ81A		X		X	X
AZ91C		X		X	X
AZ92A		X		X	X
EK41A			X		X
EZ33A			X		X
HK31A			X		X
HZ32A			X		X
K1A			X		X
QH21A			X		X
ZE41A			X		X
ZH62A			X		X
ZK51A			X		X
ZK61A			X		X

*Refer to ANSI/AWS A5.19, *Specification for Magnesium Alloy Welding Electrodes and Rods*, for additional information.

radiation hazard is involved in the handling of the thorium-containing alloys.

The possibility of ignition when welding magnesium alloys in thicknesses greater than 0.25 mm (0.01 in.) is extremely remote. Magnesium alloy product forms will not ignite in air until they are at fusion temperature. Then, sustained burning will occur only if the ignition temperature is maintained. Inert gas shielding during welding prevents ignition of the molten weld pool. Magnesium fires may occur with accumulations of grinding dust or machining chips. Accumulation of grinding dust on clothing should be avoided. Graphite-based (G-1) or proprietary salt-based powders recommended for extinguishing magnesium fires should be conveniently located in the work area. If large amounts of fine particles, or fines, are produced, they should be collected in a waterwash-type dust collector designed for use with magnesium. Special precautions pertaining to the handling of wet magnesium fines must be followed.

The accumulation of magnesium dust in a water bath also can present a hazard. Dust of reactive metals like magnesium or aluminum can combine with the oxygen in the water molecule, leaving hydrogen gas trapped in a bubbly froth on top of the water. A heat source may cause this froth to explode.

Adequate ventilation, protective clothing, and eye protection must be used when working with these materials to avoid toxic effects, burns, or other injuries that they may cause.

General safety issues are covered in the *Welding Handbook*, Volume 1, 8th Edition, Chapter 16, published by the American Welding Society; Miami, Florida.

MAGNESIUM RESISTANCE WELDING

Spot Welding. Magnesium alloy sheet and extrusions can be joined by resistance spot welding in thicknesses ranging from about 0.5 to 3.3 mm (0.02 to 0.13 in.). Alloys recommended for spot welding are M1A, AZ31B, AZ61A, HK31A, HM21A, HM31A, and ZK60A. Spot welding is used for low-stress applications where vibration is low or nonexistent. Magnesium alloys are spot welded using procedures similar to those for aluminum alloys.

Electrodes. Spot welding electrodes for magnesium alloys should be made of RWMA Group A, Class 1 or Class 2 alloy. The faces of the electrodes must be kept clean and smooth to minimize the contact resistance between the electrode and the adjacent part. Cleaning should be done with an electrode dressing tool with the proper face contour covered with a very fine polishing cloth of 280-grit abrasive course.

Copper pickup on the spot weld surfaces increases the corrosion susceptibility of magnesium. Therefore, the copper should be completely removed from the surfaces by a suitable mechanical cleaning method. The presence of copper on spot welds can be determined by applying 10% acetic acid solution. A dark spot will form if copper is present on the surface.

Joint Strength. Typical shear strengths for spot welds in several thicknesses of two magnesium alloys are shown in Table M-9. Refer to American Welding Society, *Welding Handbook*, 8th Edition, Vol. 3, 1996; American Welding Society, Miami, Florida, for additional information on resistance spot welding of magnesium.

MAGNET

A bar of steel, tungsten or cobalt steel in which the alignment of the atoms and the motion of the atomic electrons within the metal exert attractive forces on iron and steel. The ends of the bar are called *poles*. Every bar magnet has at least two poles, usually one near each end. Poles always exist in pairs. A magnet exerts the greatest attractive force at points near the ends.

MAGNETIC ARC BLOW

A nonstandard term for ARC BLOW.

MAGNETIC CONTACTOR

A device operated by an electromagnet which opens and closes an electrical circuit.

MAGNETIC FIELD

The region around a magnet in which magnetic force exists, and would act on a piece of iron or on another magnet brought into the region. In a compass, the direction in which the north-seeking pole of the compass needle points is called the direction of the magnetic field at that place.

MAGNETIC FLUX

The total amount of magnetism induced across a surface; the magnetic flux is equal to the number of

Table M-9
Typical Shear Strengths of Single Spot Welds in Wrought Magnesium Alloys

				Spot Shear Strength					
Thickness		Average Spot Diameter		AZ31B		HK31A		HM21A	
mm	in.	mm	in.	N	lb	N	lb	N	lb
0.5	0.020	3.5	0.14	980	220	—	—	—	—
0.6	0.025	4.1	0.16	1200	270	—	—	—	—
0.8	0.032	4.6	0.18	1465	330	1335	300	—	—
1.0	0.040	5.1	0.20	1825	410	1670	375	1600	360
1.3	0.050	5.8	0.23	2355	530	2445	550	—	—
1.6	0.063	6.9	0.27	3335	750	3200	720	2935	660
2.0	0.080	7.9	0.31	3960	890	—	—	—	—
2.5	0.100	8.6	0.34	5250	1180	—	—	—	—
3.2	0.125	9.7	0.38	6805	1530	6625	1490	5425	1220

magnetic lines of force in a magnetic circuit. *See* MAGNETIC LINES OF FORCE.

MAGNETIC FLUX DENSITY

The number of lines of magnetic flux per square centimeter or per square inch.

MAGNETIC FORCE

The attractive (or repulsive) force exerted by one magnet on another or by a magnet on a ferromagnetic material. The force between two magnets at distances much larger than the lengths of the magnets varies inversely with the distance between the magnets. As the distance is increased, there is a rapid decrease in the force.

MAGNETIC INDUCTION

When iron is placed in a solenoid with current flowing through the solenoid circuit, the iron becomes magnetized, adding the lines of its own magnetic flux to the magnetic lines produced by the current. The total flux per square centimeter is no longer numerically equal to the magnetizing force, but to a larger quantity called the *magnetic induction.*

This quantity is represented by the letter B, where B is the sum of the magnetic lines produced by the current and those produced by the iron.

MAGNETIC INSPECTION OF WELDS

A nonstandard term for MAGNETIC PARTICLE INSPECTION. *See* MAGNETIC PARTICLE INSPECTION.

MAGNETIC LINES OF FORCE

The concept of *magnetic lines of force* was invented by Michael Faraday and is useful in understanding magnetic and electrostatic phenomena. It is defined in the following way: on a sphere with a radius of one centimeter surrounding a unit *pole*, each square centimeter will contain a single line of force. The surface of a sphere is $4 \pi r^2$, thus the total number of lines of force due to a unit pole is 4π. Again, it should be understood that these magnetic lines are purely imaginary. But the concept is a useful study tool, and many technicians are in the habit of referring to magnetic lines as if they actually exist in the space around every magnet.

MAGNETIC MATERIALS

All substances, whether in the form of liquid, solid, or gas, will respond in some manner to an applied magnetic field, although in varying degrees. The magnetic field can be produced by an electric current or it may be the flux from either a permanent magnet or an electromagnet.

Ferromagnetism is the magnetic property of greatest interest in the context of welding metallurgy, because this particular magnetic behavior is frequently involved in welding operations.

Ferromagnetic Materials. Of all the elements in the periodic table only three, iron, cobalt, and nickel, are ferromagnetic at room temperature. However, ferromagnetic alloys can be formulated using various metallic elements which individually are not ferromagnetic. Alnico is an example of an Al-Ni-Co-Cu-Fe alloy used to make permanent magnets, although individually some of the elements of the magnet are not ferromagnetic. Ferromagnetic materials are divided into two classifications: magnetically soft materials, and hard or permanent magnet materials.

Magnetically Soft Materials. Soft ferromagnetic materials are easy to magnetize, but retain little or none of the induced magnetism when the magnetizing force is removed. Magnetically soft materials made in large quantities include high-purity iron, silicon steels, iron-nickel alloys, iron-cobalt alloys, and ferrites.

Permanent (Hard) Magnet Materials. Hard ferromagnetic materials are difficult to magnetize, but they retain a significant degree of magnetization when the applied magnetic force is removed. Permanent magnet materials include both plain high-carbon steels and high-carbon alloy steels, magnet alloys that have useful magnetic properties from the combination of specific elements but which are virtually free of carbon, and metallic oxides that possess unique magnetic properties that make them commercially important.

Martensitic alloys are the best known and oldest of permanent magnet materials. The optimum magnetic properties result from untempered martensite in plain high-carbon steels (0.8 to 1.0 percent carbon). Permanent magnet alloy materials include iron-chromium-carbon, and cobalt magnet steel.

Alnico types are probably the most popular of permanent magnet steels. There are a number of Alnico alloys, with a typical alloy containing 12Al-28Ni-5Co. Some alloys have copper and titanium contents. All these alloys are hard, brittle, and unmachinable, so they must be cast or finish-ground to shapc.

MAGNETIC PARTICLE INSPECTION (MT)

Magnetic particle inspection (MT) is a nondestructive method used for locating surface or near surface discontinuities in ferromagnetic materials. Magnetic particle inspection is based on the principle that magnetic lines of force will be distorted by a change in material continuity; i.e., a discontinuity creating magnetic field leakage. *See* Figure M-1. Magnetic particles, scattered on the plate, will be retained at the location of magnetic flux leakage. The accumulation of particles will be visible under proper lighting conditions.

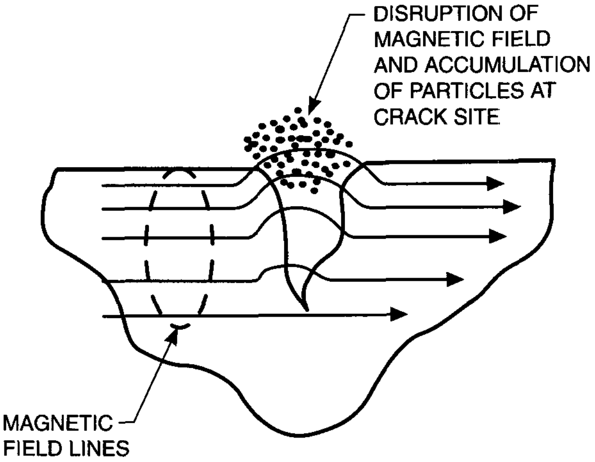


Figure M-1—Magnetic Particles Attracted to Discontinuities by Flux Leakage

A weld can be magnetized by passing an electric current through the weld (direct magnetization), or by placing it in a magnetic field (indirect magnetization).

Direct Magnetization. The direct magnetization method is illustrated in Figure M-2. This method is normally used with direct current (dc), half-wave direct current (HWDC) or full-wave direct current (FWDC). These types of current have penetrating abilities that generally enable slightly subsurface discontinuities to be detected. Direct magnetization can also be used with alternating current (ac), which is limited to the detection of surface discontinuities only.

Indirect Magnetization. Detection of subsurface discontinuities depends on several different variables--the magnetizing method, the type of current, the direction and density of the magnetic flux, and the material properties of the weld to be inspected.

When evaluating surface discontinuities only, ac is preferred with the indirect magnetization method. *See* Figure M-3. Alternating current has a very low penetrating ability, which allows the magnetic field to be concentrated at the surface of the weld. The alternating nature of the current provides continuous reversal of the magnetic field. This action provides greater particle mobility, and, in turn, aids the detection of surface discontinuities.

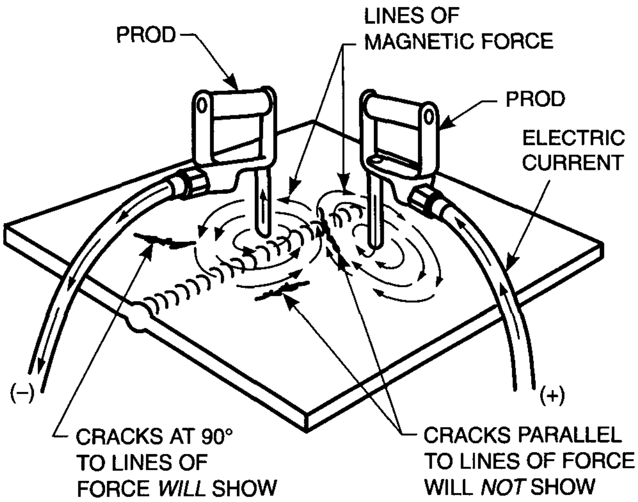


Figure M-2—Direct Magnetization Using DC Prods

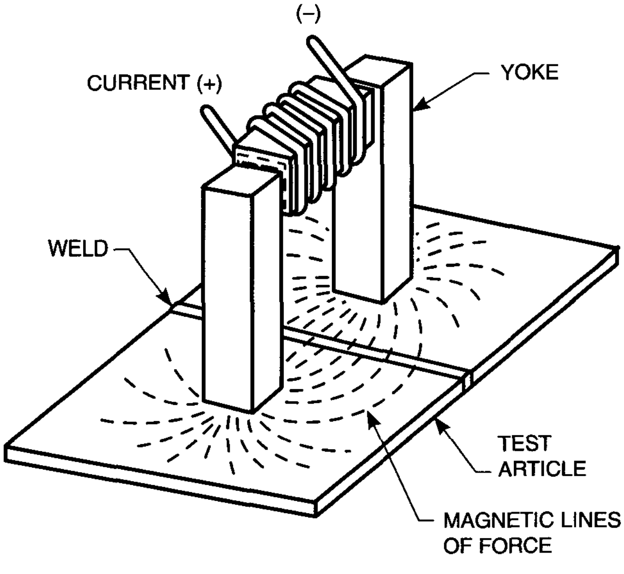


Figure M-3—Indirect Magnetization Using a Yoke

When the magnetic field has been established within the weld, magnetic particles (medium) are applied to the inspection surface. After the excess particles are removed, the residual particles trapped in the leakage field of a discontinuity reveal the location, shape and size of a detectable discontinuity. These indications are usually distinguishable by their appearance as sharp, well defined lines of medium against the background of weld surface.

Advantages of MT Inspection. Magnetic particle inspection is considerably less expensive than radiography (RT) or ultrasonic inspection (UT). Magnetic particle inspection equipment is relatively low in price compared to equipment required by the RT and UT methods of nondestructive inspection. Less training time is generally required for personnel to become competent in performing magnetic particle inspection and evaluating discontinuities.

Using the MT method, the inspector obtains an instant visual indication that assists in locating a defect. Compared to penetrant inspection (PT), the MT method has the advantage of revealing discontinuities that are not open to the surface (i.e., cracks filled with carbon, slag or other contaminants) and therefore not detectable by penetrant inspection. Magnetic particle inspection is generally faster, requires less surface preparation, and is usually more economical than penetrant inspection.

Disadvantages of MT Inspection. The MT method is limited to ferromagnetic material. This method cannot be used to inspect nonferromagnetic materials such as aluminum, magnesium or austenitic stainless steel. Difficulties may arise when inspecting welds where the magnetic characteristics of the weld differ appreciably from those of the base metal, e.g., austenitic steel surfacing on a low-carbon steel weld. Welded joints between metals of dissimilar magnetic characteristics may create magnetic particle indications even though the welds themselves are sound. Most weld surfaces are acceptable for magnetic particle inspection after the removal of slag, spatter, and other extraneous material that may mechanically hold the medium.

MAGNETICALLY IMPELLED ARC WELDING

An arc welding process in which an arc is created between the butted ends of tubes and propelled around the weld joint by a magnetic field, followed by an upsetting operation. See STANDARD WELDING TERMS.

MAGNETIZING FORCE

The magnetic lines of force caused by an electric current.

Magnetizing force, generated by current flowing through a coil of wire, is proportional to the current and the number of turns of wire in the coil. Dividing the *magnetizing force* by the area in centimeters of the iron or steel core through which the force is acting, yields the magnetizing force in lines per square centimeter. The unit is called the *oersted,* designated by the letter H.

MALLEABLE CAST IRON

A cast iron made by the prolonged annealing of a white cast iron in which either carburization or graphitization, or both, takes place. This process eliminates all or almost all cementite from the microstructure. *See* CAST IRON, Malleable.

MALLEABILITY

A property of some metals that allows them to be hammered or rolled into thin sheets without rupture. Malleability is the property that permits the manufacture of sheets, bars, and forgings, and permits fabrication by hammering and bending. Malleability is the direct opposite of brittleness. Gold is the most malleable of all metals. Copper is very malleable except when near its melting point. Zinc is malleable only between 140 and 160°C (284 and 320°F), while iron and steel become much more malleable at elevated temperatures.

Table M-10 shows the comparative malleability of various metals at room temperature, in order of decreasing malleability (1 is the most malleable and 8 is the least malleable).

Table M-10
Comparative Malleability of Various Metals

1. Gold	5. Tin
2. Silver	6. Lead
3. Aluminum	7. Zinc
4. Copper	8. Iron

Note: 1 is the most malleable and 8 is the least malleable.

MALLEABLIZING

An annealing operation with slow cooling in which some of the combined carbon in white cast iron is transformed into graphite, and in some cases is entirely removed from the iron. *See* ANNEALING.

MANGANESE

(Chemical symbol, Mn). A gray-white, nonmagnetic metallic element resembling iron, but harder and very brittle. It alloys readily with iron, copper, and nickel, forming important commercial alloys. Manganese is an essential alloying element used in steel; it increases hardness, strength, wear resistance, and other properties. Manganese minerals are widely distributed with oxides, the most common of which are silicates and carbonates. Atomic weight, 54.93; atomic number 25; melting point, 1260 °C (2300 °F); boiling point, 1900°C (3452°F).

Metallic manganese is obtained by the reduction of manganese oxide with sodium, magnesium or aluminum, or by electrolysis. High-grade ores containing manganese are mined in India, Brazil, Russia, and South Africa. Some ores are found in the United States but the greater tonnage is imported. For steel making, manganese is imported in the form of ferromanganese. Ferromanganese is prepared by melting mixed ores of iron and manganese in either a blast furnace or electric furnace.

Ferromanganese is an indispensable alloying element used in steel making, principally to deoxidize and desulfurize the steel. Some manganese is used for this purpose in all steels. All steels contain a small amount of residual manganese.

Manganese is an effective and inexpensive agent for cleansing molten steel of impurities that would decrease the strength and ductility of the finished product. A manganese content up to about 0.80% is commonly present in finished steel for the sole purpose of combining with sulfur and phosphorus to offset embrittlement and hot shortness.

Higher content (10 to 15%) of manganese in steel increases the toughness and also increases the hardening capability of the steel. An exception, however, is when manganese is present in steel between 3 to 4%, it tends to promote embrittlement of the steel.

Manganese is added to magnesium-aluminum alloys to improve corrosion resistance.

MANGANESE BRONZE

Manganese bronzes (numbers C86100 to C85800) are actually high-tensile yellow brass that contain 22 to 38% zinc with varying amounts of manganese, aluminum, iron, and nickel. Manganese bronze is weldable provided the lead content is low. Gas shielded arc (gas tungsten arc or gas metal arc) welding methods are recommended. Manganese bronzes can be brazed and soldered with special fluxes.

MANGANESE STEEL

Manganese steel, sometimes called *high manganese steel*, and also *Hadfield steel*, can be identified by using a magnet. Carbon steel is magnetic; manganese steel is not. The addition of manganese to steel accomplishes three purposes:

(1) It combines with oxygen in the molten steel and thus assists in its deoxidation.

(2) It ties up any sulfur that may be present to avoid the formation of iron-sulfide inclusions that cause hot cracking.

(3) It promotes greater strength by increasing the hardenability of the steel.

A bonus effect of manganese is that the fracture toughness is usually improved.

One of the most important characteristics of manganese steel is its work-hardening quality. It is relatively soft and very tough after being cast and then quenched in cold water, but as it is pounded under repeated blows in service, it becomes much harder and tougher. Under impact it will flow readily at first, but the flow sets and hardens under repeated blows. It is this quality which accounts for the difficulty in machining it with cutting tools. Machining manganese steel castings is so slow as to be impractical, and in almost all cases they are ground where necessary.

Manganese Steel Alloys

Research on Hadfield's composition of carbon and manganese has shown that small additions of other alloying elements, such as nickel, molybdenum, and vanadium, can improve impact toughness.

Commercial alloys have a nominal composition of 1.0 to 1.4% carbon, and 10 to 14% manganese. However, in steel making practice, the carbon content is held to the mid-range and the manganese content to between 12 to 13%, since a lower range has somewhat inferior tensile properties and the upper range has no economic advantage.

Castings

Austenitic manganese steel castings are widely used as components of crushing, earthmoving, and material handling equipment. In the railroad industry they are widely used for such items as switch points, crossings, and frogs, where impact resistance and resistance to abrasive wear are primary criteria. Their nonmagnetic properties make them useful for parts for electromagnets, induction furnaces, and other electrical equipment.

Electrodes for Welding Manganese Steels. Early electrodes for welding manganese steels were based on the addition of nickel to alloys from which manganese steel welding rods and electrodes are made. These alloys contained from 3 to 5% nickel, carbon varying from 0.80 to 1.15%, silicon ranging from 0.45 to 2%, and 13 to 14% manganese. In addition to coated electrodes, tubular steel electrodes with metallic powders inside, consisting of proportions of the various elements required, have been used. However, most of the electrodes are the coated type, and in some instances a carbon steel wire core electrode is coated with the additional manganese and nickel required.

Arc Welding. Direct current electrode positive (DCEP) is recommended for welding manganese steel. Suitable welding current seems to be the minimum at which the electrode will properly flow and produce satisfactory penetration, and the arc should be as short as possible. Manufacturer's specifications and directions should be followed for each type of electrode.

Welding Procedure. When building up the surface of a manganese steel casting, the build-up area should be divided into squares, for example, about 4 cm (1-1/2 in.) square, and the deposit confined to this square. While this deposit is hot, it should be peened vigorously to relieve strains from localized heat. Another section, at a distance from the first, may then be welded using the intermittent sequence method to keep the temperature of the casting as low as possible. It is usually recommended that the bead be rather wide, and applied with a semi-circular motion.

Safety. The maximum fume exposure guideline when welding manganese steels is 0.6 mg/m^3. Local exhaust or a respirator or both should be used to prevent inhalation of fume concentration above the threshold limit value (TLV).

See Hadfield Steel.

MANIFOLD

See STANDARD WELDING TERMS. *See* CYLINDER MANIFOLD.

MANIPULATORS

Manipulators are powered by electric motors and are used to orient the welding head(s) used with automatic welding machines. Manipulators typically consist of a vertical mast and horizontal boom that carries the automatic welding head. A large welding head manipulator is shown in Figure M-4. Manipulators are powered to move the boom up and down the mast, and in most units the mast swivels on the base. In some cases, the welding head may move by power along the boom, while in others the boom itself may move horizontally on the mast assembly. Most manipulators also have slow-speed vertical and transverse motion control capabilities. This allows the operator to adjust the position of the welding head to compensate for variations along the weld joint.

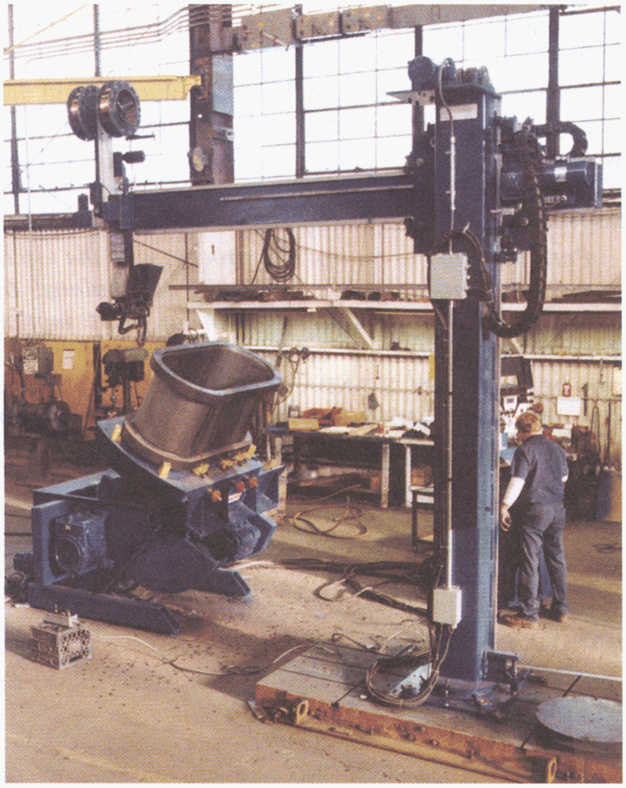


Figure M-4—A Submerged Arc Welding Head Shown Mounted on a Manipulator

Photo courtesy of Pandjiris, Inc.

It is essential during the welding operation that the boom or welding head move smoothly at speeds that are compatible with the welding process being used. The carriage itself must also move smoothly and at constant speeds if the manipulator is designed to move along tracks on the shop floor. In selecting and specifying a welding manipulator, it is important to determine the actual weight to be carried at the end of the boom. The manipulator must be rigid and the deflection minimized during the welding operation. Manipulators are more versatile than side beams because they are capable of linear motion in three axis.

The desirable features that a manipulator should have are:

(1) *Safety.* Under no conditions of load or failure should the boom crash or slide down the mast.

(2) The maximum vertical deflection should be guaranteed for various rated loads on either end of the beam.

(3) Rigidity should guarantee that the boom will follow a straight line weld joint within the full limits of its length.

(4) The manipulator should be absolutely rigid and steady in all its actions, with no lost motion or wobble.

MANUAL, *adj.*

Pertaining to the control of a process with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled material feeders may be used. See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL, AUTOMATIC, MECHANIZED, ROBOTIC, *and* SEMIAUTOMATIC.

MANUAL BRAZING

See STANDARD WELDING TERMS. *See* MANUAL WELDING.

MANUAL SOLDERING

See STANDARD WELDING TERMS. *See* MANUAL WELDING.

MANUAL THERMAL CUTTING

See STANDARD WELDING TERMS. *See* MANUAL WELDING.

MANUAL THERMAL SPRAYING

See STANDARD WELDING TERMS. *See* MANUAL WELDING.

MANUAL WELDING

Welding with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled filler material feeders may be used. Variations of this term are MANUAL BRAZING, MANUAL SOLDERING, MANUAL THERMAL CUTTING, and MANUAL THERMAL SPRAYING. See also ADAPTIVE CONTROL WELDING, AUTOMATIC WELDING, MECHANIZED WELDING, ROBOTIC WELDING, *and* SEMIAUTOMATIC WELDING. *See* STANDARD WELDING TERMS.

MARAGING STEELS

Maraging steels are a group of iron-nickel alloys characterized by a combination of high strength and toughness. They are strengthened by precipitation of one or more intermetallic compounds in a matrix of essentially carbon-free martensite. In addition to nickel, these steels generally contain either molybdenum, titanium, aluminum, and either cobalt or chromium. The nominal compositions of six commercial alloys are shown in Table M-11.

Table M-11
Nominal Compositions of Commercial Maraging Steels

	Nominal Composition, %						
Grade[a]	Ni	Co	Cr	Mo	Ti	Al	Fe
	Sheet and Plate						
ASTM A538							
Gr A (200)	18	8	—	4	0.2	0.1	bal.
Gr B (250)	18	8	—	5	0.4	0.1	bal.
Gr C (300)	18	9	—	5	0.7	0.1	bal.
18Ni (350)	18	12	—	4	1.3	0.1	bal.
Cast 18Ni	17	10	—	5	0.3	0.1	bal.
ASTM A590	12	—	5	3	0.3	0.4	bal.

[a] Carbon = 0.03% max.

To achieve optimum properties, the carbon and impurity elements in maraging steels are deliberately kept very low.

Properties. Differences in physical properties between maraging and mild steels are not significant, except for thermal conductivity. Heat loss by conduction during welding would be lower in maraging steels. Maraging steels are noted for toughness and high strength. The Charpy V-notch and fracture toughness properties are more than twice those of conventional quenched and tempered high-strength steels. To a great extent, toughness is dependent on the purity of the steel. The maximum service temperature for maraging steels is about 400°C (750°F). Above this temperature, long- term strength drops off rapidly due to overaging.

Welding. Gas tungsten arc welding (GTAW) is the most widely used process for welding maraging steels, but they are readily welded by most arc welding processes. The GTAW process allows good control of heat input and protection from weld oxidation. Gas tungsten arc welded joints have better toughness than those made by gas metal arc welding.

Procedures. Welding procedures and postweld heat treatment procedures vary with the alloy being welded, and the steel manufacturer's recommendation should be followed. Filler metal of the same composition as the base metal should be used. In general, the following rules apply:

(1) No preheat is required. However, if the temperature of the metal falls below 0°C (32°F), it is best to preheat the weld joint area to 21°C (70°F).

(2) Anneal at approximately 815°C (1500°F).

(3) Austenite aging (ausage) should be at approximately 700°C (1300°F).

(4) Perform cold working, if necessary or required.

(5) Refrigerate (if possible) at –73°C (–100°F).

(6) Marage (martensite age) at approximately 480°C (900°F).

(7) Cool in still air.

MARTENSITE

Named in honor of A. Martens, martensite is the hardest microstructure that can be formed in a carbon or alloy steel. In a polished and etched steel specimen, martensite appears as an acicular microconstituent. The level of hardness in a fully martensitic microstructure is commensurate with the carbon content of the steel; almost regardless of the amounts of other alloying elements present. Consequently, a very low-carbon steel, even in the martensitic condition, will not be very hard. It is important to note that with a carbon content of about 0.60%, the maximum hardness that can be achieved in steel is roughly 68 HRC; and a higher carbon content will not achieve any real increase in the maximum obtainable hardness.

A martensitic structure is produced when austenite is continuously cooled at a rate faster than that steel's critical cooling rate. With low hardenability, austenitized steel must usually be cooled by quenching, in oil or water, to produce a martensitic microstructure. Some alloy steels with high hardenability will form martensite when the austenitized structure is air cooled. Regions of steel that are austenitized by the localized heat of welding have the potential for forming martensite because cooling rates in welds can be notably fast, but the final microstructure also depends on the hardenability of the steel.

The higher hardness in the martensitic microstructure is accompanied by lower ductility and toughness that, under many circumstances, can increase susceptibility to cracking. These shortcomings can be relieved by thermal tempering of the martensitic microstructure. Postweld stress relief of steel welds is the most effective procedure to obtain highly satisfactory combinations of strength, hardness, ductility and toughness in steel. Welds in steel with a carbon content of 0.25% or less are not very susceptible to cracking due to martensitic formation in the weld or heat-affected zone. Thus, most structural steels can be used in the as-welded condition without concern for martensitic cracking.

Tempering of Martensite. Martensite, in the as-quenched condition, is generally unsuitable for engineering applications because it can be quite brittle. It requires a tempering heat treatment to effectively increase its ductility and toughness while only moderately reducing its strength. Tempering consists of reheating the steel to an appropriate temperature (always below the austenitizing temperature, A_1) and holding at that temperature for a short time. The heat treatment allows the carbon to precipitate in the form of very small carbide particles. The resulting microstructure is tempered martensite. The necessary compromise between hardness and toughness can be obtained by adjustments to the correct tempering temperature and holding time. The higher the temperature, the softer and tougher the steel.

MASH RESISTANCE SEAM WELDING

A nonstandard term for MASH SEAM WELDING.

MASH SEAM WELDING

A resistance seam welding process variation that makes a lap joint primarily by high-temperature plastic working and diffusion as opposed to melting and solidification. The joint thickness after welding is less than the original assembled thickness. See STANDARD WELDING TERMS.

Mash seam welding requires high electrode force, continuous welding current, and accurate control of force, current, welding speed, overlap and joint thickness to obtain consistent welding characteristics. Overlap is maintained to close tolerances by clamping or tack-welding the workpieces.

This seam welding process requires considerably less overlap than a conventional lap joint. With proper welding procedures, the overlap is about 1 to 1.5 times the sheet thickness. Wide, flat-faced wheel electrodes that completely cover the overlap are used.

Mash seam welding produces continuous seams that have good appearance and are free of crevices. Crevice-free joints are necessary in many applications with strict contamination or cleanliness requirements, such as joints in food containers or refrigeration liners. To obtain acceptable welds, the materials to be mash seam welded must have wide plastic temperature ranges. Low-carbon steel and stainless steel can be mash seam welded in certain applications.

MASK, Thermal Spraying

A device for protecting a substrate surface from the effects of blasting or adherence of a thermal spray deposit. See STANDARD WELDING TERMS.

MATRIX

A matrix is the principal substance (usually more than 50%) in which a constituent is embedded. For example, when a plain carbon steel with 0.20% carbon is cooled very slowly from the molten state to room temperature, platelets or lamellae of ferrite and iron carbide are alternately formed. This microstructure is called *pearlite*, and it forms a constituent in an alpha-iron or ferrite base that is called the matrix. The pearlite is said to be embedded in a ferrite matrix.

MECHANICAL BOND, Thermal Spraying

The adherence of a thermal spray deposit to a roughened surface by the mechanism of particle interlocking. See STANDARD WELDING TERMS.

MECHANICALLY MIXED FLUX, Submerged Arc Welding

A type of flux produced by mixing two or more agglomerated, bonded, or fused fluxes. See STANDARD WELDING TERMS.

MECHANICAL METALLURGY

Mechanical metallurgy is an area of knowledge that deals with the behavior and response of metals to applied forces or loads. It covers aspects of physical metallurgy, applied mechanics, and plastic forming of metals, as well as the engineering aspects of mechanical failure of metals. Although it is not a precisely defined area, much data concerning weldments can be determined by mechanical testing.

Basic data concerning the strength of metals, and measurements for routine control of mechanical properties are obtained from a relatively small number of standardized mechanical tests. Common testing techniques associated with the mechanical testing of welds are tension, torsion, fatigue, hardness, bend, creep, and impact testing. The results of these tests are used to indicate how the metals and weldments will perform in service and how metallurgical variables are affected by the mechanics of these tests. *See* METALLURGY.

MECHANICAL TESTING

Application of engineering test methods to determine the physical properties or mechanical properties, or both, of base metal or weldments.

The tests usually result in the destruction of the test specimen, but not always, as in the case of hardness testing. *See* TENSION TEST, BEND TEST, FATIGUE TESTING, IMPACT TEST, HARDNESS TESTING *and* TUBE TESTING.

MECHANICAL WORKING

The plastic deformation of a metal by subjecting the metal to pressure exerted by rolling, pressing, or hammering, to change its form or to affect the structure and mechanical properties.

Mechanical working has two objectives: (1) to produce a desired shape, and (2) to improve the properties of the metal. These objectives are accomplished by altering the distribution of microconstituents, refining grain size, and introducing strain hardening. Mechanical working operations are classified as *hot-working* and *cold-working* operations. Hot working is the initial step in the mechanical working of most metals and alloys.

MECHANICALLY OPERATED TORCH

A torch using an electric motor to provide steady feed motion at speeds adjustable to the thickness of the metal being welded or cut.

MECHANICAL PROPERTIES, Metal

Characteristics of metal such as strength, toughness, and ductility which make metals useful.

The properties which govern the design and service behavior of the weldment are the following:

(1) Modulus of elasticity
(2) Elastic limit
(3) Yield strength
(4) Tensile strength
(5) Fatigue strength
(6) Ductility
(7) Fracture toughness
(8) Low temperature properties
(9) Elevated temperature properties

MECHANIZED, *adj.*

Pertaining to the control of a process with equipment that requires manual adjustment of the equipment controls in response to visual observation of the operation, with the torch, gun, wire guide assembly, or electrode holder held by a mechanical device. See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL, AUTOMATIC, MANUAL, ROBOTIC, *and* SEMIAUTOMATIC.

MECHANIZED BRAZING

See STANDARD WELDING TERMS. *See* MECHANIZED WELDING.

MECHANIZED OFC EQUIPMENT

Mechanized oxyfuel gas cutting (OFC) equipment is similar to manual equipment in principle, but differs in design to accommodate higher fuel pressures, faster cutting speeds, and means for starting the torch. Many variations of mechanized cutting systems are available commercially. Some machines are designed for special purposes, such as making vertical cuts, preparing edges for welding, and pipe cutting and beveling.

Mechanized OFC equipment varies in complexity from simple hand-guided machines to sophisticated numerically-controlled units. Depending on the application, mechanized OFC equipment will require additional facilities:

(1) A machine to move one or more torches in the required cutting pattern

(2) Torch mounting and adjusting arrangements on the machine

(3) A cutting table to support the work

(4) Means for loading and unloading the cutting table

(5) Automatic preheat ignition devices for multiple torch machines.

MECHANIZED SOLDERING.

See STANDARD WELDING TERMS. *See* MECHANIZED WELDING.

MECHANIZED THERMAL CUTTING

See STANDARD WELDING TERMS. *See* MECHANIZED WELDING.

MECHANIZED THERMAL SPRAYING

See STANDARD WELDING TERMS. *See* MECHANIZED WELDING.

MECHANIZED WELDING

Welding with equipment that requires manual adjustment of the equipment controls in response to visual observation of the welding, with the torch, gun, or electrode holder held by a mechanical device. Variations of this term are MECHANIZED BRAZING, MECHANIZED SOLDERING, MECHANIZED THERMAL CUTTING, and MECHANIZED THERMAL SPRAYING. See STANDARD WELDING TERMS. *See* ADAPTIVE CONTROL WELDING, AUTOMATIC WELDING, MANUAL WELDING, ROBOTIC WELDING, *and* SEMIAUTOMATIC WELDING.

MEDIUM VACUUM ELECTRON BEAM WELDING (EBW-MV)

An electron beam welding process variation in which welding is accomplished at a pressure of 10^{-1} *to* 3×10^3 *pascals (approximately* 10^{-3} *to 25 torr). See* STANDARD WELDING TERMS. *See* ELECTRON BEAM WELDING.

MELTBACK TIME

The time interval at the end of crater fill time to arc outage during which electrode feed is stopped. See STANDARD WELDING TERMS. *See* Appendix 19.

MELTING POINT

The temperature at which a pure metal, compound, or eutectic changes from a solid to a liquid; the temperature at which the solid and liquid are in equilibrium. *See* Table M-12.

Table M-12
Melting Points or Ranges of Metals and Alloys

	Melting Point, or Melting Range	
Material	**°C**	**°F**
Aluminum	660	1220
Copper	1083	1981
Iron	1535	2798
Magnesium	650	1202
Nickel	1453	2647
Silver	961	1761
Titanium	1668	3035
Tungsten	3410	6170
Zirconium	1852	3366
Steel, 0.2% Carbon	1490–1520	2720–2770
Steel, 0.8% Carbon	1380–1490	2520–2710
Stainless Steel, 18-8	1400–1450	2550–2650
Cast iron, 3.5% Carbon	1130–1200	2065–2200

MELTING RANGE

The temperature range between solidus and liquidus. See STANDARD WELDING TERMS. *See* Table M-12.

MELTING RANGE, ALLOYS

See MELTING RANGE.

Pure metals that are elements have a definite melting point, i.e, solid and liquid are in equilibrium at a specific temperature. Alloys, because they are a mixture of two or more metals, melt or solidify within a range of temperatures and not at a single temperature. For example, with an alloy, a liquidus is found, (*liquidus* is the temperature at which various compositions of the alloy system begin to freeze on cooling, or complete their melting on heating), and a solidus is found (*solidus* is the temperature at which freezing is complete on cooling, or at which melting begins in the solid alloy on heating). Noting the range of temperature between liquidus and solidus can yield important information about an alloy because it can be indicative of susceptibility of the particular alloy to cracking during solidification. A large difference between liquidus and solidus favors conditions that promote hot cracking. Reference: Linnert, George E. Welding Metallurgy, Volume 1, 4th Edition. American Welding Society, Miami, Florida. 1994.

MELTING RATE

The weight or length of electrode, wire, rod, or powder melted in a unit of time. See STANDARD WELDING TERMS.

MELT-THROUGH

Visible root reinforcement produced in a joint welded from one side. See STANDARD WELDING TERMS. *See* Figure C-9.

MERCURY

(Chemical symbol; Hg). Mercury is a heavy silver-white, shiny, toxic metallic element, the only common metal that is liquid at room temperature. It is a fair conductor of heat and electricity. Mercury occurs free in nature, but the chief source is the sulfide (cinnabar, HgS), from which it may be obtained by heating in air. Mercury is used extensively in electrical apparatus, and because of its linear coefficient of thermal expansion, it is used in laboratory thermometers, barometers, and many other instruments. Atomic weight 200.61; atomic number 80; melting point –38.87 °C (–39 °F); boiling point 356.9°C (673°F).

MESSERSCHMITT PROCESS

A method of producing hydrogen developed from the principle that if steam is passed over a red-hot iron, the steam is decomposed into hydrogen and oxygen. The oxygen in the steam unites with the iron forming iron oxide and the free hydrogen is accumulated.

METAL

An opaque, lustrous elemental chemical substance that is a good conductor of heat and electricity, usually malleable, ductile, and more dense than other elemental substances. See STANDARD WELDING TERMS.

Defined chemically, metal is an element whose hydroxide is alkaline.

METAL ARC CUTTING

See ARC CUTTING (AC). *See also* AIR CARBON ARC CUTTING, GAS METAL ARC CUTTING, GAS TUNGSTEN ARC CUTTING, PLASMA ARC CUTTING, *and* SHIELDED METAL ARC CUTTING.

METAL ARC WELDING

See ARC WELDING (AW). *See also* FLUX CORED ARC WELDING, GAS METAL ARC WELDING, GAS TUNGSTEN ARC WELDING, SHIELDED METAL ARC WELDING, *and* ARC STUD WELDING.

METAL, BASE

The metal or alloy that is welded, brazed, or cut. *See* BASE MATERIAL *and* SUBSTRATE.

METAL-BATH DIP BRAZING

A dip brazing process variation. See STANDARD WELDING TERMS.

In this process, the molten metal bath provides heat for brazing and the filler metal. *See also* DIP BRAZING.

METAL CORED ELECTRODE

A composite tubular filler metal electrode consisting of a metal sheath and a core of various powdered materials, producing no more than slag islands on the face of a weld bead. External shielding may be required. See STANDARD WELDING TERMS.

METAL, DEPOSITED

Filler metal that has been added during welding, brazing or soldering.

METAL ELECTRODE

A filler or nonfiller metal electrode used in arc welding and cutting that consists of a metal wire or rod that has been manufactured by any method and *that is either bare or covered. See* STANDARD WELDING TERMS.

METAL, FILLER

The metal or alloy in the form of welding electrodes, welding rods or welding wire added in making a welded, brazed, or soldered joint.

METAL IDENTIFICATION

It is essential to identify the base metal to be welded, brazed, or soldered. If metals have become mixed during storage and identifying marks have been lost, it is necessary that some means be taken to sort out the mixed metals and identify each item. Obviously, the best and most reliable method is to perform a spectrographic or quantitative chemical analysis. This is not always possible or practical. There are some relatively quick and fairly reliable tests to identify metals in a shop or construction environment.

Carbon and Structural Steels

Carbon and structural steels may be satisfactorily identified by one or more of the following tests:

Spark Test. The most common test to sort grades of structural carbon steel and tool steels is the spark test. The piece to be identified is touched against a grinding wheel; this results in a definite pattern of sparks. These sparks can then be compared to steels of known composition either by (1) using a comparison chart showing sparks from known steel compositions or (2) by sparking a steel specimen of known composition and comparing it with the unknown steel. Many shops that use a variety of steels will keep sample specimens of steels of known composition to compare with unknown specimens. A technician experienced with this technique can make rapid identification of steel specimens.

Chip Test. In this relatively simple test the metal to be identified is chipped with a cold chisel. Identification is made by comparing the size of chips, color of metal, hardness, and surface condition of chipped metal with a known metal. Additional tests such as magnetic tests, hardness tests, or specific gravity may be necessary.

Hardness Test. The hardness can be approximated with a file test. It is done by comparing the resistance of the metal to the cutting action of the file. Again, an experienced welder, machinist, or technician can approximate the Rockwell or Brinell hardness number.

Magnetic Test. Magnetic properties are determined using a bar magnet. All structural and carbon steels are magnetic, as are most tool steels.

Stainless Steels

Some quick tests can be used to separate stainless steels from other metals and also to identify the grade of stainless steel.

Copper Sulfate Spot Test. This is one of the simplest tests to differentiate between carbon steels and all types of stainless steel. A solution of 5 to 10% copper-sulfate (blue vitriol) in water is used. Before performing the spot test the areas to be tested should be thoroughly cleaned and roughened with a mild abrasive. A drop of the test solution is then released on the cleaned and prepared area. Carbon steel or iron will become coated with metallic copper in a few seconds; stainless steel will show no deposit or copper color.

Magnet Test. This test is used to distinguish between austenitic stainless steel (300 series) and ferritic stainless steels (400 series). Annealed austenitic stainless steel types are nonmagnetic; if heavily cold-worked, they exhibit a slight attraction to a magnet. Ferritic stainless steels are always strongly attracted to a magnet.

Nitric Acid Spot Test. Stainless steels are noted for their resistance to nitric acid attack. This property makes it easy to separate them from other metals and alloys. Only high-carbon stainless steel alloys (420 and 440) may show signs of a slight attack by nitric acid. Carbon and structural steels are vigorously attacked by dilute nitric acid.

Spark Test. This test has somewhat limited value for separating stainless steels, although an experienced technician can classify stainless steels into four groups but usually cannot identify individual classifications. The four groups with their characteristic spark appearance follow:

Group 1: Types 302, 303, 304, and 316 produce a short reddish spark with few forks.

Group 2: Types 308, 309, 310, and 446 produce few short red sparks with few forks.

Group 3: Types 410, 414, 416, 430, and 431 produce long white streams with few forks.

Group 4: Types 420, 420F, and 440 A, B, C, and F produce long white to reddish sparks with pronounced bursts.

METAL POWDER CUTTING (POC)

An oxygen cutting process that uses heat from an oxyfuel gas flame, with iron or other metal powder to aid cutting. See STANDARD WELDING TERMS.

The metal powder cutting process is a technique for supplying an oxyfuel cutting torch with a stream of iron-rich powered material. Iron powder and mixtures of metallic powders, such as iron and aluminum, are used. The powdered material promotes and accelerates the oxidation reaction and also the melting and spalling action of hard-to-cut materials. The powder is directed into the kerf through either the cutting tip or single or multiple jets external to the tip. When the first method is used, gas-conveyed powder is introduced into the kerf by special orifices in the cutting tip. When the powder is introduced externally, the gas conveying the powder imparts sufficient velocity to the powder particles to carry them through the preheat envelope into the cutting oxygen stream. Their short time in the preheat envelope is sufficient to produce the desired reaction in the cutting zone.

Some of the powders react chemically with the refractory oxides produced in the kerf and increase their fluidity. The resultant molten slags are washed out of the reaction zone by the oxygen jet. Fresh metal surfaces are continuously exposed to the oxygen jet and powder.

Cutting of oxidation-resistant steels by the powder cutting method can be done at approximately the same speeds as oxygen cutting of carbon steel of equivalent thickness. The cutting oxygen flow must be slightly higher with the powder process.

Powder is dispensed from a hopper by a controllable vibratory device, and delivered through a hose to the torch. The other type of dispenser is a pneumatic device coordinated with a fluidizing unit. The powder is picked up by a gas stream that serves as the transporting medium to the torch. A special manual powder cutting torch mixes the oxygen and fuel gas and then discharges this mixture through a cutting tip with multiple orifices. The powder valve is an integral part of the torch.

METAL SPRAYING

See THERMAL SPRAYING.

METAL TRANSFER MODE, Arc Welding

The manner in which molten metal travels from the end of a consumable electrode across the welding arc to the workpiece. See STANDARD WELDING TERMS. *See also* GLOBULAR TRANSFER, PULSED SPRAY TRANSFER, SPRAY TRANSFER, ROTATIONAL SPRAY TRANSFER, *and* SHORT CIRCUITING TRANSFER.

METAL, White

A group of white-colored metals with relatively low melting points (antimony, bismuth, tin, lead, cadmium, and zinc) and alloys based on these metals. Most of these metals and their alloys are difficult to weld.

METALLIC BOND

The principal bond that holds metals together. It is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together. See STANDARD WELDING TERMS. *See also* BONDING FORCE, COVALENT BOND, IONIC BOND, *and* MECHANICAL BOND.

METALLIZING

A nonstandard term when used for THERMAL SPRAYING, or the application of a metal coating.

METALLOGRAPHY

The term *metallography* originally covered the microscopic study of metals under substantial magnification and the recording of microstructural details by photography. Initially all the work was done with an ordinary visible-light microscope, and photographs made of the details observed at various magnifications were called photomicrographs. In about 1960, the electron microscope was put to use in examination of metallic structures. In recent years, variations of the electron microscope have developed, such as the transmission electron microscope (TEM), and the scanning electron microscope (SEM), scanning transmission electron microscopy (STEM), and ion microscopy. Associated with these advances in microscopy were developments in chemical analysis of microstructural constituents, using an electron-probe microanalyzer, ion-probe microanalyzer, and Auger electron spectroscopy among other late 20th century analytical developments.

The following information is confined to the practical knowledge of the structure of metals as obtained using the optical metallograph. The optical metallograph is a special microscope with an inverted stage that allows a flat specimen to be placed face-down on it so that portions of interest on the specimen can be scanned. The metallograph usually has an integral camera (often a Polaroid camera), and can have a number of features for changing specimen illumination and for measuring details observed on the specimen.

Specimen Preparation. Metallographic examination requires a small metal specimen, usually not over 25 mm (1 in.) diameter or square, that is cut to provide a flat surface. The flat surface is ground and polished by a specific procedure until it is as scratch-free as possible. A complete procedure for preparing metallographic specimens is found in ASTM Standard E3, *Standard Methods for Preparation of Metallographic Specimens.* A polished specimen surface, when examined with the metallograph at a magnification in the range of 100 to 500X, is uniformly reflective and featureless unless there are cracks, porosity, or nonmetallic inclusions in the metal.

It is necessary to etch the polished surface of the metallographic specimen to reveal the microstructure. Etching can be accomplished in a number of different ways, depending on the metal or alloy, and conditions such as whether the metal is cast, wrought, or weld metal. Many ferrous specimens can be etched by merely dipping or swabbing for a few seconds in a solution of 1 to 5% nitric acid in alcohol (commonly called 2% nital). Metals and alloys that are resistant to acid attack, such as nickel or stainless steel, can be electrolytically etched. Details for etching various metals and alloys can be found in ASTM E407, *Standard Methods for Microetching Metals and Alloys.*

Specimens containing a weld often present a challenge to the metallographer because of the marked difference in etching rates between the base metal, heat-affected zone, and weld metal, especially when working with welded joints of dissimilar metals.

Grain Size. The first feature noted by the metallographer during the examination of the microstructure of a polished and etched metal is its grain size. The size of the grains exerts a profound effect on the properties of a metal, especially its mechanical properties. In most metals and alloys, both grain growth or grain size reduction can be accomplished by either mechanical working or heat treatment or both.

Standardized methods of measuring grain size to permit evaluation of metal properties, specifications, and control have evolved, and are described in ASTM E112, *Standard Methods for Determining Average Grain Size.*

Because weldments may benefit or may suffer from grain growth in cold-worked metal, the mechanics of recrystallization must be considered. During cold-working the grains in a metal are severely deformed and heavy reductions produce very elongated grains, but grain boundaries persist despite severe grain deformation. When the temperature is raised, the grains distorted by cold-working recrystallize to undistorted equiaxed grains. The temperature at which the distorted grains are replaced by equiaxed grains is called the *recrystallization temperature.* Metal that is heated above the recrystallization temperature and held for long periods of time will experience the growth of abnormally large grains. The temperature at which grain growth becomes significant depends a great deal on the metal and alloy.

Where the weld is made in a single pass, the grain size and grain growth in the weld zone are largely dependent on the travel speed of the pass. Welds made at slow travel speed tend to be relatively coarse-grained while welds made at fast travel speeds tend to be relatively fine-grained. Welds of the latter type tend to have solidified last at the centerline and are susceptible to centerline hot cracking. Welds made at moderate travel speed are more typical of commercial practice and a fine grain structure is developed in the weld zone.

In the case of multiple pass welds, the first pass is reheated during the making of the second weld pass so that the first weld pass is tempered and the grain structure is refined. Each successive pass tempers and refines grain of the previous passes. This produces a weld microstructure that is desirable since a substantial portion of the weld has been grain-refined and tempered by subsequent weld passes. These multipass welds usually have excellent mechanical properties and are usually much tougher than a single pass weld.

For a specific type of steel and strength level, fine-grained steels have superior mechanical properties compared to the coarse-grained steels, especially strength, ductility, and notch toughness. For elevated temperature service, coarse-grain steels have superior performance since fine-grain steels will exhibit lower strength. Obviously, grain size is a feature of the microstructure that deserves close scrutiny in the examination of metal structures.

Austenitic Grain Structure. The austenitic grain size of a steel depends on the austenitizing temperature. Grain refinement occurs when a steel that will transform is heated to a temperature slightly above its A_3 temperature and is then cooled to room temperature. A fine grain size is desirable for improved toughness and ductility. Steel forgings and castings frequently are normalized specifically to produce grain refinement.

At higher austenitizing temperatures (over 1000°C [1800°F]), steels usually develop a coarse austenitic grain structure. Coarse-grained steels usually are inferior to fine-grained steels in strength, ductility, and toughness.

Microstructure of Metals. Much of the practical knowledge of the structure of metals has been obtained using the optical metallograph. This knowledge was obtained by examination of polished and etched metallurgical specimens at magnifications from 50 to 1500X. Steel and other iron alloys have been more extensively studied than other metals and alloys because of their wide commercial usage. This knowledge has been applied to the weldments of iron and steel to insure that the metallurgical structures in the weldments are suitable for the service conditions expected of the structure. Microstructures in steel weld metal are markedly different from those of either cast or wrought base metals. The microstructure of weld metal is controlled principally by composition and cooling rate.

METALLURGICAL BOND

A nonstandard term for METALLIC BOND.

METALLURGY

Metallurgy is defined as the science and technology of metals, and consists of two broad divisions:

(1) Process metallurgy, which involves the reduction of ores, refining of metals, alloying, casting, and the working and shaping of metal into semifinished and finished products

(2) Physical metallurgy, which includes heat treatment, mechanical testing, metallography and other subjects dealing with the application, design, testing, and inspection of metal products.

Both process metallurgy and physical metallurgy are involved in welding. Welding can be compared to a series of metallurgical operations involved in metal production, like steel making, but welding is performed on a small scale with the pertinent steps carried out in rapid succession. During most welding processes, a volume of molten metal (weld pool) is formed (cast) within the confines of solid base metal (mold). Weld metal initiates solidification in a unique manner, unlike molten metal cast in a conventional mold. Weld metal is susceptible to blowholes and internal porosity caused by the evolution of gases, as experienced in ingot making and castings.

The base metal of a weld can be preheated to retard the cooling rate and solidification, just as preheated molds are used to retard the solidification of castings. The striking difference between welding and other metal-producing operations is the contrast in the mass of metal involved and the effect of mass on physical and metallurgical changes. Welding involves comparatively small masses that are heated very rapidly by intense heat sources and that cool rapidly because of intimate contact with a larger surrounding mass of colder base metal. Consequently, it can be expected that weld zones are prone to display unusual structures and properties.

Welding involves many metallurgical phenomena, such as melting, freezing, solid state transformations, thermal strains and shrinkage stresses that can cause many practical problems. These problems can be avoided or solved by applying appropriate metallurgical principles to the welding process.

An understanding of welding metallurgy requires a broad knowledge of general metallurgy. For this reason, general metallurgy is addressed first, followed by specific aspects of welding metallurgy. The brief description of general metallurgy is only an outline of topics necessary to provide a basis for welding metallurgy. For a more complete treatment of metallurgy the reader should refer to the specific references at the end of this article.

General Metallurgy

Structure of Metals. Solid metals have a crystalline structure in which the atoms of each crystal are arranged in a specific geometric pattern. This orderly arrangement of the atoms, called a lattice, is responsible for many of the properties of metals. The most common lattice structures found in metals are listed in Table M-13. Their atomic arrangements are illustrated in Figure M-5.

Each grain in a pure metal at any particular temperature has the same crystalline structure and the same atomic spacing as all of the other grains. However, each grain grows independently of every other grain, and the orientation of the grain lattice differs from one grain to another. The periodic and orderly arrangement of the atoms is disrupted where the grains meet, and the grain boundaries form a continuous network throughout the metal. Because of this grain boundary disorder, differences in the behavior of the metal often occur at those locations.

Up to this point, only pure metals have been considered. However, most common engineering metals contain residual or intentionally added metallic and nonmetallic elements dissolved in the matrix. These

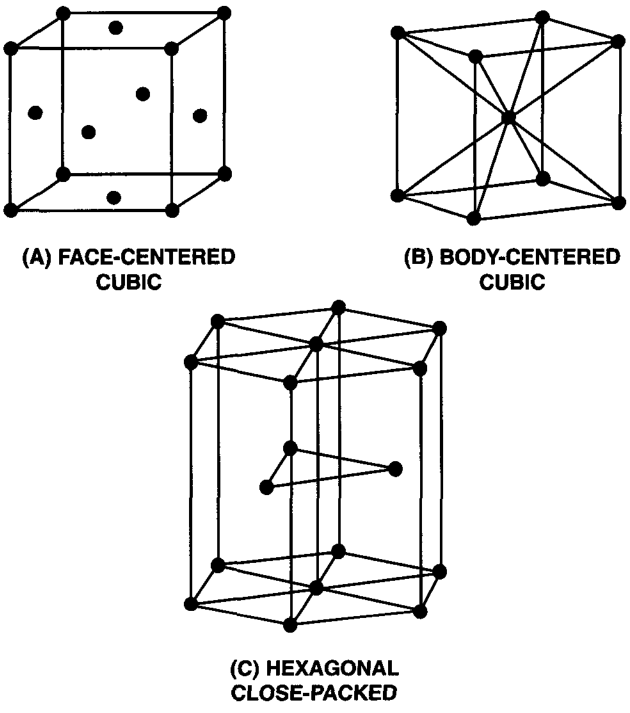
Table M-13
Crystal Structures of Common Metals

A. **Face-Centered Cubic** [Figure M-5(A)]	
Aluminum	Iron[b]
Cobalt[a]	Lead
Copper	Nickel
Gold	Silver
B. **Body-Centered Cubic** [Figure M-5(B)]	
Chromium	Titanium[c]
Iron[b]	Tungsten
Molybdenum	Vanadium
Columbium	Zirconium[c]
C. **Hexagonal Close-Packed** [Figure M-5(C)]	
Cobalt[a]	Titanium[c]
Magnesium	Zinc
Tin	Zirconium[c]

a. Cobalt is face-centered cubic at high temperature and transforms to hexagonal close packed at lower temperatures.

b. Iron is body-centered cubic near the melting temperature and again at low temperatures, but at intermediate temperatures iron is face-centered cubic.

c. Titanium and Zirconium are body-centered cubic at high temperatures and hexagonal close packed at low temperatures.



(A) FACE-CENTERED CUBIC

(B) BODY-CENTERED CUBIC

(C) HEXAGONAL CLOSE-PACKED

Figure M-5—The Three Most Common Crystal Structures in Metals

ingredients, called alloying elements, affect the properties of the base metal. The atomic arrangement (crystal structure), the chemical composition, and the thermal and mechanical history have an influence on the properties of an alloy.

Alloying elements, called *solutes*, are located in the parent metal matrix in one of two ways. The solute atoms may occupy lattice sites replacing some of the parent metal atoms, called *solvent*. Alternatively, if the solute atoms are small enough, they may fit into the spaces between the solvent atoms.

Substitutional Alloying. If the solute atoms are similar in size and chemical behavior to the solvent atoms, they may occupy sites at the lattice locations as shown in Figure M-6 (A). This type solid solution is called *substitutional*. Examples of substitutional solid solutions are gold dissolved in silver, or copper dissolved in nickel.

Interstitial Alloying. When the alloying atoms are very small in relation to the parent atoms, they can locate (or dissolve) in the spaces between the parent metal atoms without occupying lattice sites. This type of solid solution is called *interstitial*, and is illustrated in Figure M-6 (B). Small amounts of carbon, nitrogen, or hydrogen for example, alloy interstitially in iron and other metals.

Multiphase Alloys. Frequently, the alloying atoms cannot dissolve completely, either interstitially or substitutionally. The result, in such cases, is the formation of mixed atomic groupings (different crystalline structures) within a single alloy. Each different crystalline structure is referred to as a *phase*, and the alloy is called a *multiphase alloy*. The individual phases may be distinguished from one another, under a microscope at magnifications of 50X to 2000X, when the alloy is appropriately polished and etched.

All commercial metals consist of the primary or basic element and smaller amounts of one or more alloying elements. The alloying elements may be intentionally added or may be residual (tramp) elements. Commercial metals can be single or multiphase alloys. Each phase will have its own characteristic crystalline structure.

The overall arrangement of the grains, grain boundaries, and phases present in a metal alloy is called the *microstructure* of the alloy. The microstructure is largely responsible for the physical and mechanical properties of the metal. It is affected by both the chemical composition and the thermal and mechanical history of the metal. Consequently, microstructure is also

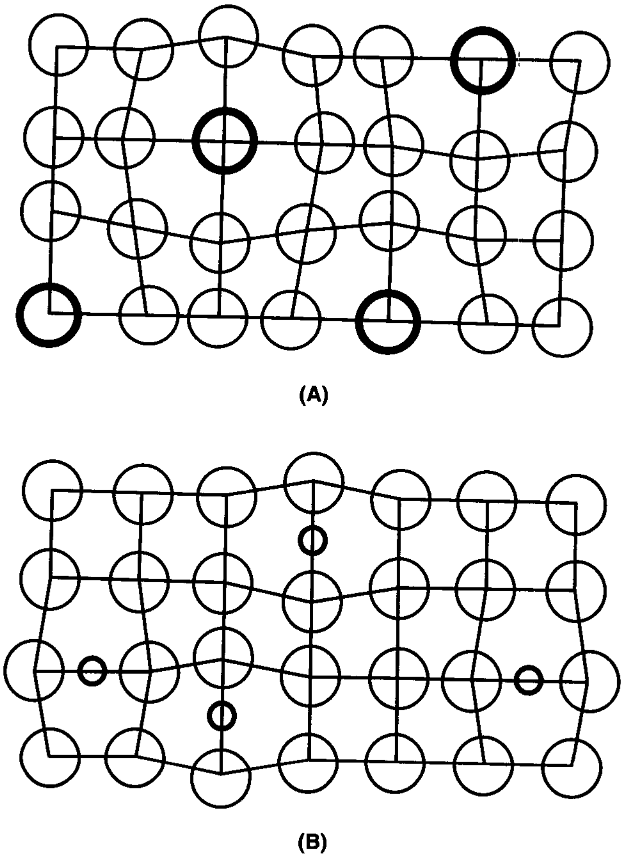


Figure M-6—Schematic Illustration of Substitutional and Interstitial Solid Solutions

affected by welding, but the effect is confined to the local region of the weld. The metallurgical changes in the local region (called the *heat-affected zone*) can have a profound effect on the service performance of a weldment.

Fine-grained materials generally have better mechanical properties for service at room and low temperatures. Conversely, coarse-grained materials generally perform better at high temperatures.

Phase Transformations

Critical Temperatures. At specific temperatures, the atoms of many metals change their crystallographic structure. For example, the crystalline structure of pure iron at temperatures up to 910°C (1670°F) is body-centered cubic, Figure M-5 (B). From 910 to 1390°C (1670 to 2535 F), the structure is face centered cubic, Figure M-5 (A), and from 1390 to 1535°C (2535 to 2795°F), the melting temperature, it is again body centered cubic. A phase change in crystal structure in the solid state is known as an *allotropic transformation.*

Other metals that undergo allotropic transformations are titanium, zirconium, and cobalt. Factors that influence the temperature at which transformation takes place are chemical composition, cooling rate, and the presence of stress.

A metal also undergoes a phase change when it melts or solidifies. Pure metals melt and solidify at a single temperature. Alloys, on the other hand, usually melt and solidify over a range of temperatures. The exception to this rule is the eutectic composition.

Phase Diagrams. Metallurgical events, such as phase changes and solidification, are best illustrated with a drawing called a *phase diagram* (sometimes referred to as an *equilibrium diagram* or a *constitution diagram*).

Phase diagrams only approximately describe commercial alloys because most published phase diagrams are based on two-component systems at equilibrium. Most commercial alloys have more than one component, and equilibrium conditions are approached only at high temperatures. However, with a knowledge of the normal responses of the alloy, a phase diagram is a powerful tool in understanding the behavior of commercial metals.

Phase diagrams for systems with more than two components are complex and more difficult to interpret, but still provide the best way to study most alloy systems.

Effects of Deformation and Heat Treatment

Deformation and Annealing of Metals. When metals are plastically deformed at room temperature, a number of changes takes place in the microstructure. Each individual grain must change shape to produce the anticipated overall deformation. As deformation proceeds, each grain becomes stronger and, therefore, more difficult to deform further. This behavior is called *work hardening.* When the metal is deformed below a critical temperature, there is a gradual increase in the hardness and strength of the metal and a decrease in ductility. This phenomenon is known as *cold working.*

If the metal is worked moderately or severely and then heated to progressively higher temperatures, several things happen. At temperatures up to about 205°C (400°F) there is a steady decline in the residual stress level, but there is virtually no change in microstructure or properties. At about 205 to 230°C (400 to 450°F), a relatively low level of residual stress remains, but the microstructure has not changed. The strength of the metal remains relatively unchanged compared to that of the original cold-worked material, and the ductility, while improved, is still rather low. This reduction in stress level and the improvement in ductility are attributed to the metallurgical phenomenon called *recovery*, a term indicating a reduction in crystalline stresses without accompanying microstructural changes.

When the cold-worked metal is heated to a temperature above 230°C (450°F), mechanical property changes become apparent, as do changes in microstructure. In place of the deformed grains, a new group of grains form and grow. These grains replace the old grains, and eventually all signs of the deformed grains disappear. The new microstructure resembles the original microstructure (before cold-working), and the metal is softened and made more ductile than it was in the cold-worked condition. This process is called *recrystallization*, a necessary part of annealing procedures. (Annealing refers to a heating and cooling process usually applied to induce softening). When heated to higher temperatures, the grains begin to grow and the hardness and strength of the metal are significantly reduced. Metals are often annealed prior to further cold working or machining.

Metallurgy of Welding

A welded joint consists of weld metal (which has been melted), heat-affected zones, and unaffected base metals. The metallurgy of each weld area is related to the base and weld metal compositions, the welding process, and the procedures used. Most typical weld metals have rapidly solidified, and usually have a fine grain dendritic microstructure. The weld metal is an admixture of melted base metal and deposited (filler) metal, if used. Some welds (autogenous) are composed of only remelted base metal. Examples of autogenous welds are gas tungsten arc and electron beam welds made without filler metal, and resistance welds. In most arc welding processes, a filler metal is used.

To achieve mechanical and physical properties that nearly match those of the base metal, a filler metal is often selected which is similar in chemical composition to the base metal. This is not a universal rule; sometimes the weld metal composition is deliberately made significantly different from that of the base metal. The intent is to produce a weld metal with properties compatible with the base metal. Therefore, variations from the base metal composition are not uncommon in filler metals.

When a weld is deposited, the first grains to solidify are nucleated by the unmelted base metal, and these grains maintain the same crystal orientation. Depending on composition and solidification rates, the weld solidifies in a cellular or a dendritic growth mode. Both modes cause segregation of alloying elements. Consequently, the weld metal may be less homogeneous than the base metal.

The weld heat-affected zone is adjacent to the weld metal. The heat-affected zone is that portion of the base metal that has not been melted, but whose mechanical properties or microstructure have been altered by the heat of welding. The width of the heat-affected zone is a function of the heat input. The heat-affected zone may in theory include all regions heated to any temperature above the ambient. From a practical viewpoint, however, it includes those regions which are actually influenced by the heat of the welding process.

For a plain carbon as-rolled steel, the heat of welding has little influence on those regions heated to less than about 700°C (1350°F). For a heat-treated steel that was quenched to martensite and tempered at 315°C (600°F), heating above this temperature would change the mechanical properties of the metal. For a heat-treated aluminum alloy age hardened at 120°C (250°F), any portion of a welded joint heated above this temperature is the heat-affected zone.

Heat-affected zones are often defined by the response of the welded joint to hardness variation or microstructural changes. Thus, changes in microstructure produced by the welding heat which are seen in etching or in hardness profiles may be used to establish the heat-affected zone. In many cases, these are arbitrary measures of the heat-affected zone, although they may be of practical value in testing and evaluating welded joints.

Adjacent to the heat-affected zone is the unaffected base metal. The base metal is selected by the designer for the specific application based on a specific property or combination of properties, such as yield or tensile strength, notch toughness, corrosion resistance, or density. It is the job of the welding engineer to select the welding consumables and process to develop welding procedures that allow the design properties to be fully utilized in service. The characteristic of a metal that allows it to be welded without losing its desirable properties is called *weldability.*

Weld Metal. The microstructure of the weld metal is considerably different from that of the base metal. The difference in microstructure is not related to chemical compositions, but to different thermal and mechanical histories of the base metal and the weld metal. The structure of the base metal is a result of a hot rolling operation and multiple recrystallization of the hot-worked metal. In contrast, the weld metal has not been mechanically deformed and therefore, has an as-solidified dendritic structure. This structure and its attendant mechanical properties are a direct result of the sequence of events that occur as the weld metal solidifies. These events include reactions of the weld metal with gases in the vicinity of the weld and with nonmetallic liquid phases (slag or flux) during welding, and also reactions that took place in the weld after solidification.

Solidification. The unmelted portions of grains in the heat-affected zone at the solid-liquid interface serve as nucleation sites for weld metal solidification. Metals grow more rapidly in certain crystallographic directions. Therefore, favorably oriented grains grow for substantial distances, while the growth of others that are less favorably oriented is blocked by other grains.

As a result, weld metal often exhibits a microstructure, described as columnar, in which the grains are relatively long and parallel to the direction of heat flow. This structure is a natural result of the influence of favorable crystal orientation on the competitive nature of solidification grain growth.

Dendrites. Weld metal solidification of most commercial metals involves micro-segregation of alloying and residual elements. This action is associated with, and, in large measure, responsible for the formation of *dendrites*. A dendrite is a structural feature which reflects the complex shape taken by the liquid-solid interface during solidification.

As the primary dendrites solidify, solutes that are more soluble in the liquid are rejected by the solid material and diffuse into the remaining liquid, lowering the freezing point. As the solute alloys concentrate near the solid-liquid interface, crystal growth is arrested in that direction. The grains then grow laterally, producing the dendrite arms characteristic of as-solidified metals. Many dendrites may grow simultaneously into the liquid from a single grain during solidification. Therefore, each of these dendrites has the same crystal orientation, and they will all be part of the same grain. However, a solute-rich network will exist among the dendrites in the final structure.

The general tendency is for weld-metal grain size to increase with heat input, but there is no fixed relationship. The grain size may be influenced by nucleating agents, vibration, or other process variables, but the dendrite arm spacing is exclusively a function of solidification rate which is controlled by heat input.

Gas Metal Reactions

Gas-metal reactions depend on the presence of oxygen, hydrogen, or nitrogen used alone or combined, in the shielding atmosphere. There are many sources for these elements. Oxygen is intentionally added to argon in gas metal arc welding of steel to stabilize the arc. It can also be drawn in from the atmosphere or result from the dissociation of water vapor, carbon dioxide, or a metal oxide. Air is the most common source of nitrogen, but there are many sources of hydrogen, principally from atmospheric moisture, moisture in electrode coatings, slag, and shielding gases. Hydrogen may be present in solid solution in nonferrous metals or in surface oxides and lubricating compounds from the wire drawing operation.

Welding Ferrous Metals. Gas-metal reactions in welding steels occur in several steps. First, the gas molecules are broken down in the high temperature of the welding atmosphere and then the gas atoms dissolve in the liquid metal. Oxygen and nitrogen will generally react with intentionally added deoxidizers such as manganese, silicon, and aluminum. These oxides will form a slag and float to the surface of the weld or precipitate as discreet oxides. Oxides and nitrides are present as small discreet particles. Although they reduce the ductility and notch toughness of steel weld metal, the resulting mechanical properties are satisfactory for most commercial applications.

In consumable electrode welding, the oxide content of steel weld metal is significantly greater than the nitrogen content because oxygen is intentionally present in arc atmospheres, whereas nitrogen is not. If the weld metal does not contain sufficient deoxidizers, the soluble oxygen will react with soluble carbon to produce CO or CO_2 during solidification. The gas molecules will be rejected during solidification and produce porosity in the weld metal.

Hydrogen is always present in the arc atmosphere, if only in small quantities. Hydrogen atoms are soluble in liquid steel and less soluble in solid steel. Excess hydrogen that is rejected during solidification will cause porosity. A more significant problem is created by the hydrogen that remains dissolved in the solid steel.

Welding Nonferrous Metals. The primary gas-metal reactions of concern are the solution, reaction, and evolution of hydrogen or water vapor. These gases, therefore, should be excluded from the molten weld pool. With aluminum and magnesium, hydrogen is often introduced into the weld pool from hydrated oxides on the surfaces of the filler wire or workpieces, or both. It is rejected from the metal during solidification to produce porosity. For this reason, cleaned aluminum and magnesium filler metals should be stored in sealed, desiccated containers. Mechanical cleaning or vacuum heating at 150°C (300°F) is recommended for workpieces or filler metals which have been exposed to moist air. The hydrogen solubility difference between the liquid and solid states for magnesium is less than that for aluminum. Consequently, the tendency for hydrogen-produced porosity is lower in magnesium.

In the case of copper and copper alloys, hydrogen will react with any oxygen in the molten weld pool to produce water vapor, and thus porosity, during solidification. The filler metals for copper alloys contain deoxidizers to prevent this reaction. Porosity caused by water vapor will not form in alloys of zinc, aluminum, or beryllium because these elements form stable oxides. Porosity from water vapor can form in nickel-copper and nickel alloy weld metal, and filler metals for these alloys should contain strong deoxidizers.

Titanium alloys are embrittled by reaction with a number of gases including nitrogen, hydrogen, and oxygen. Consequently, these elements should be excluded from the arc atmosphere. Welding should be done using carefully designed inert gas shielding or in a vacuum. Titanium heat-affected zones are also significantly embrittled by reaction with oxygen and nitrogen. Titanium weldments should be shielded so that any surface heated to over 260°C (500°F) is completely protected by an inert gas. Hydrogen is the major cause of porosity in titanium welds. The hydrogen source, as in other nonferrous and ferrous metals, can be the filler metal surface. In addition, soluble hydrogen in the filler metal and the base metal can contribute significantly to the total hydrogen in the molten weld pool.

Liquid Metal Reactions. During the welding process, nonmetallic liquid phases that interact with the molten weld metal are frequently produced. These liquid phases are usually slag formed by the melting of an intentionally added flux.

The slags produced in the shielded metal arc welding (SMAW), submerged arc welding (SAW), and electroslag welding (ESW) processes are designed to absorb deoxidation products and other contaminants produced in the arc and molten weld metal. The quantity and type of nonmetallic deoxidation products generated when arc welding steel are primarily silicates of aluminum, manganese, and iron, that float to the surface of the molten weld pool and become incorporated in the slag. Some products can be trapped in the weld metal as inclusions.

Hot Cracking. Another important effect that results from the interaction of the liquid and solid state is the weld defect referred to as hot cracking. Shrinkage stresses produced during solidification become concentrated in a small liquid region and produce microcracks between the dendrites. These cracks are called *hot cracks* because they occur at temperatures close to the solidification temperature.

The most common cause of hot cracking is the presence of low-melting alloy sulfides that wet the dendrite surfaces. In some ferrous alloys, such as stainless steels, silicates have also been found to produce cracking. Avoidance of cracking in these alloys is usually accomplished by controlling both the amount and type of sulfides that form and the minor alloy constituents that may promote cracking.

Solid State Reactions. In terms of the behavior of weld metals, there are a number of solid state reactions that are important as strengthening mechanisms in the weld metal itself. There are some important phenomena involving solid state transformations and subsequent reactions with dissolved gases in the metal. The most significant of these phenomena is the formation of cold cracks in steel weld metal or heat-affected zones, often referred to as *delayed cracking*. The steels most susceptible to this type of cracking are those that can transform to martensite on cooling from the weld thermal cycle. The cracking occurs after the weld has cooled to ambient temperature, sometimes hours or even days after welding. It is always associated with dissolved hydrogen in the weld metal which remains there during solidification and subsequent transformation to martensite.

Because delayed cracking is always associated with dissolved hydrogen, two precautions are universally used to minimize the risk of delayed cracking. They are:

(1) Preheating the base metal to slow the cooling rate.
(2) Using low-hydrogen welding processes.

The use of preheat prevents the formation of a crack-susceptible microstructure and also promotes the escape of hydrogen from the steel by diffusion.

Hydrogen is relatively soluble in austenite, and virtually insoluble in ferrite. On rapid cooling, the austenite transforms either to an aggregate of ferrite and carbide or to martensite, and hydrogen is trapped in solution. In a plain carbon steel, this transformation takes place at a relatively high temperature, even if cooling is rapid, and the hydrogen atoms have sufficient mobility to diffuse out of the metal. A rapidly cooled hardenable steel transforms at a much lower temperature where the hydrogen atoms have lower mobility, the microstructure is martensitic, and crack sensitive, and this combination will likely cause cracking. The association of hydrogen with delayed cracking led to the development of low-hydrogen covered electrodes. Low-hydrogen electrode coverings must be kept essentially moisture free since moisture is a primary source of hydrogen.

Another solid state reaction that affects weld joint mechanical properties in ferrous and nonferrous alloys is the precipitation of second phases during cooling. Precipitation of a second phase in grain boundaries is particularly deleterious because the grain boundaries are continuous throughout the metal. A concentration of a second phase at grain boundaries may significantly reduce ductility and toughness.

Strengthening Mechanisms in Weld Metal

The practical methods for strengthening weld metals are fewer than for base metals. For example, weld metal is not usually cold worked. There are four mechanisms for strengthening weld metal, and where applicable they are additive: (1) solidification grain structure, (2) solid solution strengthening, (3) transformation hardening, and (4) precipitation hardening. The first mechanism is common to all welds, the second is applicable to any alloy type, but the third and fourth apply only to specific types of alloys.

Solidification Grain Structure. Weld metal freezes rapidly, creating a segregation pattern within each grain. The resulting microstructure consists of fine dendrite arms in a solute-rich network. This type of microstructure impedes plastic flow during tensile testing. As a result, weld metals typically have a higher yield-to-tensile strength ratio than base metals.

Solid Solution Strengthening. Weld metal is strengthened by alloying elements present. Both substitutional and interstitial alloying elements will strengthen ferrous and nonferrous weld metal.

Transformation Hardening. Hardening will result in ferrous weld metal even if the austenite decomposition product is not martensite. The rapid cooling rates, achieved during the cooling portion of weld thermal cycles, decrease the austenite transformation temperature. The ferrite-carbide aggregate formed at low transformation temperatures is finer and stronger than that formed at higher transformation temperatures. The effect of transformation temperature on the ultimate tensile strength of steel weld metal is shown in Figure M-7.

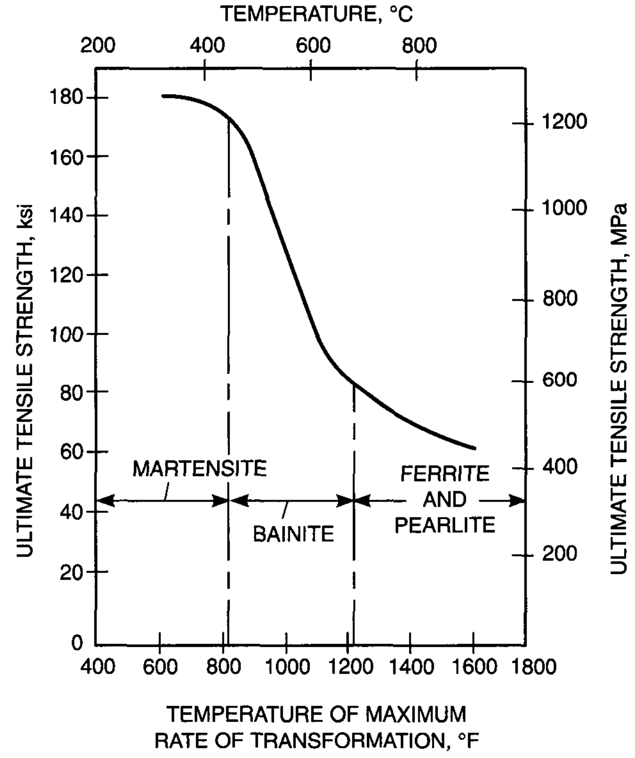


Figure M-7—Effect of Transformation Temperature on Strength

Precipitation Hardening. Weld metal of precipitation hardening alloy systems can be strengthened by an aging process. In most commercial applications, the precipitation hardened weldments are aged after welding without the benefit of a solution heat treatment. In multipass welds, some of the zones of weld metal will be aged or overaged from the welding heat. The heat-affected zone will also contain overaged metal. An aging heat treatment will strengthen the weld metal and the heat-affected zone. The weld metal and the heat-affected zone may not strengthen to the same level as the base metal due to the presence of overaged metal. Some aluminum precipitation hardening weld metals will age naturally at room temperature.

The Heat-Affected Zone

The strengthened toughness of the heat-affected zone in a welded joint is dependent on the base metal, the welding process, and the welding procedure. Because the weld thermal cycle is generally a rapid one, the base metals most influenced by welding will be those strengthened or annealed by heat treatments. The temperatures in the weld heat-affected zone vary from ambient to near the liquidus temperature. Metallurgical processes that proceed slowly at lower temperatures can proceed rapidly to completion at temperatures close to the liquidus.

To understand the various effects of welding heat on the heat-affected zone, these effects can basically be considered in terms of four different types of alloys that can be welded. Some alloys can be strengthened by more than one of these processes, but for simplicity the processes are considered separately.

Solid-Solution Strengthened Alloys. Solid-solution alloys normally exhibit the fewest weld heat-affected zone problems. If they do not undergo a solid state transformation, the effect of the thermal cycle is small, and the properties of the heat-affected zone will be largely unaffected by welding. Grain growth will occur next to the fusion line as a result of the high peak temperature. This will not significantly affect mechanical properties if the grain-coarsened zone is only a few grains wide.

Commonly used alloys strengthened by solid solution are annealed aluminum alloys, annealed copper alloys, and hot rolled and annealed low-carbon steels. Annealed ferritic and austenitic stainless steels come under essentially the same category.

Strain Hardened Base Metals. Strain hardened base metals will recrystallize when heated above the recrystallization temperature. The heat of welding will recrystallize the heat-affected zones in cold worked metals and soften the metal considerably. The recrystallized heat-affected zone is softer and weaker than the cold worked base metal, and the strength cannot be recovered by heat treatment.

If the cold worked materials undergo an allotropic transformation when heated, the effects of welding are even more complex. Steel and titanium alloys may have two recrystallized zones. The first fine-grained zone results from recrystallization of the cold worked alpha phase. The second fine-grained zone results from the allotropic transformation to the high temperature phase.

Precipitation-Hardened Alloys. Alloys that are strengthened by precipitation hardening respond to the heat of welding in the same manner as work hardened alloys; that is, the heat-affected zone undergoes an annealing cycle. The response of the heat-affected zone is more complex because the welding thermal cycle produces different effects in different regions. The heat treating sequence for precipitation hardening is: solution treat, quench, and age. The welding heat will re-solution treat the heat-affected zone regions closest to the weld, and produce a relatively soft single phase solid solution with some coarse grains. This region can be hardened by a post weld aging treatment.

Those regions of the heat-affected zone that are heated to temperatures below the solution treatment temperature will be overaged by the welding heat. A postweld aging treatment will not reharden this region. If the welding heat does not raise the heat-affected zone temperature above the original aging temperature, the mechanical properties are not significantly affected.

It is difficult to weld high-strength precipitation hardenable alloys without some loss of strength, but three techniques may be used to minimize the loss. The most effective of these techniques is to re-solution treat, quench, and age the weldment. This technique is expensive, and in many cases may not be practicable. A second approach would be to weld precipitation-hardened base metal and then re-age the weldment. This raises the strength of the solution-treated region of the heat-affected zone, but does not improve the strength of the overaged zone. Another alternative is to weld the base metal in the solution treated condition and age the completed weldment. The overaged zone is still the weakest link, but the overall effect may be an improvement over the previous approaches.

Since it is the weld thermal cycle that lowers the strength of the heat-treated base metal, high heat input welding processes are not recommended for precipitation-hardened alloys. Low heat input will minimize the width of the heat-affected zone and the amount of softened base metal.

Transformation Hardening Alloys. The transformation hardening alloys of interest are the steels with sufficient carbon and alloy content to transform to martensite upon cooling from welding. These may be steels which are already heat treated to tempered martensite prior to welding, or steels that have adequate hardenability to transform to martensite during a weld thermal cycle, even though they may not have been heat treated. In either case, the heat-affected zone is affected by the weld thermal cycle in approximately the same manner. The heat-affected zones, together with the steel portion of the iron-carbon phase diagram, are illustrated in Figure M-8.

In Figure M-8, the grain coarsened region is near the weld interface (Region 1). Rapid austenitic grain growth takes place in this region when exposed to the near melting point temperatures. The large grain size increases hardenability, and this region can readily transform to martensite on cooling. Region 2 is austenitized, but the temperature is too low to promote grain growth. The hardenability of Region 2 will not be significantly increased by grain growth, but may still transform to martensite if the cooling rate is fast enough or if the alloy content is great enough. In Region 3, some grains transform to austenite and some do not. The austenite grains are very fine. No austenitic transformation takes place in Region 4 next to the unaffected base metal, but the ferrite grains may be tempered by the heat of welding.

The width of the heat-affected zone and the widths of each region in the heat-affected zone are controlled by the welding heat input. High heat inputs result in slow cooling rates, and therefore, the heat input may determine the final transformation products.

High-carbon martensite is hard and strong, and it can create problems in the heat-affected zone. The hardness of the weld heat-affected zone is a function of the base metal carbon content. The hardness and crack-susceptibility increase and the toughness decreases with increasing carbon content. Martensite alone will not cause cracking; dissolved hydrogen and residual stresses are also present.

The same precautions used to prevent delayed cracking in weld metal will also prevent cracking in

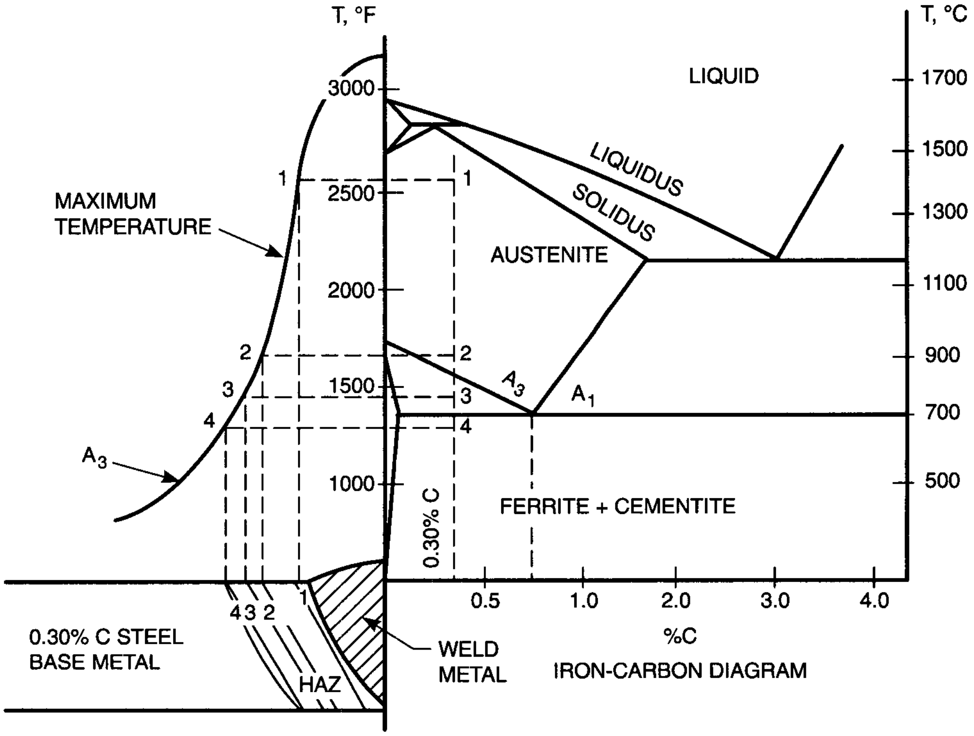


Figure M-8—Approximate Relationships Among Peak Temperature, Distance from Weld Interface, and the Iron-Carbon Phase Diagram

the heat-affected zone. The hardness of a weld heat-affected zone is usually a good indication of the amount of martensite present and the potential for cracking. Cracking rarely occurs when the weld hardness is 250 HB or less, but is common when the hardness approaches 450 HB and no precautions are taken.

Special precautions may be necessary when welding hardenable steels that have been intentionally heat treated to produce a tempered martensitic microstructure. It is usually desirable to use a low welding heat input to control the size of the heat-affected zone, and a high preheat temperature to control the cooling rate of the weld. The welding recommendations of the steel manufacturer should be followed in preparing welding procedures for low-alloy, high-strength steels.

Base Metal

The third component in a welded joint is the base metal. Many of the common engineering materials available today are readily weldable. However, some materials are more difficult to weld and require special precautions.

Weldability. Weldability is the capacity of a material to be welded into a specifically designed structure under the imposed fabrication conditions, and to perform satisfactorily in the intended service. Some systems may have poor weldability under certain conditions and have satisfactory weldability under other conditions. For example, all grades of ASTM A514 (a heat treated 690 MPa [100 ksi] yield strength constructional alloy steel) have satisfactory weldability, provided the base metal is sufficiently preheated, a low-hydrogen welding process is followed, and the heat input limitations are not exceeded.

The primary factor affecting the weldability of a base metal is its chemical composition or the grade of the material. Each grade of material has welding procedural limits within which sound weldments with satisfactory properties can be fabricated. If these limits are wide, the grade is said to have good weldability. If the limits are narrow, the material is said to have poor weldability. If extraordinary precautions are necessary, then the material is often said to be "unweldable." Yet, in some cases and in some industries, "unweldable" materials are routinely welded under tight controls with vigorous inspection procedures and acceptance criteria. These methods are followed because welding may be the only (or at least the best) method to achieve the desired function within the design criteria for the whole assembly.

References:

(1) American Welding Society, *Welding Handbook* Vol.1, 8th Ed., Miami, Florida: American Welding Society, 1987.

(2) Linnert, G. E. *Welding Metallurgy,* Vol.1 (Fundamentals), 4th Ed., Miami, Florida: American Welding Society, 1994.

METALWORKING MACHINES

Any of a variety of portable or stationary machines that cut, bend, punch or otherwise prepare metal for fabrication.

METRIC SYSTEM

A system of measurement which has been in existence for approximately two hundred years. It is widely used in Europe; however variations in terms and units existed between countries, and in 1960 this variety of metric units was replaced by the *International System of Units (SI).* For more complete information on the SI system, including units, symbols and conversion practices, refer to ANSI/AWS *A1.1, Metric Practice Guide for the Welding Industry.*

SI is a modernized metric system of measurement that has been officially recognized by all industrial nations. It has features that make it superior to the U.S. Customary and to other metric systems. These features are the following:

(1) *An Absolute Base.* A base that is not defined by the action of gravity.

(2) *Coherence.* Coherence is the characteristic which relates any derived unit to any other, or to base units from which it is formed, without conversion factors.

(3) *Unique Units.* The use of only one unit for each physical quantity; for example, SI units for force, energy, and power are the same regardless of whether the process is mechanical, electrical, or thermal.

(4) *Decimal System.* SI is a decimal system; it is easier to use because it is easier to work in multiples of ten and in decimal notations than in fractions and decimalized fraction equivalents common to the U.S. Customary system.

This combination of features makes SI a reliable system suitable for all kinds of measurements. Although areas remain that can and no doubt will be improved, the SI system is practical for universal application and is rapidly becoming the commonly used world measurement system.

SI Units Pertaining to Welding. The recommended SI units used in welding nomenclature are shown in Appendix 14. The selection of these terms was based on the use of (1) SI base units where practicable; (2) numbers of reasonable size, and (3) accepted units currently in use or anticipated to be used.

Special Conversions for Welding. Terms that are commonly used in the welding industry and conversions between U.S. Customary and SI units are shown in Appendix 14.

MHO

The practical unit of conductance defined as the conductance of a body through which one ampere of current flows when the potential difference is one volt. The conductance of a body in *mho* is the reciprocal of the value of its resistance in ohms.

MICROETCH TEST

A test in which the specimen is prepared with a polished finish, etched, and examined under high magnification. See STANDARD WELDING TERMS.

MICROGRAPH

A graphic reproduction of a metallic surface (a section of metal which has been ground, polished and etched) at a magnification of 10 diameters or greater. When reproduced by photography it is called a *photomicrograph. See* METALLOGRAPHY.

MICROSTRUCTURE

The term *microstructure* is used to describe the structure of metals. A basic visual examination of etched metal surfaces and fractures will reveal some configurations in etched patterns that relate to structure, but magnification of minute details will yield considerably more information.

Three widely used tools for the examination of structures in metals and their applications are:

(1) The low-power magnifying glass, when applied to etched metal surfaces reveals gross details in microstructure.

(2) The metallograph, an optical microscope, usually fitted with an inverted stage for convenience in scanning the flat face of prepared specimens. Metallographic examination usually requires magnification in the range of 50 to 1500X (X = diameters). Because of the wave length of visible light, there is an upper limit of about 2000X for magnification of an optical microscope.

(3) The electron microscope, capable of magnifying at least 200 000X with remarkably good depth of focus and resolution. Images of metal microstructure are obtained either by electron beams transmitted through a specimen or by beams that are reflected and emitted.

MIG SPOT WELDING

A nonstandard term for a spot weld made using either gas metal arc welding (GMAW) or flux cored arc welding (FCAW). *MIG* is an abbreviation for "metal inert gas." *See* GAS METAL ARC SPOT WELDING.

MIG WELDING

A nonstandard term for *gas metal arc welding* and *flux cored arc welding. See* GAS METAL ARC WELDING *and* FLUX CORED ARC WELDING.

MILD STEEL

A generic term for a low-carbon structural steel with a carbon content of less than 0.25%.

MISMATCH

See STANDARD WELDING TERMS. *See* WELD JOINT MISMATCH.

MIXED ZONE

The portion of the weld metal consisting of a mixture of base metal and filler metal. See STANDARD WELDING TERMS. *See also* UNMIXED ZONE.

MIXING CHAMBER

The part of a welding or cutting torch in which a fuel gas and oxygen are mixed. See STANDARD WELDING TERMS.

MODULUS OF ELASTICITY

A measure of the rigidity of a material is called the *modulus of elasticity.* Specifically, the slope of the initial linear portion of the stress-strain curve is the modulus of elasticity; when obtained in compression or tension it is *Young's modulus.* Since the modulus of elasticity is needed for computing deflection of beams and other members in a structure, it is an important design value.

The modulus of elasticity is determined by the binding forces between the atoms in the material. These forces cannot be changed without changing the basic nature of the material, and it follows that modulus of elasticity is one of the most structure-insensitive of all the mechanical properties. The modulus of elasticity is only slightly affected by alloying additions, heat treatment or cold work. However, only increasing the temperature results in a decrease in the modulus of elasticity.

MOHS HARDNESS SCALE

Mohs Hardness Scale is a scratch-hardness evaluation of materials and is the oldest hardness evaluation. The Mohs Hardness Scale (circa 1822) was developed by mineralogists and is based on the capability of a harder material to scratch the surface of a softer material. The ten minerals listed in Table M-14 were selected to form the Mohs scale, and each makes a permanent scratch (one that cannot be rubbed off) on all minerals listed below it. There is a very great difference between diamond and corundum compared to the relatively small differences between softer minerals. A human fingernail can scratch gypsum. A hardness approximation of a polished metal surface can be obtained by determining which pair of adjacent minerals scratch and do not scratch the sample. Hardened tool steel is between 8 and 9 on the Mohs scale. Low-carbon steel is usually between 3 and 4, while annealed copper is between 2 and 3. The Mohs scratch test is not normally applied to metals because of its semi-quantitative nature; however, a uniformly applied scratch with the tip of a sharp needle across the face of a polished and etched metallographic specimen can give useful information on the metal's microconstituents. Careful observation and perhaps measurement of the scratch width along its length, can provide an indication of the relative hardness of the microconstituents. *See* HARDNESS TESTING.

Table M-14
Mhos Scale of Hardness

Material	Position	Material	Position
Diamond	10	Apatite	5
Corundum	9	Fluorite	4
Topaz	8	Calcite	3
Quartz	7	Gypsum	2
Feldspar	6	Talc	1

MOLDING SHOE

A nonstandard term for BACKING SHOE.

MOLTEN METAL SPRAYING

See THERMAL SPRAYING.

MOLTEN WELD POOL

A nonstandard term for WELD POOL.

MOLYBDENUM

(Chemical symbol: Mo). A hard, silver-white metal, molybdenum is a significant alloying element in the production of engineering steels, corrosion resistant steels, tool steels, and cast irons. Atomic number 42; atomic weight, 95.95; melting point, 2620°C (4748°F); boiling point 4804°C (8680°F), and specific gravity 10.2.

Molybdenum does not occur free in nature but is obtained from molybdenite (MoS_2) and from wulfenite ($PbMoO_4$). The metal is prepared by the reduction of the oxide with carbon, usually in an electric furnace.

Small additions of molybdenum to steel promote relatively uniform hardness and strength even throughout heavy sections. In addition, molybdenum contributes the following properties:

(1) Increases the resistance of commonly used engineering steels to softening after tempering.

(2) Increases the strength and creep resistance of low- and high-alloy steels at elevated temperatures.

(3) Improves the resistance to corrosion by pitting in engineering steel, and improves the general corrosion resistance of chromium and chromium-nickel corrosion resistant steels.

(4) Tends to retard intergranular corrosion in austenitic chromium-nickel steels if some delta ferrite is present.

In addition, molybdenum contributes other properties when added to steel. Molybdenum does not cause the formation of a tightly adherent scale on steel when the steel is heated in an oxidizing atmosphere for hot working. This assists in subsequent cleaning operations when the steel is pickled or sand blasted; a tight scale is more difficult and costly to remove.

When added to cast iron, molybdenum improves the high-temperature strength and toughness. It is neither a graphitizer nor a strong carbide stabilizer in cast iron. The addition of molybdenum to gray cast iron increases the tensile strength; this is attributable to direct solid solution effect in ferrite and to retardation of transformation of austenite.

MOLYBDENUM WELDING

Welding process selection is determined by the physical and metallurgical properties of molybdenum. Molybdenum has an extremely low room-temperature solubility limit (1 ppm or less) for oxygen, nitrogen, and carbon.Warm-working below the recrystallization temperature breaks up grain boundary films and produces a fibrous grain structure. This structure will have good ductility and strength in the direction of working, but not transverse to it.

Alloys. Some alloying is necessary to improve the high-temperature and room-temperature properties. Molybdenum is alloyed with small amounts of titanium, zirconium, and carbon to improve high-temperature and room-temperature strength properties. An alloy designated a TZM (Mo-0.5Ti-0.087Zr-0.015C) is produced commercially. Also, an addition of about 20 atomic percent of rhenium to molybdenum greatly improves ductility near room temperature.

Surface Preparation. Prior to welding, the surfaces must be clean and free of dirt, grease, oil, oxides and other foreign matter. The molybdenum components should be first degreased in a suitable, safe solvent; followed by a cleaning method recommended by the molybdenum supplier, rinsing in clean water, and air drying.

Welding. Fusion welding must be done in a pure inert gas atmosphere or in a high vacuum to prevent contamination by oxygen and nitrogen. Any fixtures used should provide minimum restraint on the weldment, especially when welding a complex structure. The components should be preheated above the transition temperature of the metal. Weldments should be stress-relieved promptly at a temperature below the recrystallization temperature of the base metal.

For arc welding, molybdenum can be joined by the gas tungsten arc welding process using direct current electrode negative. Argon or helium may be used for shielding. Welds should be made using procedures that give a narrow heat-affected zone with minimum input of heat.

The electron beam welding process is well suited for joining molybdenum because of its high energy density. Narrow, deep welds can be produced by this process using less energy than with arc welding. Since electron beam welding is done in a high vacuum, contamination of the weld metal with oxygen or nitrogen is prevented. *See also* CARBON STEEL *and* STAINLESS STEEL.

MONEL®

The term *Monel*® is the registered trade mark of the International Nickel Company, Inc. for a series of nickel-copper alloys. The nominal composition of Monel® is 67% nickel, 30% copper, 1.7% iron, 1.1% manganese, with small residuals (<0.1%) of carbon and silicon. Monel® is used where high strength and resistance to corrosion are required. It is useful against many common corrosives, such as sea water, dilute sulfuric acid and strong caustic solutions. It should not be used in sulfurizing atmospheres above 370°C (700°F) or with strong oxidizing acids such as nitric acid.

Welding. Commercial nickel alloys, including Monel®, that contain 30 to 45% copper, are tough and ductile. Except for free-machining (high-sulfur) alloys, these alloys are readily joined by welding, brazing, and soldering, with proper precautions. *See* NICKEL ALLOY WELDING.

MOTOR GENERATOR

A power source which converts mechanical energy into electrical power suitable for arc welding. The source of mechanical power is usually an induction motor-driven welding generator available for 200, 240, 480, and 600 V, three-phase, 60 Hz input. The motors of welding generators usually have a good power factor (80 to 90%) when under load. This type of power source can be used with shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and submerged arc welding (SAW).

MOVABLE-COIL CONTROL

A movable-coil transformer consists essentially of an elongated core on which are located primary and secondary coils. Either the primary coil or secondary coil may be movable, while the other one is in a fixed position. Most a-c transformers of this design have a fixed-position secondary coil. The primary coil is normally attached to a lead screw and, as the screw is turned, the coil moves closer to, or further from, the secondary coil.

Figure M-9 shows one form of a movable-coil transformer with coils spread apart for minimum output and a steep slope volt-ampere curve. Figure M-10 shows the coils close together. The volt-ampere curve is indicated at maximum output with less slope than the curve in Figure M-9.

MOVABLE-SHUNT CONTROL

The movable-shunt control is often used with a-c transformer-type welding power supplies. It may also be used with ac-dc power sources. The shunt acts to divert the magnetic flux around the coils. (In this usage, the term *flux* refers to the magnetic lines of force). In this design, the primary coils and the secondary coils are in fixed position. Control is obtained with a laminated iron core shunt that is moved between the primary and secondary coils. It is made of the same material as used in the transformer core.

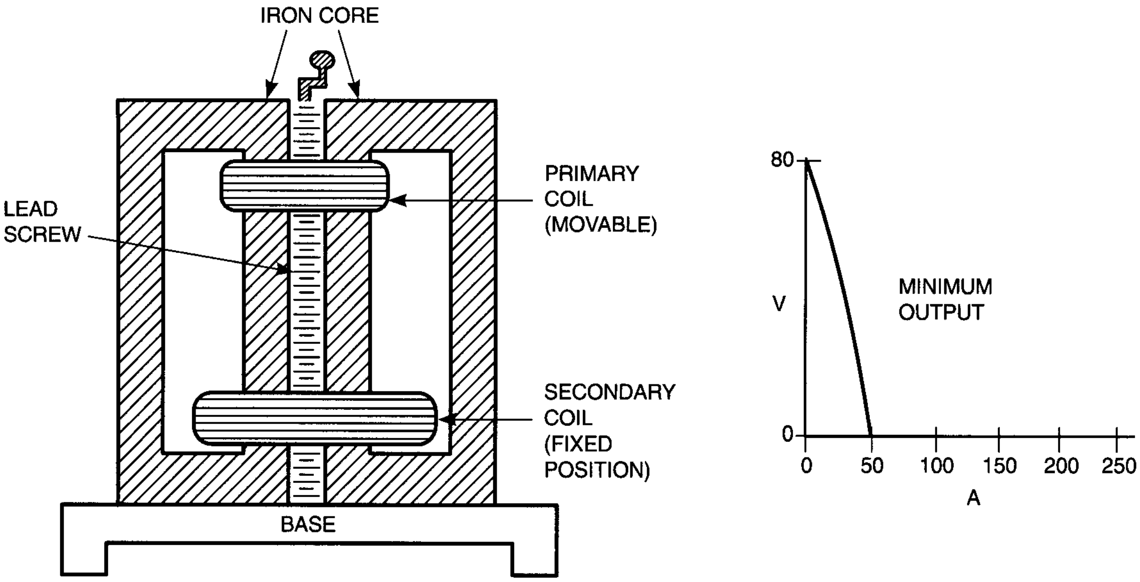


Figure M-9—Movable-Coil AC Power Source with Coils Set for Minimum Output

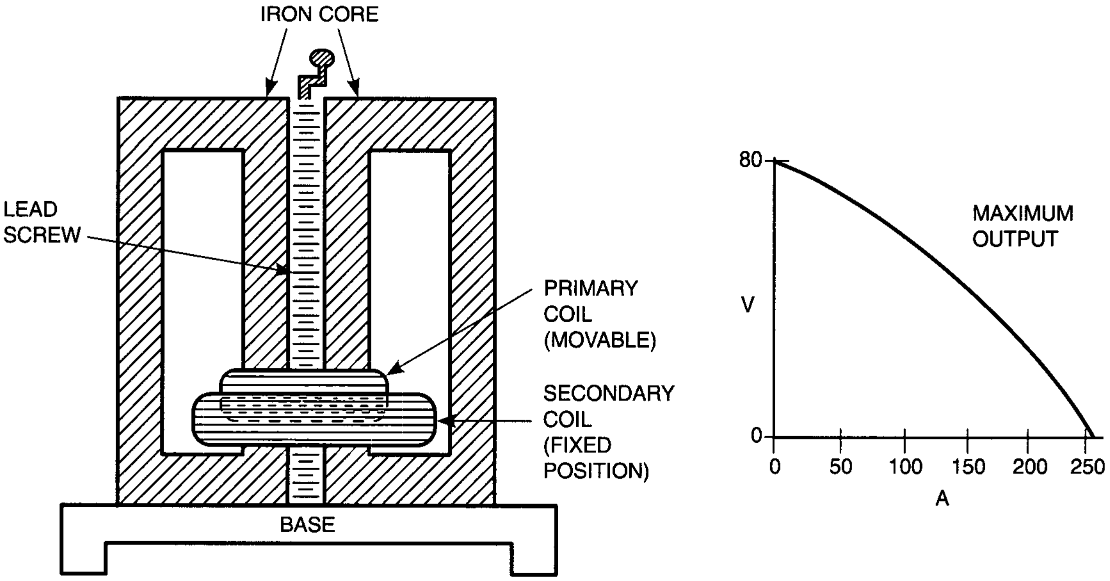


Figure M-10—Movable-Coil AC Power Source with Coils Set for Maximum Output

As the shunt is moved into position between the primary and secondary coils, it diverts more or less of the available flux field. The more magnetic lines of force diverted, the less the output current.

MOVING SHOE

A backing shoe that slides along the joint during welding. See STANDARD WELDING TERMS.

MULTIPASS FILLET WELD

See STANDARD WELDING TERMS.

MULTIPASS WELD

A fusion weld produced by more than one progression of the arc, flame or energy source along the joint. See STANDARD WELDING TERMS.

MULTIPLE-IMPULSE WELDING

A resistance welding process variation in which welds are made by more than one impulse. See STANDARD WELDING TERMS. *See* Figure I-1.

MULTIPORT NOZZLE

A constricting nozzle of the plasma arc torch that contains two or more orifices located in a configuration to achieve some control over the arc shape. See STANDARD WELDING TERMS.

MULTIPLE WELDING POSITION

An orientation for a nonrotated circumferential joint requiring welding in more than one welding position. See STANDARD WELDING TERMS. *See* 5F, 5G, 6F, 6G, *and* 6GR.

Color metallographic analysis is a useful tool for evaluating reactive and refractory metal structures. This specimen is a C103 alloy weld showing the interface region of an equiaxed base metal structure with an as-cast (elongated) grain structure in the weld area. This weld was produced using the electron beam welding process on 3-in. thick material (400X).

N

NARROW GAP WELDING

A nonstandard term for narrow groove welding.

NARROW GROOVE WELDING

A variation of a welding process that uses multiple-pass welding with filler metal. The use of a small root opening, with either a square groove or a V groove and a small groove angle, yields a weld with a high ratio of depth to width. See STANDARD WELDING TERMS.

This gas metal arc welding (GMAW) process was developed to make narrow welds in thick plates. Successful welds have been made on steel plates up to 20 cm (8 in.) thick. The process is suitable for welding in all positions, and is used on a variety of heavy section carbon and low-alloy steels with minimum distortion.

Narrow groove GMAW uses the spray transfer technique. A squared butt joint with a root opening of 6.0 to 9.0 mm (1/4 to 3/8 in.) wide is used for all plate thicknesses. A typical narrow groove joint configuration is shown in Figure N-1.

Using GMAW to weld joints in the narrow groove configuration requires special precautions to assure that the tip of the electrode is positioned accurately for proper fusion into the sidewalls. Numerous wire feeding methods for accomplishing this have been devised and successfully used in a production environment. Examples of some of these are shown in Figure N-2.

Narrow groove welds have been made with electrode wires ranging from 0.9 to 1.6 mm (0.035 to 1/16 in.) diameter. Out-of-position narrow groove welds are preferably made with 0.9 mm (0.035 in.) diameter electrode wires.

Because of the narrow groove opening, relatively high travel speeds are used during welding. If the travel speed is too slow, the weld puddle becomes too large to be controlled. The first layer is deposited against a suitable backing, and because of the high travel speed, is relatively thin. Weld beads are deposited one on top of the other, with approximately 10 passes required for each 25 mm (1 inch) of plate thickness being welded. Close control over the composition of narrow groove welds can be maintained with this technique.

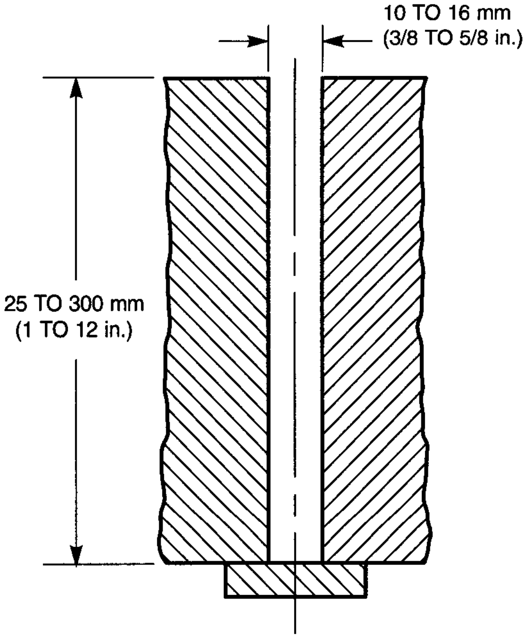


Figure N-1—Typical Narrow Groove Joint Edge Preparation

Among the many advantages of narrow groove welding are:

(1) Improved economy because less filler metal is required

(2) Good mechanical properties in both the weld metal and the heat-affected zone because of the relatively low heat input

(3) Improved control of distortion

(4) Fully automatic operation in all welding positions, including overhead, using the spray transfer technique.

NATURAL GAS

Natural gas consists of gaseous hydrocarbons which have been distilled from mineral oils stored in porous strata in the earth. It is found in all oil-producing localities all over the world. Natural gas is obtained from wells and distributed by pipelines. Its chemical composition varies widely, depending on the locality from

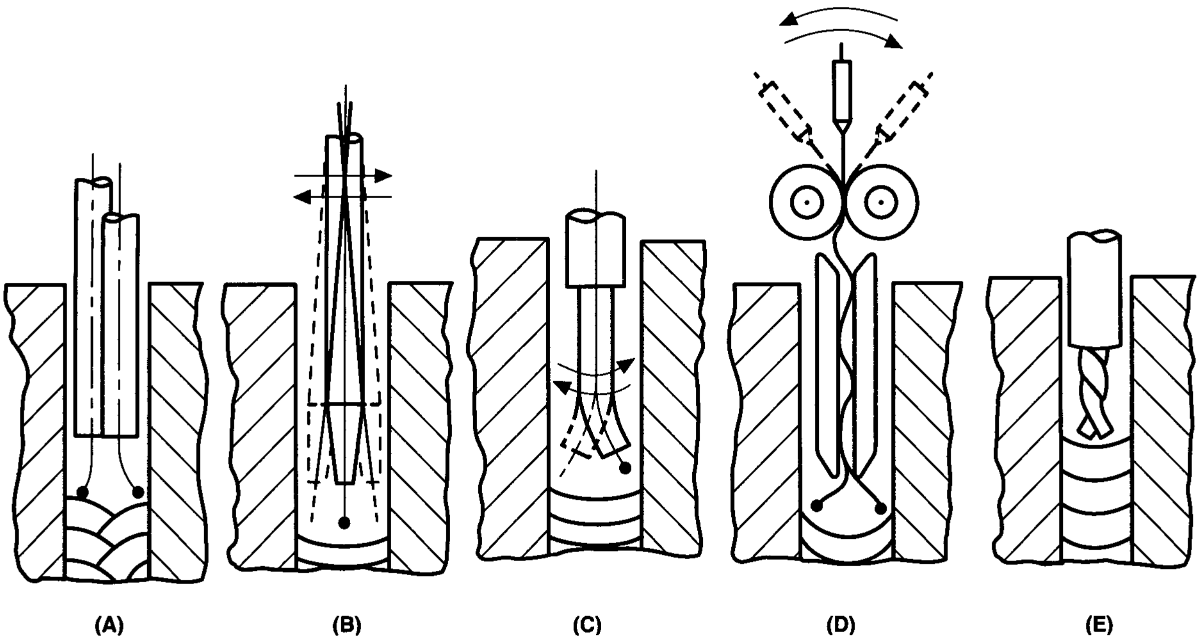


Figure N-2—Typical Wire Feeding Techniques for Narrow Gap Gas Metal Arc Welding

which it is obtained. The principal constituents of most natural gases are methane (CH_4) and ethane (C_2H_6).

Natural gas finds its principal use in the welding industry as a fuel gas for oxygen cutting and heating operations. The volumetric requirement of natural gas is about 1-1/2 times that of acetylene to produce an equivalent amount of heat.

Natural gas is not suitable for welding due to the oxygen-to-fuel-gas ratio which produces a highly oxidizing flame and prevents the satisfactory welding of most metals. Many ferrous and nonferrous metals can be braze welded with careful adjustment of flame adjustment and the use of flux.

Natural gas is also used extensively in the chemical industry for the production of acetylene (C_2H_2), synthetic rubber, and plastics.

NAVAL BRASS

A copper-zinc alloy with a small amount of tin added to improve mechanical properties. Nominal composition: Cu—60.0, Zn—39.25, Sn—0.75. *See* COPPER ALLOY WELDING.

NEUTRON

An atomic particle found in the nucleus of an atom. It is electrically neutral; it has zero electrical charge.

NEGATIVE

In an external electrical circuit, the cathode, or point toward which the current flows; it is opposite to anode (positive).

NEGATIVE BRUSH

An electrical conductor made of copper strips or a block of carbon that makes sliding contact between a stationary and a moving part of a generator from which the current enters the armature; or in a motor, from which the current leaves the armature.

NEGATIVE POLARITY

In welding, the condition in which the electrode is negative in relation to the workpiece. Also called straight polarity. *See* DIRECT CURRENT ELECTRODE NEGATIVE (DCEN).

NEODYMIUM

(Chemical symbol: Nd). A metallic element belonging to the rare earth group.

Neodymium is used in the electronics industry. It is also used in the ceramics industry for glazes and to add color to glass. Neodymium glass can be used as a laser material instead of ruby. It has an atomic number of 60; atomic weight: 144.24; specific gravity: 7.003; melting point 1010°C (1850°F).

NEUTRAL FLAME

An oxyfuel gas flame that has characteristics neither oxidizing nor reducing. See STANDARD WELDING TERMS. *See* Figure A-1. *See also* CARBURIZING FLAME, OXIDIZING FLAME, *and* REDUCING FLAME.

A neutral flame is obtained by burning a mixture of approximately 50% acetylene and 50% oxygen; it is a well balanced flame indicating complete combustion. The cone next to the tip is white hot and beyond it is a long blue streamer. The molten metal produced in welding with a neutral flame is quiet and clean, and flows well. Few sparks are produced. *See* OXIDIZING FLAME, CARBURIZING FLAME, *and* ACETYLENE, Metalworking with Acetylene.

NEUTRAL FLUX, Submerged Arc Welding

A flux that will not cause a significant change in the weld metal composition when there is a large change in the arc voltage. See STANDARD WELDING TERMS. *See also* ACTIVE FLUX.

NICK-BREAK TEST

An impact test that can be made to provide preliminary visual inspection of the weld. Visual inspection of the broken section may reveal porosity, fracture mode, incomplete fusion, or any other defects which may be present.

A welder can use the nick-break test to check on a weld by making a test bar out of material similar to the metal being welded. If necessary, the test specimen may be cut directly out of the weld with a torch, and a new piece welded back in its place. As indicated in Figure N-3, the bar is nicked in the weld metal, 1/8 of its width on each side. It is preferable to make this nick or cut with a hacksaw, but if a hacksaw is not available, it can be made with a cutting torch.

A sharp blow with a hammer to the specimen held in a vise will break the weld metal from nick to nick. The hammer must be heavy and the blow sufficient to make a clean break. A visual inspection for defects can then be made.

The is used in welder performance testing to API 1104.

NICKEL

(Chemical symbol: Ni). A silvery white, hard, malleable, ductile metallic element, resistant to corrosion, used mainly in alloys and also as a catalyst. It is magnetic, a fair conductor of electricity, and belongs to the iron-cobalt group of elements. Atomic weight, 58.69; specific gravity, 8.90; melting point, 1453°C (2647°F).

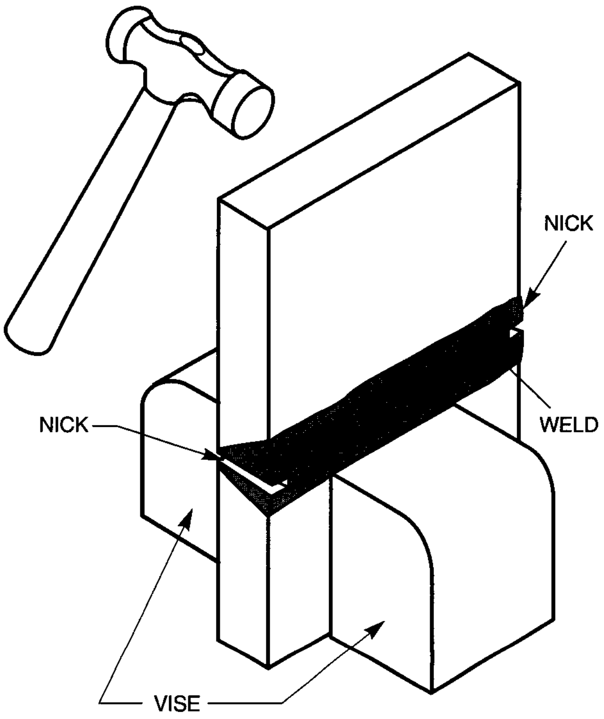


Figure N-3—Nick-Break Test

Nickel adds ductility when alloyed with steel, lowers the critical point for heat treatment, aids fatigue strength, and increases notch toughness.

Nickel is used as an alloying agent in steel to increase strength and toughness at low temperatures. Most nickel additions are from 1 to 4%, although in some applications, the nickel content runs as high as 36% or more. In all cases, the addition of nickel will increase the strength without decreasing the toughness of the steel. Steels with a nickel content of 24% have reduced magnetism. When the nickel content is increased to 36%, the steel has a very small coefficient of expansion due to heat (up to 482°C [900°F]).

NICKEL ALLOYS

Nickel alloys offer unique physical and mechanical properties and are useful in a variety of industrial applications, notably because of their resistance to attack in various corrosive media at temperatures from 200°C (400°F) to over 1090°C (2000°F), and their good low- and high-temperature mechanical strength.

In demanding industrial environments, nickel alloy welds must duplicate the attributes of the base metal to a very high degree. Welding, heat treating, and fabrication procedures should be established with this in mind. The chemical compositions of various nickel alloys are listed in Table N-1.

High-quality weldments are readily produced in nickel alloys by commonly used welding processes. Not all processes are applicable to every alloy; metallurgical characteristics or the unavailability of matching or suitable welding filler metals and fluxes may limit the choice of welding processes.

Welding procedures for nickel alloys are similar to those used for stainless steel, except the molten weld metal is more sluggish, requiring more accurate weld metal placement in the joint. Thermal expansion characteristics of nickel alloys approximate those of carbon steel and are more favorable than those of stainless steel. Thus, warping and distortion are not severe during welding.

The mechanical properties of nickel alloy base metals will vary depending on the amount of hot or cold work remaining in the finished form (sheet, plate, or tube). Some modification in the procedures may be needed if the base metal is not in the fully annealed condition.

In general, the properties of welded joints in fully annealed nickel alloys are comparable to those of the base metals. Postweld treatment is generally not needed to maintain or restore corrosion resistance in most nickel alloys. In most media, the corrosion resistance of the weld metal is similar to that of the base metal. Welds made on Ni-Mo alloy N10001 and Ni-Si cast alloys commonly are solution annealed after welding to restore corrosion resistance to the heat-affected zone (HAZ).

Over-alloyed filler metals are often used (sometimes in lieu of postweld heat treatment) to fabricate components for very aggressive corrosive environments. The over-matching composition offsets the effects of weld metal segregation when using a matching composition. Examples are the use of filler metal NiCrMo-3 products to weld the "super" stainless alloys, containing 4 to 28% molybdenum, and the use of filler metal NiCrMo-10 to fabricate components of the base metal Ni-Cr-Mo alloy C-276 (UNS N10276).

Postweld heat treatment may be required for precipitation hardening in specific alloys. Postweld stress relief may be necessary to avoid stress-corrosion cracking in applications involving hydrofluoric acid vapor or certain caustic solutions. For example, Ni-Cu alloy 400 (UNS N04400) immersed in hydrofluoric acid is not sensitive to stress-corrosion cracking, but it is when exposed to the aerated acid or the acid vapors.

The choice of welding process will be based on the following:

(1) Alloy to be welded
(2) Thickness of the base metal
(3) Design conditions of the structure (such as temperature, pressure, or type of stresses)
(4) Welding position
(5) Need for jigs and fixtures
(6) Service conditions and environments

Metal Characteristics

Nickel has a face-centered-cubic (FCC) structure up to its melting point. Nickel can be alloyed with a number of elements without forming detrimental phases. Nickel in some aspects bears a marked similarity to iron, its close neighbor in the periodic table. Nickel is only slightly denser than iron, and it has similar magnetic and mechanical properties. The crystalline structure of pure nickel at room temperature, however, is quite different from that of iron. Therefore, the metallurgy of nickel and nickel alloys differs from that of iron alloys.

Alloy Groups

Nickel alloys can be classified into four groups:

(1) Solid-solution-strengthened alloys
(2) Precipitation-hardened alloys
(3) Dispersion-strengthened alloys
(4) Cast alloys

Solid-Solution-Strengthened Alloys

All nickel alloys are strengthened by solid solution. Additions of aluminum, chromium, cobalt, copper, iron, molybdenum, titanium, tungsten, and vanadium contribute to solid-solution strengthening. Aluminum, chromium, molybdenum, and tungsten contribute strongly to solid-solution strengthening while others have a lesser effect. Molybdenum and tungsten improve strength at elevated temperatures.

Pure Nickel. Nickel 200 and the low-carbon version, nickel 201, are most widely used where welding is involved. Of these, the low-carbon nickel (201) is preferred for applications involving service exposure to temperatures above 315°C (600°F) because of its increased resistance to graphitization at elevated temperatures. This graphitization is the result of excess carbon being precipitated intergranularly in the temperature range of 315 to 760°C (600 to 1400°F) when nickel 200 is held there for extended time.

Table N-1
Nominal Chemical Composition of Typical Nickel Alloys

Alloy[a]	UNS Number	Composition, wt. %														
		Ni[b]	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Nb[c]	Mn	Si	W	B	Other
Commercially Pure Nickels																
200	N02200	99.5	0.08	—	—	0.2	—	0.1	—	—	—	0.2	0.2	—	—	—
201	N02201	99.5	0.01	—	—	0.2	—	0.1	—	—	—	0.2	0.2	—	—	—
205	N02205	99.5	0.08	—	—	0.1	—	0.08	—	0.03	—	0.2	0.08	—	—	0.05Mg
Solid-Solution Alloys																
400	N04400	66.5	0.2	—	—	1.2	—	31.5	—	—	—	1	0.2	—	—	—
404	N04404	54.5	0.08	—	—	0.2	—	44	0.03	—	—	0.05	0.05	—	—	—
R-405	N04405	66.5	0.2	—	—	1.2	—	31.5	—	—	—	0.1	0.02	—	—	—
X	N06002	47	0.10	22	9	18	1.5	—	—	—	—	1	1	0.6	—	—
NICR 80	N06003	76	0.1	20	—	1	—	—	—	—	—	2	1	—	—	—
NICR 60	N06004	57	0.1	16	—	bal.	—	—	—	—	—	1	1	—	—	—
G	N06007	44	0.1	22	6.5	20	2.5	2	—	—	2	1.5	1	1	—	—
IN 102	N06102	68	0.06	15	3	7	—	—	0.4	0.6	3	—	—	3	0.005	0.03Zr, 0.02Mg
RA 333	N06333	45	0.05	25	3	18	3	—	—	—	1	1.5	1.2	3	—	—
600	N06600	76	0.08	15.5	—	8	—	0.2	—	—	—	0.5	0.2	—	—	—
601	N06601	60 5	0.05	23	—	14	—	—	1.4	—	—	0.5	0.2	—	—	—
617	N06617	52	0.07	22	9	1.5	12.5	—	1.2	0.3	—	0.5	0.5	—	—	—
622	N06622	59	0.005	20.5	14.2	2.3	—	—	—	—	—	—	—	3.2	—	—
625	N06625	61	0.05	21.5	9	2.5	—	—	0.2	0.2	3.6	0.2	0.2	—	—	—
686	N06686	58	0.005	20.5	16.3	1.5	—	—	—	—	—	—	—	3.8	—	—
690	N06690	60	0.02	30	—	9	—	—	—	—	—	0.5[d]	0.5[d]	—	—	—
725	N07725	73	0.02	15.5	—	2.5	—	—	0.7	2.5	1.0	—	—	—	—	—
825	N08825	42	0.03	21.5	3	30	—	2.25	0.1	0.9	—	0.5	0.25	—	—	—
B	N10001	61	0.05	1	28	5	2.5	—	—	—	—	1	1	—	—	—
N	N10003	70	0.06	7	16.5	5	—	—	—	—	—	0.8	0.5	—	—	—
W	N10004	60	0.12	5	24.5	5.5	2.5	—	—	—	—	1	1	—	—	—
C-276	N10276	57	0.01[d]	15.5	16	5	2.5[d]	—	—	0.7[d]	—	1[d]	0.08[d]	4	—	0.35V[d]
C-22	N06022	56	0.010[d]	22	13	3	2.5[d]	—	—	—	—	0.5[d]	0.08[d]	3	—	0.35V[d]
B-2	N10665	69	0.01[d]	1[d]	28	2[d]	1[d]	—	—	—	—	1[d]	0.1[d]	—	—	—
C-4	N06455	65	0.01[d]	16	15.5	3[d]	2[d]	—	—	—	—	1[d]	0.08[d]	—	—	—
G-3	N06985	44	0.015[d]	22	7	19.5	5[d]	2.5	—	—	0.5[d]	1[d]	1[d]	1.5[d]	—	—
G30	N06030	43	0.03[d]	30	5.5	15	5[d]	2	—	—	1.5[d]	1.5[d]	1[d]	2.5	—	—
S	N06635	67	0.02[d]	16	15	3[d]	2[d]	—	0.25	—	—	0.5	0.4	1[d]	0 015[d]	0.02La
230	N06230	57	0.10	22	2	3[d]	5[d]	—	0.3	—	—	0.5	0.4	14	0 015[d]	0.02La
214	N07214	75	0.10	16	—	3	—	—	4.5	—	—	0.5[d]	0.2[d]	—	0.01[d]	0.01Y, 0.1Zr[d]
Precipitation-Hardenable Alloys																
301	N03301	96.5	0.15	—	—	0.3		0.13	4.4	0.6	—	0.25	0.5	—	—	—
K-500	N05500	66.5	0.10	—	—	1		29.5	2.7	0.6	—	0.08	0.2	—	—	—
Waspaloy	N07001	58	0.08	19.5	4	—	13.5	—	1.3	3	—	—	—	—	0.006	0.06Zr
R-41	N07041	55	0.10	19	10	1	10	—	1.5	3	—	0.05	0.1	—	0.005	—
80A	N07080	76	0.06	19.5	—	—	—	—	1.6	2.4	—	0.3	0.3	—	0.006	0.06Zr
90	N07090	59	0.07	19.5	—	—	16.5	—	1.5	2.5	—	0.3	0.3	—	0.003	0.06Zr
M 252	N07252	55	0.15	20	10	—	10	—	1	2.6	—	0.5	0.5	—	0.005	—
U-500	N07500	54	0.08	18	4	—	18.5	—	2.9	2.9	—	0.5	0.5	—	0.006	0.05Zr
713C[e]	N07713	74	0.12	12.5	4	—	—	—	6	0.8	2	—	—	—	0.012	0.10Zr
718	N07718	52.5	0.04	19	3	18.5	—	—	0.5	0.9	5.1	0.2	0.2	—	—	—
X750	N07750	73	0.04	15.5	—	7	—	—	0.7	2.5	1	0.5	0.2	—	—	—
706	N09706	41.5	0.03	16	—	40	—	—	0.2	1.8	2.9	0.2	0.2	—	—	—
901	N09901	42.5	0.05	12.5	—	36	6	—	0.2	2.8	—	0.1	0.1	—	0.015	—
C 902	N09902	42.2	0.03	5.3	—	48.5	—	—	0.6	2.6	—	0.4	0.5	—	—	—
IN 100[e]	N13100	60	0.18	10	3	—	15	—	5.5	4.7	—	—	—	—	0.014	0.06Zr, 1.0V
Dispersion-Strengthened Alloys																
TD Nickel	N03260	98	—	—	—	—	—	—	—	—	—	—	—	—	—	2 Th O_2
TD NICR	N00754	78	—	20	—	—	—	—	—	—	—	—	—	—	—	2 Th O_2

a. Several of these designations use parts of or are registered trade names. These and similar alloys may be known by other designations and trade names.
b. Includes small amount of cobalt, if cobalt content is not specified.
c. Includes tantalum (Nb+Ta).
d. Maximum value.
e. Casting alloys.

Major applications for the two alloys are food processing equipment, caustic handling equipment, laboratory crucibles, chemical shipping drums, and electrical and electronic parts.

Nickel-Copper Alloys. Nickel and copper form a continuous series of solid solutions with a face-centered-cubic crystal structure. The principal alloys in this group are alloy 400 and the free-machining version of it, R-405. These alloys have high strength and toughness, and they are important in industry primarily because of their corrosion resistance. The alloys have excellent resistance to sea or brackish water, chlorinated solvents, glass etching agents, sulfuric acids, and many other acids and alkalis.

Nickel-copper alloys are readily joined by welding, brazing, and soldering with proper precautions. To improve strength and to eliminate porosity in the weld metal, filler metals that differ somewhat in chemical composition from the base metal may be used. Welding without the addition of filler metal is not recommended for manual gas tungsten arc welding. Most automatic or mechanized welding procedures require the addition of filler metal, but a few do not.

Welding filler metals applicable to this alloy group are also widely used to weld copper alloys.

Nickel-Chromium Alloys. Nickel alloys 600, 601, 690, 214, 230, G-30, and RA-330 are commonly used. Alloy 600, which is the most widely used, has good corrosion resistance at elevated temperatures along with good high-temperature strength. Because of its resistance to chloride-ion stress-corrosion cracking, it finds wide use at all temperatures and has excellent room-temperature and cryogenic properties.

Precipitation-Hardenable Alloys

These alloys are strengthened by controlled heating, which precipitates a second phase known as *gamma prime*, from a supersaturated solution. Precipitation occurs upon reheating a solution-treated and quenched alloy to an appropriate temperature for a specified time. Each alloy will have an optimum thermal cycle to achieve maximum strength in the finished aged condition. Some cast alloys will age directly as the solidified casting cools in the mold.

The most important phase from a strengthening standpoint is the ordered face-centered-cubic gamma prime that is based upon the compound Ni_3Al. This phase has a high solubility for titanium and niobium; consequently, its composition will vary with the base-metal composition and temperature of formation. Aluminum has the greatest hardening potential, but this is moderated by titanium and niobium. Niobium has the greatest effect on decreasing the aging rate and improves weldability.

Nickel-Copper Alloys. The principal alloy in this group is K-500. Strict attention to heat-treating procedures must be followed to avoid strain-age cracking. Its corrosion resistance is similar to the solid-solution alloy 400. The alloy has been in commercial existence for well over 50 years and is routinely welded, using proper care, with the gas tungsten arc welding process. Weld metal properties using filler metals of matching composition seldom develop 100% joint efficiencies, thus a common consideration by the designer is to locate the weld in an area of low stress. ERNiFeCr-2 filler metal has been used to join this alloy, but an evaluation of service environment and the differing aging temperatures between the two alloys must be made. The base metal supplier should be consulted for recommendations for filler materials.

Dispersion-Strengthened Alloy

Nickel and nickel-chromium alloys can be strengthened to very high strength levels by the uniform dispersion of very fine refractory oxide (ThO_2) particles throughout the alloy matrix. This is done using powder metallurgy techniques during manufacture of the alloy. When these metals are fusion welded, the oxide particles agglomerate during solidification. This destroys the original strengthening afforded by dispersion within the matrix. The weld metal will be significantly weaker than the base metal. The high strength of these base metals can be retained with processes that do not involve melting the base metal. Contact the base metal supplier for recommendations for specific conditions.

Cast Alloys

Casting alloys, like wrought alloys, can be strengthened by solid-solution or precipitation hardening. Precipitation-hardening alloys high in aluminum content, such as alloy 713C, will harden during slow cooling in the mold and are considered unweldable by fusion processes. However, surface defects and service damage are frequently repaired by welding. It should be understood that a compromise is being made between the convenience of welding and the cast strength and ductility. Most nickel cast alloys will contain significant amounts of silicon to improve fluidity and castability. Most of these cast alloys are weldable by conventional means, but as the silicon content increases, so does weld-cracking sensitivity. This cracking sensitivity can be avoided using welding techniques that minimize base metal dilution.

Nickel castings that are considered unweldable by arc welding methods may be welded using the oxyacetylene process and a very high preheat temperature. Cast nickel alloys containing 30% copper are considered unweldable when the silicon exceeds 2% because of their sensitivity to cracking. However, when weldable grade castings are specified, weldability is quite good, and such welds will pass routine weld-metal inspections using methods such as radiography, liquid-penetrant testing, and pressure tests.

NICKEL ALLOYS, Weld Cladding

Nickel alloy weld metal is readily applied as cladding on carbon steels, low-alloy steels, and other base metals to increase the service life of the workpiece or to provide a corrosion-resistant surface. One of the benefits of this procedure, for example, is the cost saving realized by cladding a steel vessel with a thin corrosion-resistant layer of nickel alloy rather than making the whole vessel of nickel alloy.

Nickel-alloy cladding can be applied to cast iron, but a trial cladding should be made to determine whether standard procedures can be used. The casting skin, or cast surface, must be removed by a mechanical means such as grinding. Cladding on cast irons with high sulfur or phosphorus content may crack because of embrittlement by those elements. Cracking can often be eliminated by applying a barrier layer of AWS ENiFe-CI welding electrode or AWS ENiFeT3-CI cored wire. These filler metals were especially developed for welding cast iron, and the weld metal is more resistant to cracking caused by phosphorus, sulfur, and carbon dilution. When cladding is applied directly to cast iron without a barrier layer, amperage should be the minimum that provides proper arc characteristics in order to hold dilution at the lowest level.

Gas Metal Arc Cladding

Gas metal arc welding (GMAW) with spray transfer is successfully used to apply nickel-alloy cladding to steel. The cladding is usually produced with mechanized equipment and with weaving of the electrode. Argon is often used as the shielding gas. The addition of 15 to 25% helium, however, is beneficial for cladding with nickel and nickel-chromium-iron. Wider and flatter beads and reduced depth of fusion result as the helium content is increased to about 25%. Gas-flow rates are influenced by welding technique and will vary from 15 to 45 L/min (35 to 100 ft^3 /h). As welding current is increased, the weld pool will become larger and require larger gas nozzles for shielding. When weaving is used, a trailing shield may be necessary for adequate shielding. In any case, the nozzle should be large enough to deliver an adequate quantity of gas under low velocity to the welding area. Representative chemical compositions of automatic gas metal arc cladding are shown in Table N-2. The cladding in this table was produced with the following welding conditions:

(1) Torch gas, 24 L/min (50 ft^3 /h) argon
(2) Trailing shield gas, 24 L/min (50 ft^3 /h) argon
(3) Electrode extension, 19 mm (3/4 in.)
(4) Power source, DCEP
(5) Oscillation frequency, 70 cycles/min
(6) Bead overlap, 6 to 10 mm (1/4 to 3/8 in.)
(7) Travel speed, 110 mm/min (4-1/2 in./min)

When nickel-copper or copper-nickel cladding is to be applied to steel, a barrier layer of nickel filler metal ER61 must be applied first. Nickel weld metal will tolerate greater iron dilution without fissuring. When cladding is applied manually, the iron content of the first bead will be considerably higher than that of subsequent beads. The first bead should be applied at a reduced travel speed to dissipate much of the penetrating force of the arc in a large weld pool and reduce the iron content of the bead. The iron content of subsequent beads, as well as the surface contour of the cladding, can be controlled by elimination of weaving and maintaining the arc at the edge of the preceding bead. Such a procedure will result in a 50% overlap of beads, and the weld metal will wet the steel without excessive arc impingement. The welding gun should be inclined up to 5° toward the preceding bead so that the major force of the arc does not impinge on the steel.

Submerged Arc Cladding

The submerged arc welding (SAW) process produces high-quality nickel-alloy cladding on carbon steel and low-alloy steel. The process offers several advantages over gas metal arc cladding:

(1) High deposition rates, 35 to 50% increase with 1.6 mm (0.062 in.) diameter surfacing metal, and the ability to use larger electrodes.

(2) Fewer layers are required for a given cladding thickness. For example, with 1.6 mm (0.062 in.) surfacing metal, two layers applied by the submerged arc process have been found to be equivalent to three layers applied by the gas metal arc welding process.

(3) The welding arc is much less affected by minor process variations such as welding wire condition and electrical welding fluctuations.

Table N-2
Chemical Composition of Gas Metal Arc Cladding on Steel[a]

Surfacing Filler Metal	Current, A	Voltage, V	Layer	Chemical Composition of Weld Metal, wt. %											
				Ni	Fe	Cr	Cu	C	Mn	S	Si	Mg	Ti	Al	Nb+Ta
ERNi-1	280–290	27–28	1	71.6	25.5	—	—	0.12	0.28	0.005	0.32	—	2.08	0.06	—
			2	84.7	12.1	—	—	0.09	0.17	0.006	0.35	—	2.46	0.07	—
			3	94.9	1.7	—	—	0.06	0.09	0.003	0.37	—	2.76	0.08	—
ERNiCu-7[b]	280–300	27–29	2	66.3	7.8	—	19.9	0.06	2.81	0.003	0.84	0.008	2.19	0.05	—
			3	65.5	2.9	—	24.8	0.04	3.51	0.004	0.94	0.006	2.26	0.04	—
ERCuNi[b]	280–290	27–28	2	41.1	11.5	—	45.8	0.04	0.53	0.007	0.14	—	0.84	—	—
			3	35.6	3.1	—	60.1	0.01	0.61	0.006	0.08	—	0.43	—	—
ERNiCr-3	280–300	29–30	1	51.3	28.5	15.8	0.07	0.17	2.35	0.012	0.20	0.017	0.23	0.06	1.74
			2	68.0	8.8	18.9	0.06	0.040	2.67	0.008	0.12	0.015	0.30	0.06	2.27
			3	72.3	2.5	19.7	0.06	0.029	2.78	0.007	0.11	0.020	0.31	0.06	2.38

a. Automatic cladding with 1.6 mm (0.062 in.) diameter filler metal on SA 212 Grade B steel.
b. First layer applied with ERNi-1 filler metal.

(4) Welded surfaces of submerged arc cladding are smooth enough to be liquid-penetrant inspected with no special surface preparation other than wire brushing.

(5) Increased control provided by the submerged arc process yields fewer defects and requires fewer repairs.

Chemical compositions of specific submerged arc weld claddings are shown in Table N-3.

The power supply for all weld cladding applied using weaving techniques is direct current electrode negative (DCEN) with constant voltage. DCEN produces an arc with less depth of fusion, which reduces dilution. Direct current electrode positive (DCEP) results in improved arc stability and is used when stringer-bead cladding is needed to minimize the possibility of slag inclusions.

Shielded Metal Arc Cladding

Shielded metal arc cladding on cast and wrought steels is widely used for such applications as facings on vessel outlets and trim on valves. The procedures outlined for shielded metal arc joining should be followed, except that special care must be taken to control dilution of the cladding. Excessive dilution can result in weld metal that is crack sensitive or has reduced corrosion resistance. The amperage should be in the lower half of the recommended range for the electrode. The major force of the arc should be directed at the edge of the previous bead so that the weld metal will spread onto the steel with only minimum weaving of the electrode. If beads with feather edges are applied, more layers will be required, and the potential for excessive dilution will be greater. The weld interface contour of the cladding should be as smooth as possible. A scalloped weld interface contour can result in excessive iron dilution, with subsequent cracking as the weld specimen is subjected to a 180-degree longitudinal bend test.

Hot-Wire Plasma Arc Cladding

High-quality cladding can be produced at high deposition rates with the hot-wire plasma arc process. The process offers precise control of dilution, and dilution rates as low as 2% have been obtained. For optimum uniformity, however, a dilution rate in the 5 to 10% range is recommended. High deposition rates result from the use of two filler metal wires, which are resistance heated by a separate ac power source. The filler metal is in a nearly molten state before it enters the weld pool. Deposition rates for nickel-alloy weld metal are 16 to 18 kg/h (35 to 40 lb/h), approximately double those obtained with submerged arc weld cladding. Welding conditions for hot-wire plasma arc cladding are given in Table N-4.

Table N-3
Chemical Composition of Submerged Arc Cladding on Steel, wt. %*

Flux and Filler Metal	Layer	Ni	Fe	Cr	Cu	C	Mn	S	Si	Ti	Nb+Ta	Mo
Flux 4 and	1	63.6	12.5	17.00	—	0.07	2.95	0.008	0.40	0.15	3.4	—
ERNiCr-3	2	70.0	5.3	17.50	—	0.07	3.00	0.008	0.40	0.15	3.5	—
	3	71.5	2.6	18.75	—	0.07	3.05	0.008	0.40	0.15	3.5	—
Flux 5 and	1	60.6	12.0	—	21.0	0.06	5.00	0.014	0.90	0.45	—	—
ERNiCu-7	2	64.6	4.55	—	24.0	0.04	5.50	0.015	0.90	0.45	—	—
Flux 6 and												
ERNi-1	2	88.8	8.4	—	—	0.07	0.40	0.004	0.64	1.70	—	—
ERN9Cr-3	2	68.6	7.2	18.50	—	0.04	3.00	0.007	0.37	—	2.2	—
Flux 7 and												
ERNiCrMo-3	1	60.2	3.6	21.59	—	0.02	0.74	0.001	0.29	0.13	3.29	8.6

*Cladding on ASTM SA 212 Grade B steel applied by oscillating technique with 1.6 mm (0.062 in.) diameter filler metal.

Table N-4
Typical Conditions for Hot-Wire Plasma Arc Cladding

Characteristic	ERNiCu-7 Filler Metal	ERNiCr-3 Filler Metal
Filler metal diameter	1.6 mm (0.062 in.)	1.6 mm (0.062 in.)
Plasma arc power source	DCEN	DCEN
Plasma arc current	490 A	490 A
Plasma arc voltage	36 V	36 V
Hot-wire power source	AC	AC
Hot-wire current	200 A	175 A
Hot-wire voltage	17 V	24 V
Orifice gas and flow rate	75% He, 25% Ar; 26 L/min (55 ft^3/h)	75% He, 25% Ar; 26 L/min (55 ft^3/h)
Shielding gas and flow rate	Argon; 19 L/min (40 ft^3/h)	Argon; 19 L/min (40 ft^3/h)
Trailing shield gas and flow rate	Argon; 21 L/min (45 ft^3/h)	Argon; 21 L/min (45 ft^3/h)
Standoff distance	21 mm (13/16 in.)	21 mm (13/16 in.)
Travel speed	190 mm/min (7-1/2 in./min)	190 mm/min (7-1/2 in./min)
Weave width	38 mm (1-1/2 in.)	38 mm (1-1/2 in.)
Weave frequency	44 cycles/min	44 cycles/min
Bead width	50 mm (2 in.)	56 mm (2-3/16 in.)
Bead thickness	5 mm (3/16 in.)	5 mm (3/16 in.)
Deposit rate	18 kg/h (40 lb/h)	18 kg/h (40 lb/h)
Preheat temperature	120°C (250°F)	120°C (250°F)

Welding of Nickel Alloy Clad Steel

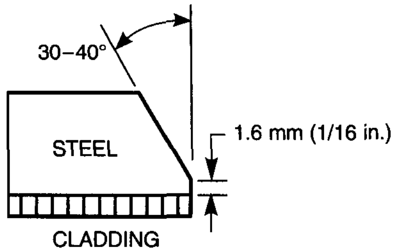
Steels clad with a nickel alloy are frequently joined by welding. Since the cladding is normally used for its corrosion resistance, the cladding alloy must be continuous over the entire surface of the structure, including the welded joints. This requirement influences joint design and welding procedure. Butt joints should be used when possible.

Figure N-4 shows recommended weld joint designs for two thickness ranges [see (A) and (B)]. Both designs include a small root face of unbeveled steel above the cladding to protect the cladding during welding of the steel. The steel side should be welded first with a low-hydrogen filler metal. It is important to avoid fusion of the cladding during the first welding pass.

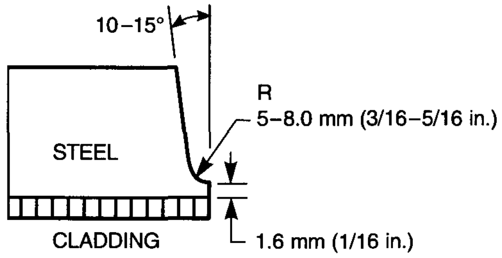
Dilution of the steel weld with the nickel-alloy cladding can cause cracking of the weld metal. The clad side of the joint should be prepared by grinding or chipping and welded with the filler metal recommended for cladding. The weld metal will be diluted with steel. To maintain corrosion resistance, at least two layers, and preferably three or more, should be applied.

The strip-back method is sometimes used instead of the procedure described above. The cladding is removed from the vicinity of the joint as shown in Figure N-4 (C). The steel is then welded using a standard joint design and technique for steel, and the nickel-alloy cladding is reapplied by weld cladding. The advantage of the strip-back method is that it eliminates the possibility of cracking caused by penetration of the steel weld metal into the cladding.

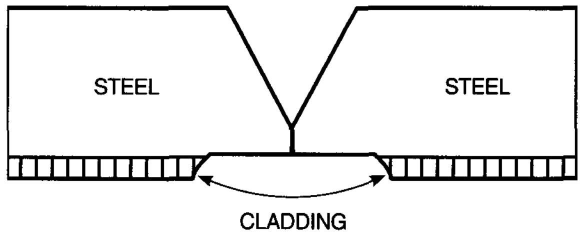
Some joints, such as those in closed vessels or tubular products, are accessible only from the steel side. In such cases, a standard joint design for steel is used, and the cladding at the bottom of the joint is welded first with nickel alloy weld metal. After the cladding is welded, the joint can be completed with the appropriate nickel alloy weld metal, or a barrier layer of carbon-free iron can be applied and the joint completed with steel weld metal. If the thickness of the steel is 8 mm (5/16 in.) or less, it is usually more economical to complete the joint with nickel alloy welding filler metal. Figure N-5 shows the most commonly used fabrication sequence when both sides are accessible.



(A) MATERIAL 4.8 TO 16 mm (3/16 TO 5/8 in.) THICK



(B) MATERIAL 16 TO 25 mm (5/8 TO 1 in.) THICK



(C) STRIP-BACK METHOD OF JOINT PREPARATION

Figure N-4—Joint Designs for Clad Steel

NICKEL ALLOY CUTTING

Nickel alloy plate can be successfully cut by any one of several thermal cutting processes: metal powder cutting (POC), air carbon arc cutting (CAC-A), plasma arc cutting (PAC), and laser beam cutting (LBC). Other processes used are abrasive cutting and machining, and water jet cutting.

Initially, metal powder cutting (POC), which employs an oxidizing powder with an oxyfuel torch, was the only thermal method used, but the process has been superseded. Plasma arc cutting (PAC) is the most widely used of the thermal cutting processes.

Plasma-Arc Cutting. Cutting with the plasma arc process is fast and versatile, and it produces high-quality cuts. High power concentration and gas velocity are required for cutting, so that the molten metal is blown out of the cut as the torch progresses.

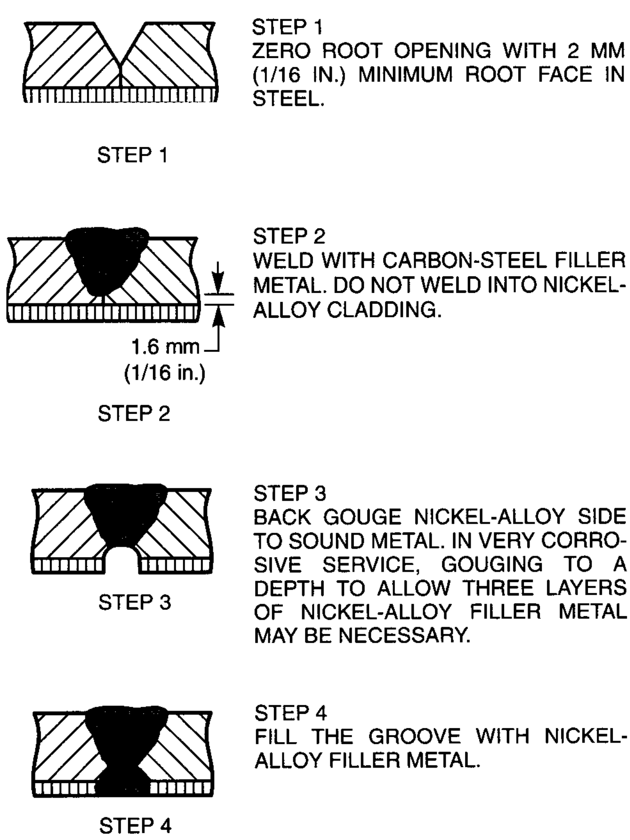


Figure N-5—Clad Metal Joint Design and Welding Fabrication Sequence When Both Sides of Joint are Accessible

Gases used for plasma cutting include argon-hydrogen mixtures, nitrogen-hydrogen mixtures, oxygen and nitrogen. The choice of gas depends on the application and the type of equipment used. The equipment manufacturer's recommendations should be followed.

Cuts up to 150 mm (6 in.) thick have been made in high-nickel alloys. Because of the constricted plasma jet and the speed of the process, heat-affected zones are usually only 0.25 to 0.4 mm (0.010 to 0.015 in.) wide. The cut surfaces of sections thinner than 75 mm (3 in.) are superior to those produced by the powder cutting process. They are similar to sheared edges but have less bevel. For many applications they can be welded without intermediate cleaning operations. Quality of cuts in heavy sections is about equal to that of cuts produced by powder cutting.

Air Carbon Arc Cutting (CAC-A). This process is more effective for gouging operations than for cutting and is widely used for back-gouging on welds and for the removal of fillet welds. By controlling the depth of the groove, limited thicknesses of material can be cut. Grooves up to 25 mm (1 in.) deep can be made in a single pass, but increments of 1 mm (0.004 in.) can also be removed. The width of the groove is determined primarily by the size of electrode. Torch angle and speed affect depth of the groove and the heat-affected zone.

Laser Beam Cutting (LBC). Laser beam cutting is a thermal cutting process that severs material by locally melting or vaporizing, with the heat generated by a laser beam. The process is used with or without assist gas to aid in the removal of molten and vaporized material.

Laser cutting has the advantage of high speeds, narrow kerf widths, high quality edges, low heat input, and minimum workpiece distortion. It is an easily automated process that can cut most metals.

Most nickel-base alloys are intended for some form of severe service, i.e., high temperatures or corrosive environments. While these metals are easily laser-cut, it is usually necessary to examine the workpiece for such metallurgical defects as micro-cracking and grain growth to ensure that the part will perform properly.

Water Jet Cutting. Water jet cutting severs metals and other hard materials using a high-velocity water jet. The water stream, with a flow rate of 0.4 to 19 L/min (0.8 to 40 ft^3/h is usually manipulated by a robot or gantry system, but small workpieces maybe guided past a stationary water jet by hand. Metals and other hard materials are cut by adding an abrasive in powder form to the water stream. Higher flow rates of water are required to accelerate the abrasive particles.

Materials are cut cleanly, without ragged edges, without heat, and generally faster than on a band saw. A smooth, narrow 0.8 to 2.5 mm (0.030 to 0.100 in.) kerf is produced. There is no problem of thermal delamination, or deformation, when water jet cutting is properly applied.

Metal Powder Cutting (POC). Metal powder cutting is based on the use of an oxygen jet into which finely divided powder is fed. The powder initiates an exothermic reaction that supplies the heat necessary for cutting. Nickel alloys can be readily cut with an iron powder or mixtures of iron and aluminum powders.

In powder cutting, considerable amounts of oxide and burned material accumulate on the metal, with the greatest buildup occurring on the top surface. This slag is more adherent on nickel-copper alloys than on nickel or nickel-chromium alloys. All adherent slag, powder or dross must be removed prior to any further operation.

The depth affected by heat from powder cutting is extremely shallow. Corrosion resistance of the metal is not impaired if all discoloration is removed.

Reference: American Welding Society, *Welding Handbook*, 8th Edition, Volume 2. Miami, Florida: American Welding Society, 1991.

NICKEL ALLOY WELDING

With minor modifications, the welding procedures used for joining steel are applicable to nickel alloys, such as nickel-copper, or nickel-chromium. Since a number of processes are capable of producing satisfactory joints, the selection can be determined by the following considerations:

(1) Corrosive environment to which the product will be exposed (to establish whether welding, silver brazing or soft soldering is applicable)

(2) Gauge of metal

(3) Design of the product

(4) Design of the individual joints in the product

Filler Metals and Fluxes

Covered Electrodes. In most cases, the weld metal composition from a covered electrode resembles that of the base metal with which it is used. Invariably, its chemical composition has been adjusted to satisfy weldability requirements; usually additions are made to control porosity, enhance micro cracking resistance, or improve mechanical properties. Covered electrodes normally have additions of deoxidizing ingredients such as titanium, manganese, and niobium. ANSI/AWS A5.11, Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding, is used almost universally in filler metal selection. Sometimes military specifications will apply, such as the MIL-E-22200 series, but they duplicate the AWS specification in most respects.

Fluxes. Fluxes are available for submerged arc welding of many nickel alloys. Fluxes, in addition to protecting the molten metal from atmospheric contamination, provide arc stability and contribute important additions to the weld metal. Therefore, the filler metal and the flux must be jointly compatible with the base metal. An improper flux can cause excessive slag adherence, weld cracking, inclusions, poor bead contour, and undesirable changes in weld metal composition. Fluxes used to weld carbon steel and stainless steel are not suitable.

Surface Preparation

Cleanliness is the single most important requirement for successful welding of nickel alloys. At high temperatures, these alloys are susceptible to embrittlement by many low-melting substances. Such substances are often found in materials used in normal manufacturing processes. Nickel alloys are embrittled by sulfur, phosphorus, and metals with low melting points such as lead, zinc, and tin. Lead hammers, solders, and wheels or belts loaded with these materials are frequent sources of contamination. Detrimental elements are often present in oils, paint, marking crayons, cutting fluids, and shop dirt.

Arc Welding

Nickel alloys are weldable by all the processes commonly used for steel and other base metals. Welded joints can be produced to stringent quality requirements in the precipitation-hardenable group, as well as the solid-solution group.

Applicable Processes. Some arc welding processes broadly applicable to nickel alloys are identified by individual alloy in Table N-5. Note that the shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) processes are not applicable to the welding of the precipitation-hardenable alloys. Covered electrodes for welding the age-hardenable alloys suffer from dramatically reduced mechanical properties of the weld and interbead slag adhesion, while the GMAW process results in high heat input, to which most of the age-hardenable alloys are sensitive.

Heat Input Limitations. High heat input during welding may produce undesirable changes in nickel alloys. Some degree of annealing and grain growth will take place in the heat-affected zone (HAZ). The heat input of the welding process and the preheat temperature will determine the extent of these changes. High heat input may result in excessive constitutional liquation, carbide precipitation, or other harmful metallurgical phenomena. These, in turn, may cause cracking or loss of corrosion resistance.

Gas Tungsten Arc Welding (GTAW)

Gas tungsten arc welding is widely used in the welding of nickel alloys, especially for the following applications:

(1) Thin base metal

(2) Root passes when the joint will not be back-welded

(3) When flux residues from the use of coated electrodes would be undesirable

Table N-5
Arc Welding Processes Applicable to Some Nickel Alloys

		Process[b]			
Alloy[a]	**UNS Number**	**SMAW**	**GTAW, PAW**	**GMAW**	**SAW**
		Commercially Pure Nickel			
200	N02200	X	X	X	X
201	N02201	X	X	X	X
		Solid-Solution Nickel Alloys (Fine Grain)[c]			
400	N04400	X	X	X	X
404	N04404	X	X	X	X
R-405	N04405	X	X	X	—
X	N06002	X	X	X	—
NICR 80	N06003	X	X	—	—
NICR 60	N06004	X	X	—	—
G	N06007	X	X	X	—
RA 333	N06333	—	X	—	—
600	N06600	X	X	X	X
601	N06601	X	X	X	X
625	N06625	X	X	X	X
20Cb3	N08020	X	X	X	X
800	N08800	X	X	X	X
825	N08825	X	X	X	—
B	N10001	X	X	X	—
C	N10002	X	X	X	—
N	N10003	X	X		
		Precipitation-Hardenable Nickel Alloys			
K-500	N05500	—	X	—	—
Waspaloy	N07001	—	X	—	—
R-41	N07041	—	X	—	—
80A	N07080	—	X	—	—
90	N07090	—	X	—	—
M 252	N07252	—	X	—	—
U-500	N07500	—	X	—	—
718	N07718	—	X	—	—
X-750	N07750	—	X	—	—
706	N09706	—	X	—	—
901	N09901	—	X	—	—

a. Several of these designations use parts of or are registered trade names. These and similar alloys may be known by other designations and trade names.

b. SMAW —Shielded metal arc welding
GTAW —Gas tungsten arc welding
PAW —Plasma arc welding
GMAW—Gas metal arc welding
SAW —Submerged arc welding

c. Fine grain is ASTM Number 5 or finer.

The GTAW and plasma arc welding processes are also the best joining processes for welding the precipitation-hardenable alloys.

Shielding Gases. The recommended shielding gas is helium, argon, or a mixture of the two. Small quantities of hydrogen (about 5%) may be added to argon for single-pass welds. The hydrogen addition produces a hotter arc because of its higher voltage gradient. However, hydrogen may cause porosity in multiple-pass welds with some alloys. The choice of shielding gas for arc characteristics and depth of fusion shape should be based on trial welding for the particular production weld.

Electrodes. Either pure tungsten or those alloyed with thorium, cerium or lanthanum may be used. A 2% alloyed electrode will give good results for most GTAW welding. The alloyed electrodes yield longer life, resulting from low vaporization of the electrode and cooler operation. It is important to avoid overheating the electrode through the use of excessive current. Arc stability is best when the tungsten electrode is ground to a flattened point. Cone angles of 30 to 60 degrees with a small flat apex are generally used. The point geometry, however, should be designed for the particular application and can vary from sharp to flat. With higher amperages, the use of a larger diameter flat area is often desirable. The shape of the electrode has an effect on the depth of fusion and bead width, with all other welding conditions being equal. Thus, the welding procedure should spell out its configuration.

Welding Current. The polarity recommended for both manual and mechanized welding is direct current electrode negative (DCEN). Frequently incorporated in the welding machine is a high-frequency circuit to enhance arc initiation and a current-decay unit to gradually decrease the size of the weld crater when breaking the arc.

Alternating current can be used for mechanized welding if the arc length is closely controlled. Superimposed high-frequency power is required for arc stabilization. High-frequency power is also useful with dc power to initiate the arc.

Filler Metals. Filler metals for the GTAW process are generally similar to the base metals with which they are used. However, a weld is a casting with an inherent dendritic structure, as opposed to the relative uniform grain size of the wrought base metal. Based on this knowledge, adjustments in chemical composition are frequently made to bring the base metal and weld metal properties into closer agreement.

Plasma Arc Welding (PAW)

Nickel alloys can be readily joined with the plasma arc welding process. The constricted arc permits greater depth of fusion than that obtainable with the gas tungsten arc, but the welding procedures with both processes are similar. Square-groove welds can be made in base metal up to about 8 mm (0.3 in.) thick with a single pass when keyhole welding is used. Thin base metal can be welded with melt-in welding, as with gas tungsten arc welding. Base metal over 8 mm (0.3-in.) thick can be welded using one of the other groove weld joint designs. The first pass can be made with keyhole welding and the succeeding passes with melt-in welding. The root face should be about 5 mm (0.18 in.) wide, compared to 2 mm (0.06 in.) for gas tungsten arc welding. Special techniques are required for keyhole welding of thicknesses of 3 mm (0.13 in.) and greater. Upslope of the orifice gas flow and the welding current is required to initiate the keyhole; downslope of these conditions is needed to fill the keyhole cavity at the end of the weld bead. Argon or argon-hydrogen mixtures are normally recommended for the orifice and shielding gases. Hydrogen addition to argon increases the arc energy for keyhole welding and high-speed autogenous welding. Additions up to 15% may be used, but these should be used with care because hydrogen can cause porosity in the weld metal. Therefore, the gas mixture for a specific application should be determined by appropriate tests.

Shielded Metal Arc Welding (SMAW)

This process is used primarily for welding nickel and solid-solution-strengthened alloys. These alloys are readily welded in all positions, with the same facility as steel. Welding techniques similar to those used in making high-quality welds in stainless steel should be used. Shallower depth of fusion and relatively sluggish molten weld metal require minor variations in technique. Shielded metal arc welding is seldom used to weld the precipitation-hardenable alloys. The alloying elements that contribute to precipitation hardening are difficult to transfer across the welding arc. Structures that are fabricated from these age-hardenable alloys are welded with better results by one of the gas-shielded processes. If this process is used to weld age-hardenable alloys, interpass bead cleaning to remove oxides is critical to making a sound weld. Also, joint efficiencies will be significantly lower than those made using the gas tungsten arc welding or plasma arc process.

Joint design will vary according to the material thickness and the joining process used. Because nickel-alloy weld metal does not spread readily, joints must be more open than those used for mild or low-alloy steels to permit manipulation of the filler metal and placement of the weld bead.

Preheat is generally not required. However, if the base metal temperature is cold, it is advisable to warm a 250 to 300 mm (10 to 12 in.) area surrounding the weld location to approximately 15 to 20°C (60 to 70°F) to prevent condensation.

Welding current should be kept as low as possible, consistent with smooth arc action. The best procedure is to follow the manufacturers recommendations for the particular electrode and materials being welded.

Postweld heat treatment is not needed to restore corrosion resistance of high-nickel alloys for most applications.

Weld slag removal is accomplished by scratching with the corner of a cold chisel and brushing with a stainless steel wire brush. Slag should be removed from each crater before making a re-strike, and completely removed before each pass in multi-pass welding.

Electrode diameters should be chosen for weld quality rather than for production speed. The size of the electrode should not be so large that it interferes with proper manipulation or results in excessive heat buildup.

Gas Metal Arc Welding (GMAW)

The gas metal arc welding process can be used to weld all the solid-solution nickel alloys except high-silicon castings, but it is an inferior choice of process for welding many of the age-hardenable alloys.

The dominant mode of metal transfer is spray transfer, but short circuiting and pulsed spray welding are widely employed. Spray transfer of filler metal is more economical because it uses higher welding currents and larger diameter welding wires, but the pulsed spray welding method using smaller welding wire and lower currents is more amenable to welding positions other than flat. Both methods are widely used in the production of low-dilution weld cladding on less corrosion-resistant base metal (such as carbon and low alloy steels).

Globular transfer is seldom used, because the erratic depth of fusion and uneven bead contour it produces are conducive to defect formation.

Shielding Gases. The protective atmosphere for GMAW is normally argon or argon mixed with helium. The optimum shielding gas will vary with the type of metal transfer used.

Using spray and globular transfer, good results are obtained with pure argon. The addition of helium, however, has been found to be beneficial. Increasing helium content leads to progressively wider and flatter beads and less depth of fusion. Used alone, helium tends to produce excessive spatter.

A shielding gas of oxygen or carbon dioxide added to the argon, a mixture commonly used to weld some base metals, should be avoided when welding nickel and cobalt alloys, because even small amounts will result in heavily oxidized and irregular bead faces. Such additions also cause severe porosity in nickel and nickel-copper alloys.

Filler Metals. Filler metals for the GMAW process are identical, almost without exception, to those used with the gas tungsten arc welding process.

Submerged Arc Welding (SAW)

The submerged arc welding process leaves as-welded surfaces ready for dye-penetrant inspection without machining, grinding, or other special preparation. Additional advantages of submerged-arc welding are that gas shielding problems and operator discomfort are virtually eliminated.

Filler metals and fluxes are available for submerged arc welding of several solid-solution nickel alloys. The process is not recommended for joining thick nickel-molybdenum alloys, because the high heat input and slow cooling rate of the weld results in low weld ductility and loss in corrosion resistance due to changes in chemical composition from flux reactions.

Because of its high deposition rate, the submerged arc process is an efficient method for joining thick base metal. Compared to other arc welding processes, bead surfaces are smoother, a proper flux will be self-peeling, and welding operator discomfort is less. The double-U-groove is the preferred design for all joints that permit its use. It can be completed in less time with less filler metal and flux, and yields lower residual welding stresses. Deposition rates for submerged arc welding for two filler metal and flux combinations are shown in Table N-6.

Fluxes. Submerged arc fluxes are available for several nickel alloys, and they are designed for use with a specific welding wire. Fluxes used to weld carbon steels and stainless steel are invariably unsuitable for welding nickel alloys. In addition to protecting the

Table N-6
Deposition Rates for Submerged Arc Welding for Specific Filler Metal and Flux Combinations

Filler Metal and Flux	Wire Diameter mm	Wire Diameter in.	Polarity	Deposition Rate kg/h	Deposition Rate lb/h
ERNiCr-3	1.6	1/16	DCEN	7.3–8.2	16–18
with Flux 4*	1.6	1/16	DCEP	6.4–7.7	14–17
	2.4	3/32	DCEN	9.1–9.5	20–21
	2.4	3/32	DCEP	7.3–7.7	16–17
ERNiCu-7	1.6	1/16	DCEN	7.3–7.7	16–17
with Flux 5*	1.6	1/16	DCEP	6.4–7.3	14–16
	2.4	3/32	DCEN	9.1–9.5	20–21
	2.4	3/32	DCEP	7.3–7.7	16–17

*Proprietary flux from Inco Alloys International, Inc. Weight of flux consumed is approximately equal to weight of filler metal.

molten metal from atmospheric contamination, the fluxes provide arc stability and contribute important additions to the weld metal.

The flux cover should be only sufficient to prevent the arc from breaking through. An excessive flux cover can cause deformed weld beads. Slag is easily removed and should be discarded, but unfused flux can be reclaimed. However, in order to maintain consistency in the flux particle size, reclaimed flux should be mixed with an equal amount of unused flux.

Submerged arc fluxes are chemical mixtures and can absorb moisture. Storage in a dry area and resealing opened containers are standard practice. Flux that has absorbed moisture can be reclaimed by heating. The flux manufacturer should be consulted for the recommended procedure.

Filler Metals. Submerged arc welding employs the same filler metals used with the gas tungsten arc welding and gas metal arc welding processes. Weld metal chemical composition will be somewhat different as additions are made through the flux to allow the use of higher currents and larger welding wires. Welding wire diameters are usually smaller than those used to weld carbon steels. For example, the maximum size used to weld thick base metal is 2.4 mm (3/32 in.), where 1.1 mm (0.045 in.) has been used to weld thin base metal.

Welding Current. Direct current electrode negative (DCEN) or direct current electrode positive (DCEP) may be used. DCEP is preferred for groove joints, yielding flatter beads and greater depth of fusion at low voltage (30 to 33V). DCEN is frequently used for weld surfacing, yielding higher deposition rates and reduced depth of penetration, thus reducing the amount of dilution from the base metal. However, DCEN requires a deeper flux cover and causes an increase in flux consumption. DCEN also increases the possibility of slag inclusions, especially in butt joints where the molten weld metal is thicker and solidification occurs from the sidewalls as well as the root of the weld.

Electron Beam Welding (EBW)

Some advantages of electron beam welding are:

(1) Single pass welds with nearly parallel sides can be made because of the high depth-to-width ratio and full penetration of EBW.

(2) The process is extremely efficient because it converts electrical energy directly to beam output energy.

(3) The heat input per unit length for a given depth of penetration is less than with arc welding. This results in a narrower heat-affected zone with its attendant lower distortion and adverse thermal effects.

(4) Rapid travel speeds are possible because of the high melting rates associated with the concentrated heat source. This increases productivity and efficiency by reducing welding time.

Joints that can be welded include: butt, corner, lap, edge, and T-joints. Normally, fillet welds are not attempted because they are difficult to make. Square butt welds require fixturing to maintain alignment and fit-up. Without the addition of filler metal, the fit-up is more critical than for arc welding. Poor fit-up will result in lack of fill in the joint. High quality welding requires cleanliness of the parts. Weld contamination can cause porosity and cracking along with a decrease in mechanical properties.

Usually, any metal or alloy that can be fusion welded by other welding processes can be joined by EBW. The weldability of a particular alloy or combination of alloys will depend on the metallurgical characteristics of that alloy or combination, the part configuration, joint design, process parameters and special welding procedure.

Laser Beam Welding (LBW)

Many of the nickel and nickel-based alloys have been successfully welded with laser beam welding. Welded joint cross sections are similar to those produced by an electron beam. Laser welding has the advantage of being done in the open, compared to the vacuum chamber required for electron beam. Some process limitations include the following:

(1) Positioning of the weld joint must be very closely controlled.

(2) Parts must be accurately clamped to assure alignment with the beam.

(3) Maximum joint thickness is commonly limited to 19 mm (0.75 in.).

(4) Because of rapid solidification, some porosity may be experienced. Workpiece cleanliness is of great importance because of possible weld contamination. Joint design is important because the laser beam must have access to the weld area.

Resistance Welding (RW)

This category includes spot, seam, and projection welding. The weld is made by the generation of heat at the faying surfaces of adjoining parts. Current is passed through the parts to be welded and the heat is generated by the resistance to the passage of current. The size and shape of the weld depends on a number of factors, some of which are: (1) the type of equipment being used, (2) the amount of current passing through the parts, (3) the length of time used to make the weld, (4) the cleanliness of the parts, and (5) the metallurgical characteristics of the materials being welded.

Generally, nickel-base alloys are readily weldable using resistance welding processes. Some cast precipitation-hardenable, low-ductility alloys can be difficult to weld without cracking. Because nickel-base alloys have high strength at elevated temperatures, high electrode forces are needed. Surface contaminants containing lead and sulfur must be removed prior to welding because these materials can cause embrittled welds. Occasionally, mechanical sticking of electrodes is encountered when welding pure nickel because of its high electrical conductivity. The values of welding currents used to join various nickel-based alloys are dependent on their resistivity and strength. As the resistivity (compared to low-carbon steel) increases, less current is required to make a satisfactory weld.

Oxyfuel Welding (OFW)

Oxyfuel welding is seldom used for welding nickel and nickel alloys. The selection of the method is determined not by the metal but by the physical characteristics of the piece to be welded: gauge of the metal, design of the workpiece and design of the individual joint. Good welding is accomplished with OFW in flat, vertical or overhead positions.

Generally, however, because OFW is slow, and because it requires fluxing and more heat input, it has been displaced by the GMAW and GTAW processes.

Welding Dissimilar Metals

Selecting the appropriate welding process and the filler metal requires careful consideration when joining dissimilar metals. The choice of both should be based on metallurgical factors such as differences in thermal expansion coefficients between the weld metal and base metal, the effects of dilution on the weld metal, and the possibility of changes in the structure of the materials after extended service at elevated temperatures.

The shielded metal arc welding process has the advantage in making dissimilar metal welds in that the amount of filler metal added is less influenced by welder technique than the GTAW or GMAW processes. In GTAW, the welder can vary filler metal addition to a very large degree.

The gas tungsten arc welding process permits more control over dilution than most other processes. The gas metal arc welding (GMAW) process is sometimes used for joining dissimilar metals, but the procedure must be carefully controlled to prevent excessive dilution. The submerged arc welding (SAW) process can also be used, but again, procedures must be controlled to avoid excessive dilution from the joint sidewall.

Filler Metals. A variety of materials can be welded using nickel alloy filler metals. Stainless and carbon steels, low-alloy steels, and high-nickel alloys are among the possibilities.

Either covered electrodes or bare filler metals are available and can be specified to suit equipment and skills. Some of the most commonly used electrodes are listed in ANSI/AWS A5.14, *Specification for Nickel and Nickel Alloy Bare Welding Rods and Electrodes;* and A5.11, *Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding.*

Welding 9% Nickel Steel

Nine percent nickel steel is generally specified for commercial applications in the production, handling, storage, and transportation of liquid gases, as well as related cryogenic applications. The following properties are required:

(1) High strength and toughness

(2) Resistance to embrittlement at temperatures as low as –196°C (–320°F)

(3) High stress allowances of pressure vessel designs

Electrodes and filler metals used to join 9% nickel steel are recommended in ANSI/AWS A5.14, *Specifications for Nickel and Nickel Alloy Bare Welding Rods and Electrodes,* and also in A5.11, *Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding.* Additional information can be found in the alloy manufacturer's literature.

Nickel Overlays

Weld overlays of high-nickel welding materials can be selectively applied to either large or small sections of tanks, shafts, rollers, tube sheets, vessels, valve seats, pumps, and other equipment made of various materials to increase the corrosion, heat, and wear resistance in harsh environments. Overlaying vulnerable equipment, old or new, can extend the service life of the equipment and provide easier maintenance. *See* NICKEL WELD CLADDING.

NICKEL SILVER

An alloy of copper, zinc and nickel. *See* COPPER ALLOY WELDING.

NICKEL STEEL

A steel alloyed with nickel to obtain characteristics such as high strength, toughness, corrosion resistance, and other properties of nickel. *See* STEEL, Alloy.

NIOBIUM

(Chemical symbol: Nb) A ductile metallic element used in alloys, tools and dies and superconductor magnets. Also known as columbium (Cb). It is used as a major alloying element in nickel-base, high-temperature alloys and as an important additive to high-strength structural steel. Atomic number, 41; atomic weight, 92.906; melting point, 2468°C (4474°F); specific gravity, 8.57 at 20°C (68°F).

NITRIDE OF IRON

A compound closely resembling cementite when etched, caused by the nitrogen of the air combining with iron at a very high temperature.

NITRIDING

A process by which certain steels can be surface hardened. The workpieces are placed in a nitriding box in a furnace. Ammonia gas is passed through the box and the furnace is kept at a temperature of about 510°C (950°F) for periods from two to ninety hours, depending on the depth of hardness required. *See* HEAT TREATMENT.

NITROGEN

(Chemical symbol: N). A gaseous element that occurs freely in nature and constitutes about 78% of the atmosphere. It is a colorless, odorless and relatively inert gas, although it combines directly with magnesium, lithium and calcium when heated with them. Nitrogen occurs in all living things as an essential element. When mixed with oxygen and subjected to electric sparks, it forms nitrogen peroxide. Atomic weight, 14.008; melting point, –210.5°C (–347°F); boiling point, –195°C (–319°F); specific gravity, 0.967 (air).

Nitrogen is produced either by liquefaction and fractional distillation of air, or by heating a water solution of ammonium nitrate (a mixture of ammonium chloride and sodium nitrite). For a description of the liquefaction process, see OXYGEN PRODUCTION.

NONBUTTING MEMBER

A joint member that is free to move in any direction perpendicular to its thickness dimension. For example, both members of a lap joint, or one member of a T-joint or corner joint. See STANDARD WELDING TERMS. *See* Figure B-15. *See also* BUTTING MEMBER.

NON-CONDUCTOR

A material which does not readily conduct electric current; an insulator.

NONCONSUMABLE ELECTRODE

An electrode that does not provide filler metal. See STANDARD WELDING TERMS.

NONCORROSIVE FLUX

A soldering flux that in either its original or residual form does not chemically attack the base metal. It usually is composed of rosin-base materials. See STANDARD WELDING TERMS.

NONDESTRUCTIVE EVALUATION

A nonstandard term for NONDESTRUCTIVE EXAMINATION.

NONDESTRUCTIVE EXAMINATION (NDE)

The act of determining the suitability of some material or component for its intended purpose using techniques that do not affect its serviceability. See STANDARD WELDING TERMS.

Nondestructive testing (NDT) and Nondestructive Inspection (NDI) are terms sometimes used interchangeably with NDE and are generally considered synonymous. Nondestructive examinations are performed on weldments to verify that the weld quality meets the specification, and to determine if weld quality is degraded during service.

Visual inspection should be the primary evaluation method of any quality control program. It can disclose flaws, signs of possible fabrication problems in subsequent operations, and can be incorporated in process control programs. Prompt and conscientious visual detection and correction of flaws or process deviations can result in significant cost savings, detecting continuities that would be found later by more expensive nondestructive examination methods.

All NDE methods must include the following to render valid examination results:

(1) A trained operator
(2) A procedure for conducting the tests
(3) A system for reporting the results
(4) A standard to interpret the results

The commonly used NDE methods that are applicable to the inspection of weldments are:

(1) Visual Inspection (VT) with or without optical aids
(2) Liquid penetrant (PT)
(3) Magnetic particle (MT)
(4) Radiographic inspection (RI)
(5) Eddy current (ET)
(6) Ultrasonic (UT)
(7) Acoustic emission (AET)

There are other NDE methods, such as heat transfer and ferrite testing, that are used for special cases. The considerations generally used in selecting an NDE method for welds are summarized in Table N-7. *See also* PENETRANT TESTING, MAGNETIC PARTICLE INSPECTION, METALLOGRAPHY, RADIOGRAPHIC EXAMINATION, *and* ULTRASONIC TESTING.

Reference documents on NDE include the following: American Society for Nondestructive Testing (ASNT) No. SNT-TC-1A, *Personnel Qualifications and Certification in Nondestructive Testing*, American Society for Nondestructive Testing, Columbus, Ohio.

American Welding Society, B1.0, *Guide for the Nondestructive Inspection of Welds*. American Welding Society, Miami, Florida, (latest edition).

NONDESTRUCTIVE INSPECTION

A nonstandard term for NONDESTRUCTIVE EXAMINATION.

NONDESTRUCTIVE TESTING

A nonstandard term for NONDESTRUCTIVE EXAMINATION.

NONFERROUS

Metals containing no ferrite, or iron. Copper, brass, bronze, aluminum and lead are among the non-ferrous metals most commonly used in industrial production.

NONMAGNETIC

Materials that do not produce a field of force and are not attracted by iron.

NON-INDUCTIVE

A material having little or no inductance.

NONPRESSURE WELDING

A group of welding processes in which the weld is made without pressure, i.e. arc, gas and thermite welding.

NON-RIGID JOINT

A joint designed so that the parts are free to move and absorb the stresses during welding. *See* RIGID JOINT.

NONSYNCHRONOUS INITIATION

The closing of a resistance welding contactor without regard to the voltage wave form pattern. See STANDARD WELDING TERMS.

NONSYNCHRONOUS TIMING

A nonstandard term for NONSYNCHRONOUS INITIATION.

NONTRANSFERRED ARC

An arc established between the electrode and the constricting nozzle of the plasma arc torch or thermal spraying gun. The workpiece is not in the electrical circuit. See STANDARD WELDING TERMS. *See also* TRANSFERRED ARC.

NONVACUUM ELECTRON BEAM WELDING (EBW-NV)

An electron beam welding process variation in which welding is accomplished at atmospheric pressure. See STANDARD WELDING TERMS.

NORMALIZING

See ANNEALING.

NORMALIZING BY INDUCTION HYSTERESIS

See INDUCTION HEATING.

NORWAY IRON

A very pure low carbon iron made in Norway. Its purity and low carbon content made it especially desirable for welding rods, and in the early days of the

Table N-7
Nondestructive Testing Methods

Equipment Needs	Applications	Advantages	Limitations
Visual			
Magnifiers, color enhancement, projectors, other measurement equipment (i.e., rulers, micrometers, optical comparators, light source).	Welds which have discontinuities on the surface.	Economical, expedient, requires relatively little training and relatively little equipment for many applications.	Limited to external or surface conditions only. Limited to the visual acuity of the observer/inspector.
Radiography (Gamma)			
Gamma ray sources, gamma ray camera projectors, film holders, films, lead screens, film processing equipment, film viewers, exposure facilities, radiation monitoring equipment.	Most weld discontinuities including incomplete fusion, incomplete penetration, slag, as well as corrosion and fit-up defects, wall thickness dimensional evaluations.	Permanent record—enables review by parties at a later date. Gamma sources may be positioned inside of accessible objects, i.e., pipes, etc., for unusual technique radiographs. Energy efficient source requires no electrical energy for production of gamma rays.	Radiation is a safety hazard—requires special facilities or areas where radiation will be used and requires special monitoring of exposure levels and dosages to personnel. Sources (gamma) decay over their half-lives and must be periodically replaced. Gamma sources have a constant energy of output (wavelength) and cannot be adjusted. Gamma source and related licensing requirements are expensive. Radiography requires highly skilled operating and interpretive personnel.
Radiography (X-Rays)			
X-ray sources (machines) electrical power source, same general equipment as used with gamma sources (above).	Same application as above.	Adjustable energy levels, generally produces higher quality radiographs than gamma sources. Offers permanent record as with gamma radiography (above).	High initial cost of x-ray equipment. Not generally considered portable, radiation hazard as with gamma sources, skilled operational and interpretive personnel required.
Ultrasonic			
Pulse-echo instrument capable of exciting a piezoelectric material and generating ultrasonic energy within a test piece, and a suitable cathode ray tube scope capable of displaying the magnitudes of the reflected sound energy. Calibration standards, liquid couplant.	Most weld discontinuities including cracks, slag, inadequate penetration, incomplete fusion; lack of bond in brazing; thickness measurements.	Most sensitive to planar type discontinuities. Test results known immediately. Portable. Most ultrasonic flaw detectors do not require an electrical outlet. High penetration capability. Reference standards are required.	Surface conditions must be suitable for coupling to transducer. Couplant (liquid) required. Small welds and thin materials may be difficult to inspect. Reference standards are required. Requires a relatively skilled operator/inspector. The results of the inspection are usually reported by the operator on a preprinted form.

Table N-7 (Continued)
Nondestructive Testing Methods

Equipment Needs	Applications	Advantages	Limitations
		Magnetic Particle	
Prods, yokes, coils suitable for inducing magnetism into the test piece. Power source (electrical). Magnetic powders, some applications require special facilities and ultraviolet lights.	Most weld discontinuities open to the surface—some large voids slightly sub-surface. Most suitable for cracks.	Relatively economical and expedient. Inspection equipment is considered portable. Unlike dye penetrants, magnetic particle can detect some near surface discontinuities. Indications may be preserved on transparent tape.	Must be applied to ferro-magnetic materials. Parts must be clean before and after inspection. Thick coatings may mask rejectable indications. Some applications require parts to be demagnetized after inspection. Magnetic particle inspection requires use of electrical energy for most applications.
		Liquid Penetrant	
Fluorescent or visible (dye penetrant, developers, cleaners, solvents, emulsifiers, etc.). Suitable cleaning gear. Ultraviolet light source if fluorescent dye is used.	Weld discontinuities open to surface (i.e., cracks, porosity, seams).	May be used on all non-porous materials. Portable, relatively inexpensive equipment. Expedient inspection results. Results are easily interpreted. Requires no electrical energy except for light source. Indications may be further examined visually.	Surface films such as coatings, scale, smeared metal mask or hide rejectable defects. Bleed out from porous surfaces can also mask indications. Parts must be cleaned before and after inspection.
		Eddy Current	
An instrument capable of inducing electromagnetic fields within a test piece and sensing the resulting electrical currents (eddy) so induced with a suitable probe or detector. Calibrations standards.	Weld discontinuities open to the surface (i.e., cracks, porosity, incomplete fusion) as well as some subsurface inclusions. Alloy content, heat treatment variations, wall thickness.	Relatively expedient, low cost. Automation possible for symmetrical parts. No couplant required. Probe need not be in intimate contact with test piece.	Limited to conductive materials. Shallow depth of penetration. Some indications may be masked by part geometry due to sensitivity variations. Reference standard required.
		Acoustic Emission	
Emission sensors, amplifying electronics, signal processing electronics including frequency gates, filters. A suitable output system for evaluating the acoustic signal (audio monitor, visual monitor, counters, tape recorders, X-Y recorder).	Internal cracking in weld during cooling, crack initiation and growth rates.	Real time and continuous surveillance inspection. May be inspected remotely. Portability of inspection apparatus.	Requires the use of transducers coupled on the test part surface. Part must be in "use" or stressed. More ductile materials yield low amplitude emissions. Noise must be filtered out of the inspection system.

industry it was used almost exclusively for this purpose. The iron was imported from Norway in ingot form and drawn into wire in the United States.

NOZZLE

See STANDARD WELDING TERMS. *See* CONSTRICTING NOZZLE *and* GAS NOZZLE.

NOZZLE, Arc Spraying

A device at the exit end of the gun that directs the atomizing air or other gas. See STANDARD WELDING TERMS.

NOZZLE, Flame Spraying

A device at the exit end of the gun that directs and forms the flow shape of atomized spray particles and the accompanying air or other gases. See STANDARD WELDING TERMS.

NOZZLE ACCUMULATION

Filler metal or surfacing material deposited on the inner surface and on the exit end of the nozzle. See STANDARD WELDING TERMS.

NUCLEAR POWER PLANT

Since all of the major components of a nuclear power plant are joined by welding in accordance with Section III of the *ASME Pressure Vessel Code*, welding plays an important role in the delivery of nuclear power. Nuclear plant piping systems account for most of the welding, but it is also a major application in the reactors, steam generators, pressure vessels, and containment vessels, as well as the powerhouse structures; all are welded to specifications in Section III.

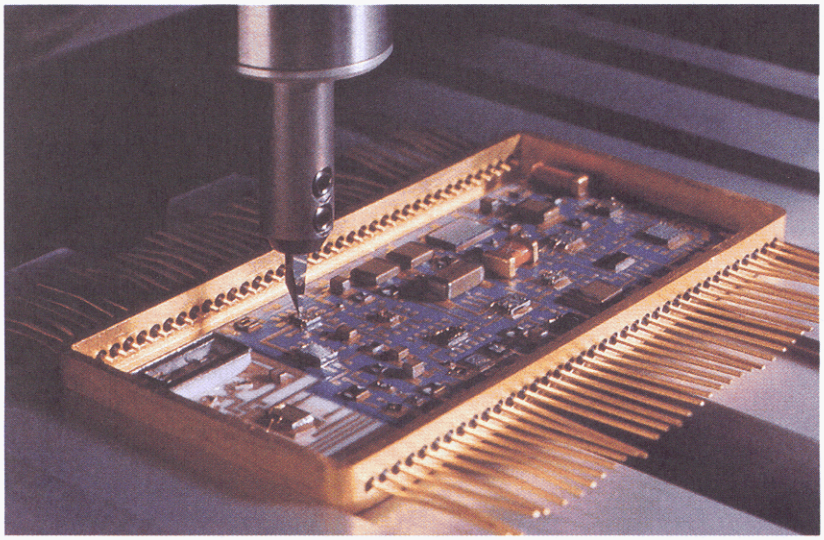
More engineering analysis, more care, and more safeguards are in place in the design and construction of nuclear plants than in any other method of power generation. The United States Nuclear Regulatory Commission is involved directly in the design, construction, licensing and operation of plants.

NUGGET

The weld metal joining the workpieces in spot, seam, or projection welds. See STANDARD WELDING TERMS.

NUGGET SIZE

A nonstandard term when used for resistance spot weld size.



Joining the minute connections in this electronic package is an example of microwelding. Paper-thin material and hair-like strands can be welded with laser beam and ultrasonic technology.

O

OCCLUSION

The chemical property of some metals to absorb gases and retain them, usually resulting in porosity in welds. Aluminum, iron and many other metals absorb hydrogen, oxygen and other gases in varying volumes, particularly when the metals are in molten or powder form. The real nature of metallic occlusions is unknown.

OFF TIME, Resistance Welding

The time during which the electrodes are off the workpieces. The term is generally used when the welding cycle is repetitive. See STANDARD WELDING TERMS. *See* Figure O-1.

OHM

A unit of electrical resistance. It is equal to the resistance of a circuit in which a potential difference of one volt produces a current of one ampere.

OHM'S LAW

The rule that gives the relation between current, voltage and the resistance of an electrical circuit. The voltage (E) is equal to the current (I) in amperes times resistance (R) in ohms, i.e. $E = I \times R$; or $R = E/I$.

1F, pipe

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat welding position by rotating the pipe about its axis. See STANDARD WELDING TERMS. *See also* Appendix 4, Figure 5.

1F, plate

A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the flat welding position. See STANDARD WELDING TERMS. *See also* Appendix 4, Figure 2.

1G, pipe

A welding test position designation for a circumferential groove weld applied to a joint in pipe, in which the weld is made in the flat welding position by rotating the pipe about its axis. See STANDARD WELDING TERMS. *See also* Appendix 4, Figure 4.

1G, plate

A welding test position designation for a linear groove weld applied to a joint in which the weld is

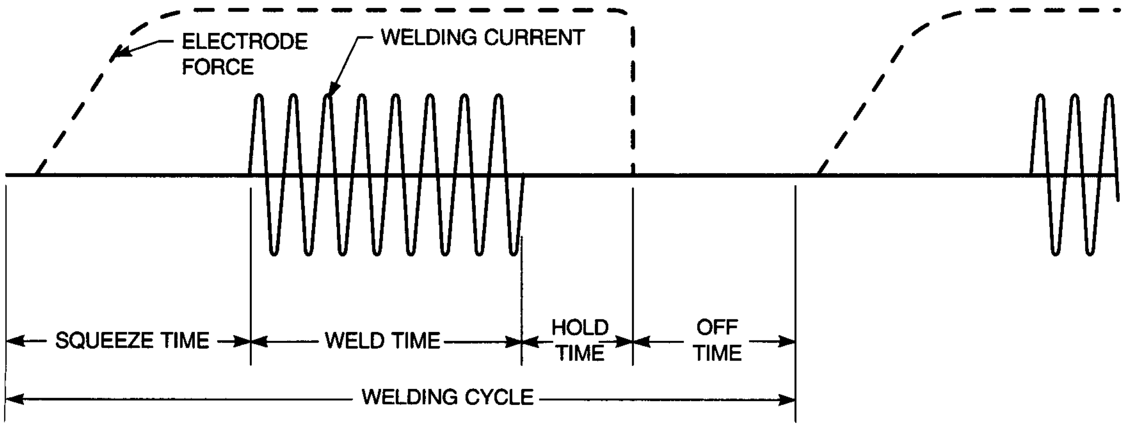


Figure O-1—Single-Impulse Resistance Spot Welding Schedule *made in the flat welding position. See* STANDARD WELDING TERMS. *See also* Appendix 4, Figure 1.

ONE SIDED ARC WELDING

A term generally applied to welding applications in which all of the filler metal is deposited from one side. The resulting welds are usually free of imperfections on the backside so that it should not be necessary to do any welding on the backside. Submerged arc welding (SAW) has been considered a "one-sided" method. For the most part, welding can be completed from one side, but sometimes there may be imperfections that necessitate back-chipping or gouging and welding on the underside.

OPEN BUTT JOINT

A nonstandard term for a butt joint with an open root.

OPEN CIRCUIT VOLTAGE

The voltage between the output terminals of the power source when no current is flowing to the torch or gun. See STANDARD WELDING TERMS.

OPEN GROOVE

A nonstandard term for OPEN ROOT JOINT.

OPEN HEARTH STEEL

Steel which has been manufactured by the open hearth process. In this process steel is smelted in a gas fired, regenerative furnace consisting of a shallow trough or hearth.

OPEN JOINT

A nonstandard term for OPEN ROOT JOINT.

OPEN ROOT JOINT

An unwelded joint without backing or consumable insert. See STANDARD WELDING TERMS.

OPTICAL PYROMETER

See PYROMETER.

ORBITAL WELDING

Orbital welding is a mechanized version of the gas tungsten arc welding (GTAW) process. In manual GTAW, the welder moves the welding torch and controls the welding current. In orbital GTAW, the tungsten is installed in a weld head that clamps on the tube or pipe. The tube remains in place while the weld head rotor revolves or orbits around the weld joint circumference to complete the weld.

The process may be used to produce autogenous welds (without the addition of filler materials), or filler may be added that becomes part of the finished weldment. The welding is done in an inert gas atmosphere to protect the metal from oxidation as it is heated to melting temperature. Gas metal arc welding (GMAW) may also be used for orbital welding.

Power Supplies. Orbital tube welding power supplies control weld parameters that typically include welding currents, background and pulse amperes (which determine the amount of heat input into the weld), travel speed (RPM), timers that control the amount of time at a particular setting, delay of rotation at the start of the weld, and a current downslope at the end of the weld.

A timed prepurge and postpurge are usually used to time the flow of inert gas into the weld head before arc initiation and to continue the purge for a timed period after the arc has been extinguished. This allows the weld to cool sufficiently to prevent oxidation before the weld head is opened to remove the welded tube.

Orbital tube welding is generally done autogenously, so additional controls used for wire feed are not required. Power supplies used for orbital tube welding generally supply 100 to 150 amperes of welding current, direct current, electrode negative.

Modern orbital tube welding power supplies are microprocessor-based. This permits the storage of weld programs or schedules for a large number of tube sizes. The programs can be written, entered into the power supply, and modified by the operator based on welding results, and programs can be changed without loss of other programs. The power supply may be able to print out the weld schedule or to interface with a computer for documentation of operational weld parameters.

Weld Heads. Weld heads for orbital tube welding typically span a range of sizes. For example, a weld head for tubing up to 38.1 mm (1-1/2 in.) outside diameter (OD) may also be able to weld tube measuring 6.4 mm (1/4 in.), 9.5 mm (3/8 in.), 12.7 mm (1/2 in.), 19.1 mm (3/4 in.), and 25.4 mm (1 in.).

Autogenous (fusion) tube welds are practical in diameters from 3.2 mm (0.125 in.) up to about 152 mm (6 in.) with wall thicknesses up to 4 mm (0.154 in.).

Standard orbital weld heads have tube clamp inserts on both sides of the weld to hold the tubes during welding, and the tungsten electrode is located in the rotor in the centerline of the head. To weld two tubes or fittings in a particular size weld head, the length of tubing or the straight section of the fitting must reach from the outside of the head to the electrode location in the weld head center. Reference: *Tube and Pipe Quarterly*, The Croydon Group, Ltd., Rockford, Ill. January/February, 1996.

ORIFICE

See CONSTRICTING ORIFICE. *See also* STANDARD WELDING TERMS.

ORIFICE GAS

The gas that is directed into the plasma arc torch or thermal spraying gun to surround the electrode. It becomes ionized in the arc to form the arc plasma, and issues from the constricting orifice of the nozzle as a plasma jet. See STANDARD WELDING TERMS. *See also* Appendix 10, Figure 1.

ORIFICE THROAT LENGTH

The length of the constricting orifice in the plasma arc torch or thermal spraying gun. See STANDARD WELDING TERMS. *See also* Appendix 10, Figure 1.

OSCILLATOR, ELECTRICAL

Any of various electronic devices that produce alternating electrical current, commonly employing tuned circuits and amplifying components.

OSCILLATOR, MECHANICAL

A mechanical device used to impart oscillatory motion to electrode holders, within limitations of stroke and amplitude in arc welding. It is used to meet a wide range of welding conditions, particularly in gas metal arc welding (GMAW).

Commercial units are available to linearly oscillate loads at frequencies of 30 to 240 cycles per minute, with infinite adjustments within this range and with running amplitude adjustment of from 0 to 18 mm (0 to 3/4 in.). Other oscillators are available in which the motion is that of a pendulum, with strokes up to 62 mm (2-1/2 in.) wide.

The types of motions imparted by oscillators are harmonic or uniform, or a combination, with dwell as required. The motions are produced by linkages or cams. The units are driven by electric motors and are controlled mechanically or by an electronic governor.

OSHA

The Occupational Safety and Health Act of 1970, known as Public Law 91-596, is the most far-reaching safety and health regulation ever enacted by the federal government. It became effective April 28, 1971. Most states also have an OSHA regulatory board that enforces safety and health regulations.

The Occupational Safety and Health Act provides the federal government with an instrument to support, encourage and carry forward into new areas the safety and health activities that American industry pioneered on a voluntary basis. Initially, the Act offered no new standards but has relied on accepted industry-developed standards. The responsibility is to build on what management, labor and government (state and national) have accomplished in job safety since the early years of this century.

The provisions of OSHA have had a great impact on employers and industry in observing specific safety and health standards. The following is required of employers:

(a) The employer must furnish to each employee, employment and a place of employment which is free from recognized hazards that are causing or likely to cause death or serious harm to these employees.

(b) Comply with the Occupational Safety and Health standards promulgated by this Act.

While the Act covers all industries and most employees, there are many areas that are of specific interest to welding. Much of the healthy and safety information available to the fabricator and consumer has originated with manufacturers of welding equipment and consumables, metals and materials, as well as the professional associations that support these groups. See Appendix ??.

OSMIUM

(Chemical Symbol: Os) A bluish-white, hard, crystalline metallic element belonging to the platinum family of elements. Discovered in 1803 by Tennant, it is used as a hardening alloy in platinum. Osmium is used for fine machine bearings, for pen points and instrument pivots. With iridium, it forms an alloy, osmiridium, which is used for making filaments in incandescent lamps. Atomic number: 76; atomic weight: 190.; melting point: 3000°C (5432°F); specific gravity: 22.48 at 20°C (68°F).

OVEN SOLDERING

A nonstandard term for FURNACE SOLDERING.

OVERHANG

A nonstandard term when used for EXTENSION.

OVERHEAD POSITION

See STANDARD WELDING TERMS. *See also* OVERHEAD WELDING POSITION.

OVERHEAD WELDING POSITION

The welding position in which welding is performed from the underside of the joint. See STANDARD WELDING TERMS. *See also* Appendix 4, Figures 1, 3, 4, *and* 6.

OVERHEAD WELD

A butt or fillet weld made by a fusion welding process with its linear direction horizontal or inclined to an angle less than 45° to the horizontal, the weld being made from the lower or under side of the parts joined. *See* WELDING POSITION.

OVERHEATING

A term applied to metals which have been heated to such high temperatures that grain growth is caused to occur, yet not heated sufficiently high to cause partial melting. In the case of steels, to which the term is usually applied, the overheated grain structure can be removed by normalizing.

OVERLAP

A nonstandard term when used for INCOMPLETE FUSION.

OVERLAP, Fusion Welding

The protrusion of weld metal beyond the weld toe or weld root. See STANDARD WELDING TERMS. *See also* Appendix 8, Figure 1-C.

OVERLAP, Resistance Seam Welding

The portion of the preceding weld nugget remelted by the succeeding weld. See STANDARD WELDING TERMS.

OVERLAYING

A nonstandard term when used for SURFACING.

OVERSPRAY, Thermal Spraying

The portion of the thermal spray deposit that is not deposited on the workpiece. See STANDARD WELDING TERMS.

OVERSTRESSING

A part is said to be over-stressed when an operating stress exceeds the limits of the metal and permanent deformation occurs. The effects of overstressing usually accompany plastic deformation. When occurring locally, such over-stressed parts may be the source of a fatigue crack if the operating stresses are of a repeated or fluctuating nature. Overstressing may be of a local or general nature.

OXIDATION

The combination of a substance with oxygen; the chemical reaction between oxygen and other elements resulting in oxides.

OXIDE, Weld Metal

Rust, corrosion coating, film, or scale. Oxygen combines with the metal and with impurities, and unless the oxide is removed by using an appropriate flux the weld will possibly be unsatisfactory.

OXIDIZING FLAME

An oxyfuel gas flame in which there is an excess of oxygen, resulting in an oxygen-rich zone extending around and beyond the cone. See STANDARD WELDING TERMS. *See also* Figure A-1(C), *and* CARBURIZING FLAME, NEUTRAL FLAME, *and* REDUCING FLAME.

OXYACETYLENE BORING

See OXYGEN LANCE.

OXYACETYLENE BRAZING

See COPPER ALLOY WELDING, *and* OXYACETYLENE WELDING.

OXYACETYLENE CUTTING (OFC-A)

An oxyfuel gas cutting process variation that uses acetylene as the fuel gas. See STANDARD WELDING TERMS. *See also* OXYFUEL GAS CUTTING.

OXYACETYLENE FLAME

The flame produced by the combustion of a mixture of oxygen and acetylene in various proportions. The proportions of these two gases affect the temperature of the flame; temperature is controlled by varying the ratio of oxygen to acetylene. *See* Table O-1, Oxyacetylene Flame Temperatures. *See also* CARBURIZING FLAME, NEUTRAL FLAME, OXIDIZING FLAME *and* REDUCING FLAME.

Historical Background

Le Chatelier is credited with discovering the oxygen-acetylene flame in 1895. This flame produces the highest flame temperature 3482°C (6300°F) known to mankind. It is the flame most commonly used in welding and cutting operations. The first oxyacetylene

Table O-1
Oxyacetylene Flame Temperatures

Ratio of Oxygen to Acetylene	Type of Flame	Temperature °C	Temperature °F
0.8 to 1.0	Carburizing	3065	5550
0.9 to 1.0	Carburizing	3150	5700
1.0 to 1.0	Neutral	3100	5600
1.5 to 1.0	Oxidizing	3427	6200
1.8 to 1.0	Oxidizing	3482	6300
2.0 to 1.0	Oxidizing	3370	6100
2.5 to 1.0	Oxidizing	3315	6000

torches were made by Fouche and Picard in 1900. *See* OXYACETYLENE WELDING.

OXYACETYLENE PRESSURE WELDING

See PRESSURE GAS WELDING (PGW).

OXYACETYLENE WELDING (OAW)

An oxyfuel gas welding process that uses acetylene as the fuel gas. The process is used without the application of pressure. See STANDARD WELDING TERMS.

Historical Background

By 1895, when Willson had established facilities to produce calcium carbide, acetylene became recognized as an important illuminating and heating gas. In about 1900, a Frenchman, Edmund Fouche, invented the oxyacetylene torch. It was a high-pressure torch which used a mixture of oxygen and acetylene, both available compressed in cylinders, the acetylene stabilized with acetone. Later, when Fouche changed jobs and went to work for a company which produced acetylene from low-pressure generators, Fouche designed a torch that would work on low fuel gas pressures. This torch received oxygen under high pressure, which entered the mixing chamber of the torch and drew acetylene from the acetylene orifice by the injector principle. These early torches incorporated the principles that are still used in modern low- and medium-pressure welding torches.

When Eugene Bournonville brought the first welding torch to the United States in 1906, welders began to find commercial applications for welding, and a major industry was started.

Acetylene is the fuel gas preferred for many oxyfuel welding applications because of its high-combustion intensity. Acetylene is a hydrocarbon compound, C_2H_2, which contains a larger percentage of carbon by weight than any of the other hydrocarbon fuel gases. Colorless and lighter than air, it has a distinctive odor resembling garlic. To stabilize acetylene in cylinders, it is dissolved in acetone; therefore it has a slightly different odor than pure acetylene.

At temperatures above 780°C (1435°F), or at pressures above 207 kPa (30 psig), gaseous acetylene is unstable, and even in the absence of oxygen, decomposition may result. This characteristic has been taken into consideration in the preparation of a code of safe practices for the generation, distribution, and use of acetylene gas. The accepted safe practice is never to use acetylene at pressures exceeding 103 kPa (15 psi) in generators, pipelines or hoses.

Theoretically, the complete combustion of acetylene is represented by the chemical equation:

$$C_2H_2 + 2.5\ O_2 \rightarrow 2CO_2 + H_2O \qquad \text{(Equation O-1)}$$

This equation indicates that one volume of acetylene (C_2H_2) and *2.5* volumes of oxygen (O_2) react to produce two volumes of carbon dioxide (CO_2) and one volume of water vapor (H_2O). The volumetric ratio of oxygen to acetylene is *2.5* to one.

Note that the reaction of this equation does not proceed directly to the end products shown. Combustion takes place in two stages. The primary reaction takes place in the inner zone of the flame (called the *inner cone*) and is represented by the chemical equation:

$$C_2H_2 + O_2 \rightarrow 2CO + H_2 \qquad \text{(Equation O-2)}$$

Here, one volume of acetylene and one volume of oxygen react to form two volumes of carbon monoxide and one volume of hydrogen. The heat content and high temperature of this reaction result from the decomposition of the acetylene and the partial oxidation of the carbon resulting from that decomposition. *See* Table O-2.

The Oxyacetylene Flame

When the gases issuing from the torch tip are in the one-to-one ratio indicated in Equation O-2, the reaction produces the typical brilliant blue inner cone in the flame. This relatively small flame creates the combustion intensity needed for welding steel. The flame is termed *neutral* because there is no excess carbon or oxygen to carburize or oxidize the metal. The end products are actually in a reducing status, a benefit when welding steel.

In the outer envelope of the flame, the carbon monoxide and hydrogen produced by the primary reaction burn with oxygen from the surrounding air. This forms

Table O-2
Properties of Common Fuel Gases

	Acetylene	Propane	Propylene	Methyl-acetylene-propadiene (MPS)	Natural Gas
Chemical Formula	C_2H_2	C_8H_8	C_3H_6	C_3H_4 (Methylacetylene, propadiene)	CH_4 (Methane)
Neutral flame temperature					
°F	5600	4580	5200	5200	4600
°C	3100	2520	2870	2870	2540
Primary flame heat emission					
btu/ft^3	507	255	433	517	11
MJ/m^3	19	10	16	20	0.4
Secondary flame heat emission					
btu/ft^3	963	2243	1938	1889	989
MJ/m^3	36	94	72	90	37
Total heat value (after vaporization)					
btu/ft^3	1470	2498	2371	2406	1000
mJ/m^3	55	104	88	90	37
Total heat value (after vaporization)					
btu/lb	21 500	21 800	21 100	21 100	23 900
kJ/kg	50 000	51 000	49 000	49 000	56 000
Total oxygen required (neutral flame)					
vol. O_2/vol. fuel	2.5	5.0	4.5	4.0	2.0
Oxygen supplied through torch (neutral flame)					
vol. O_2/vol. fuel	1.1	3.5	2.6	2.5	1.5
ft^3 oxygen/lb fuel (60°F)	16.0	30.3	23.0	22.1	35.4
m^3 oxygen/kg (15.6°C)	1.0	1.9	1.4	1.4	2.2
Maximum allowable regulator pressure					
psi	15	150	150	150	Line
kPa	103	1030	1030	1030	
Explosive limits in air: percent	2.5–80	2.3–9.5	2.0–10	3.4–10.8	5.3–14
Volume-to-weight ratio					
ft^3/lb (60°F)	14.6	8.66	8.9	8.85	23.6
m^3/kg (15.6°C)	0.91	0.54	0.55	0.55	1.4
Specific gravity of gas (60°F, 15.6°C) Air = 1	0.906	1.52	1.48	1.48	0.62

carbon dioxide and water vapor, as shown in the following secondary reaction:

$$2CO + H_2 + 1.5\ O_2 \rightarrow 2CO_2 + H_2O \quad \text{(Equation O-3)}$$

Although the heat of combustion of this outer flame is greater than that of the inner, its combustion intensity and temperature are lower because of its large cross-sectional area. The final end products are produced in the outer flame because they cannot exist in the high temperature of the inner cone.

The oxyacetylene flame is easily controlled by valves on the welding torch. By a slight change in the proportions of oxygen and acetylene flowing through the torch, the chemical characteristics in the inner zone of the flame and the resulting action of the inner cone on the molten metal can be varied over a wide range. Thus, by adjusting the torch valves, it is possible to produce a neutral, oxidizing, or carburizing flame.

Equipment

The minimum basic equipment needed to perform oxyfuel gas welding is shown schematically in Figure O-2. This equipment setup is completely self-sufficient and relatively inexpensive. It consists of fuel gas and oxygen cylinders, each with a gas regulator for reducing cylinder pressure, hoses for conveying the gases to the torch, and a torch and tip combination for adjusting the gas mixtures and producing the desired flame.

Welding Torches. A typical welding torch consists of a torch handle, mixer and tip assembly. It provides a means of independently controlling the flow of each gas, a method of attaching a variety of welding tips or other apparatus, and a convenient handle for controlling the movement and direction of the flame. Figure O-3 is a simplified schematic drawing of the basic elements of a welding torch.

The gases pass through the control valves, through separate passages in the torch handle, and to the torch head. They then pass into a mixer assembly where the oxygen and fuel gas are mixed, and finally pass out through an orifice at the end of the tip. The tip is shown as a simple tube, narrowed at the front end to produce a suitable welding cone. Sealing rings or surfaces are provided in the torch head or on the mixer seats to facilitate leak-tight assembly.

Torch Handles. Welding torch handles are manufactured in a variety of styles and sizes, from the small size for extremely light (low gas flow) work to the extra heavy (high gas flow) handles generally used for localized heating operations.

A typical small welding torch used for sheet metal welding will pass acetylene at volumetric rates ranging from about 0.007 to 1.0 m^3/h (0.25 to 35 ft^3/h). Medium sized torches are designed to provide acetylene flows from about 0.028 to 2.8 m^3/h (1 to 100 ft^3/h). Heavy-duty heating torches may permit acetylene

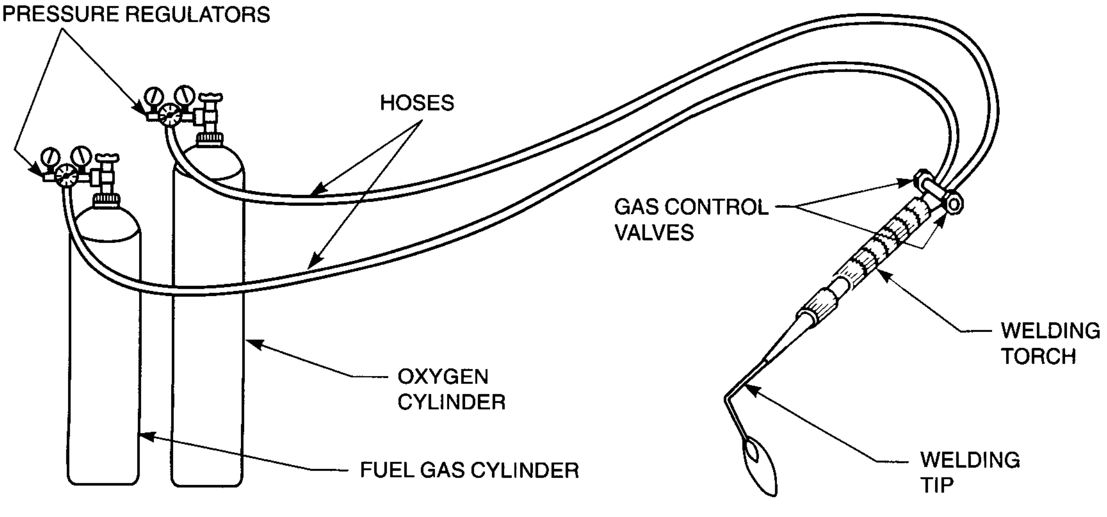


Figure O-2—Basic Oxyfuel Gas Welding Equipment

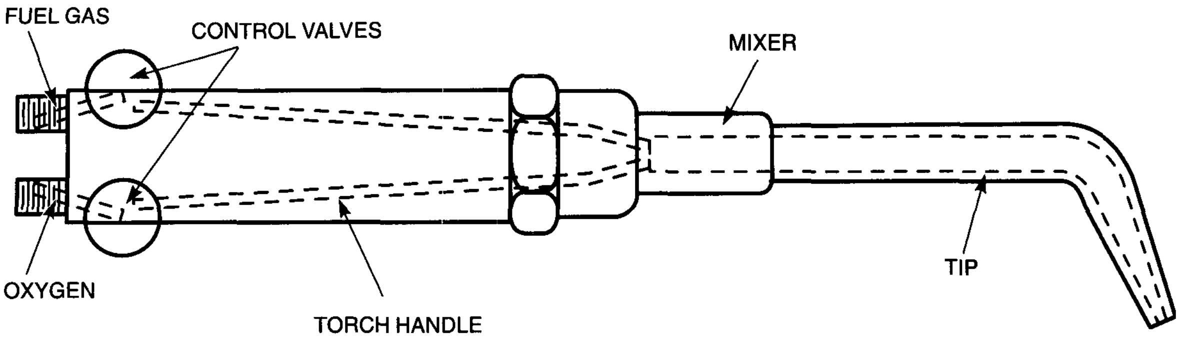


Figure O-3—Schematic Drawing of the Basic Parts of a Welding Torch

flows as high as 11 m^3/h (400 ft^3/h). Fuel gases other than acetylene may be used with even larger torches that have fuel-gas flow rates as high as 17 m^3/h (600 ft^3/h).

Mixers. The chief function of the mixer is to thoroughly mix the fuel gas and oxygen to assure smooth combustion. Another function of the mixer is to serve as a heat sink to help prevent the flame from flashing back into the mixer or torch.

Two general types of oxygen fuel-gas mixers are the *positive pressure* (also called *equal* or *medium-pressure*) and the *injector* or *low-pressure*. The positive pressure mixer requires the gases to be delivered to the torch at pressures above 14 kPa (2 psig). In the case of acetylene, the pressure should be between 14 and 103 kPa (2 and 15 psig). Oxygen is generally supplied at approximately the same pressure. There is, however, no restrictive limit on the oxygen pressure. It can range up to 172 kPa (25 psig) with the larger sized tips.

The purpose of the injector-type mixer is to increase the effective use of fuel gases supplied at pressures of 14 kPa (2 psig) or lower. In this torch, oxygen is supplied at pressures ranging from 70 to 275 kPa (10 to 40 psig), the pressure increasing to match the tip size. The relatively high velocity of the oxygen flow is used to aspirate, or draw in, more fuel gas than would normally flow at the low supply pressures.

Setting Up Equipment

It is essential that the operator follow the correct sequence in setting up equipment.

Connecting the Regulator. The first step is to slightly open the oxygen cylinder, then immediately close it. This is sometimes called "cracking the valve", which blows away any dust that might be in the cylinder valve nipple. The regulator is then connected to the cylinder, with the regulator adjustment screw turned fully counterclockwise. The valve should then be slowly opened. If the valve were opened suddenly, 13.8 MPa (2000 psi) of pressure would enter the regulator with a violent rush. If the regulator adjustment screw should happen to be screwed in, thus forcing the valve seat to the open position, it would be quickly and violently snapped back into the closed position, which might damage the seat or the nozzle, through which the oxygen passes. It is also possible under certain circumstances with certain types of regulators, to raise the temperature at the seat enough to ignite the hard rubber seat and thus create too much pressure in the regulator, damaging the gauges and the mechanism itself.

While the pressure in the acetylene cylinder is much lower than in the oxygen cylinder, and there is not the same likelihood of damage to the regulator, pressure should always be turned on slowly and carefully.

Hose Connections. Hoses should be connected to the outlet fittings of both regulators. The oxygen hose has right-hand threads on each end and the acetylene hose has left-hand fittings.

Torch Valves. Before connecting either hose line to the torch, it is important to check to see that both torch valves are closed. When the hose connections have been tightened and it has been determined that none of the joints leak, the correct size tip for the work should be screwed into the torch. The adjustment screw of the acetylene regulator should be turned to the right until the correct pressure of acetylene for the tip in use shows on the low-pressure gauge of the regulator. This is done with only the acetylene torch valve open; the oxygen torch valve remains closed. The acetylene torch valve is then closed.

The oxygen torch valve is opened and the adjustment screw of the oxygen regulator turned to the right until the correct pressure of oxygen for the tip in use is shown on the low-pressure gauge of the oxygen regulator. The oxygen torch valve is then closed. There is now pressure of both gases in the two hose lines, and in the torch up to the torch valves. To light the torch, the acetylene valve is opened and the acetylene lighted with a flint scratch lighter as it issues from the torch tip. The oxygen valve is then opened, permitting the oxygen pressure to enter the torch and burn with the acetylene at the tip, where it forms a luminous cone of flame. Further adjustment may now be made to assure that the flame is exactly neutral, and that the regulator pressures, when the torch valves are open and the flame is burning, are correct.

It is important to have regulators with two gauges, one showing the pressure of the gas in the cylinder, and the other showing the pressure of the gas in the hose line to the torch. These gauges should always be in good condition, and the regulator should never be used if the gauges are broken. Dangerous pressures can very easily develop in the hose lines if broken or inaccurate gauges are used.

Types of Torches. A number of different types of torches are available, designated by the relative pressures of the two gases. For example, the low-pressure or injector torch supplies acetylene to the torch at a pressure of less than 14 kPa (2 psi). This pressure is constant for most tip sizes. The oxygen pressure is considerably higher, ranging from 70 to 206 kPa (10 to 30 psi) or more, depending on the tip size. The tip is designed with an injector nozzle through which the oxygen passes, drawing the acetylene through the torch and to the mixing chamber in the tip. This necessitates a very small opening for the oxygen through the injector nozzle, and a much larger opening for acetylene adjacent to the mixing chamber because of the difference in the pressures of the two gases. Low-pressure torches are designed with unequal area inlets to the mixing chamber so that the oxygen pressure is often twice the acetylene pressure.

Equal pressure torches are those designed with equal area inlets to the mixing chamber of the tip for both oxygen and acetylene. Both gases are delivered from the regulators at equal pressures.

Another type of torch with an acetylene opening slightly smaller than the oxygen opening delivers the acetylene to the mixing chamber at a pressure slightly greater than the oxygen pressure.

All torches are designed to deliver one part oxygen through the torch for each part of acetylene entering through the acetylene passage. While it is true that 2-1/2 volumes of oxygen are required to completely consume one volume of acetylene, only one of these volumes is delivered through the torch, and burns at the tip of the torch to produce the luminous cone of flame, and the secondary reaction, the flame envelope. The remaining 1-1/2 parts of oxygen are obtained from the surrounding air.

Tip Size. Torch tips are interchangeable and are made in various sizes to produce large or smaller flames as may be required for the thickness of the workpiece. A very light sheet of steel, for example, requires a very small flame, hence a small tip, while a piece of 25 mm (1 in.) steel plate requires a much larger tip. The various sizes of tips deliver varying pressures of both oxygen and acetylene.

Some welders tend to increase the regulator pressure and adjust the torch valves to cut down the volume of gases which pass through the torch. This is not a good practice because it may lead to a careless adjustment of the flame. Accurate maintenance of a neutral, oxidizing, or carburizing torch flame, as required for the metal being welded, is important.

Auxiliary equipment includes protective clothing, helmet, goggles with protective lenses, and gloves. Before welding, it is imperative that the welding operator read and understand safety precautions related to oxyacetylene welding. *See* Appendix 11.

The Welding Process. Oxygen and acetylene are delivered through the hose lines to the torch, and are adjusted for either neutral, oxidizing, or carburizing flames, depending on the metal to be welded. The adjustment of the flame is probably the most critical condition of oxyacetylene welding. The welds are made by a torch (or blow pipe) flame to heat the workpiece to the melting point. Usually some new metal is added from a welding rod which is melted at the time and flowed together with the fused metal of the two edges of the joint. The temperature of the flame produced by the oxygen and acetylene delivered through the torch is in the range of 3200 to 3480°C (5800 to 6300°F).

The diameter of the welding rod to be used depends on the thickness of the workpiece. The rod maybe straight or bent to an angle as necessary. If the edges are to be beveled, the workpieces should be prepared with either a single or double V, forming a deep U shape, or in the case of sheet metal, flanging the edges upward. *See* BEVELING.

Welding proceeds either forward (away from the operator), or backward (toward the operator), depending on the required procedure. The motion of the torch depends on the operator; sometimes the flame is moved in a semi-circle and the rod straight back and forth immediately ahead of the flame in alternating motions.

Welding Rods. It is essential that the correct welding rod be used to insure weld integrity. The American Welding Society (AWS) filler metal specifications should be consulted for the recommended materials. Additionally, the manufacturer of the material to be welded, as well as the manufacturer of appropriate filler metals, are excellent sources of information concerning proper welding procedures and appropriate filler metals.

OXYACETYLENE WELDING TORCH

See OXYACETYLENE WELDING, Equipment.

OXYACETYLENE WELDING, Pressure

See PRESSURE GAS WELDING (PGW).

OXYFUEL GAS CUTTING (OFC)

A group of oxygen cutting processes that uses heat from an oxyfuel gas flame. See STANDARD WELDING TERMS. *See also* OXYACETYLENE CUTTING, OXYHYDROGEN CUTTING, OXYNATURAL GAS CUTTING, *and* OXYPROPANE CUTTING.

Oxyfuel gas cutting (OFC) processes sever or remove metal by the chemical reaction of oxygen with the metal at elevated temperatures. The necessary temperature is maintained by a flame of fuel gas burning in oxygen. In the case of oxidation resistant metals, the reaction is aided by adding chemical fluxes or metal powders to the cutting oxygen stream.

The process is known by various other names, such as burning, flame cutting, and flame machining. The actual cutting operation is performed by the oxygen stream. The oxygen-fuel gas flame is the mechanism used to raise the base metal to an acceptable preheat temperature range and to maintain the cutting operation.

The OFC torch is a versatile tool that can be readily taken to the work site. It is used to cut plates up to 2 m (7 ft) thick. Because the cutting oxygen jet has a 360° "cutting edge," it provides a rapid means of cutting both straight edges and curved shapes to required dimensions without expensive handling equipment. The cutting direction can be continuously changed during operation.

Principles of Operation

The oxyfuel gas cutting process employs a torch with a tip (nozzle). The functions of the torch are to produce preheat flames by mixing the gas and the oxygen in the correct proportions, and to supply a concentrated stream of high-purity oxygen to the reaction zone. The oxygen oxidizes hot metal and also blows the molten reaction products from the joint. The cutting torch mixes the fuel and oxygen for the preheating flames and aims the oxygen jet into the cut. The torch cutting tip contains a number of preheat flame ports and a center passage for the cutting oxygen.

The preheat flames are used to heat the metal to a temperature where the metal will react with the cutting oxygen. The oxygen jet rapidly oxidizes most of the metal in a narrow section to make the cut. Metal oxides and molten metal are expelled from the cut by the kinetic energy of the oxygen stream. Moving the torch across the workpiece at a specified rate produces a continuous cutting action. The torch may be moved manually or by a mechanized carriage.

The accuracy of a manual operation depends largely on the skill of the operator. Mechanized operation generally improves the accuracy and speed of the cut and the finish of the cut surfaces.

Kerf. When a piece is cut by an OFC process, a narrow width of metal is progressively removed. The width of the cut is called a *kerf,* as shown in Figure O-4. Control of the kerf is important in cutting operations where dimensional accuracy of the part and squareness of the cut edges are significant factors in quality control. With the OFC process, kerf width is a function of the size of tip used, speed of cutting, and flow rates of cutting oxygen and preheating gases. As material thickness increases, oxygen flow rates must usually be increased. Cutting tips with larger cutting oxygen ports are required to handle the higher flow rates. Consequently, the width of the kerf increases as the material thickness being cut increases.

Kerf width is especially important in shape cutting. Compensation must be made for kerf width in the layout of the work, or the design of the template. Gener-

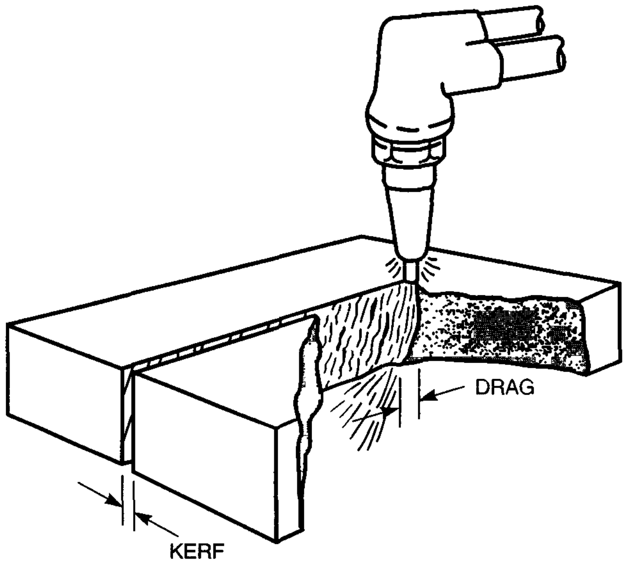


Figure O-4—Kerf and Drag in Oxyfuel Gas Cutting

ally, on materials up to 50 mm (2 in.) thick, kerf width can be maintained within +0.4 mm (+1/64 in.).

Drag. When the speed of the cutting torch is adjusted so that the oxygen stream enters the top of the kerf and exits from the bottom of the kerf along the axis of the tip, the cut will have zero drag. If the speed of cutting is increased, or if the oxygen flow is decreased, the oxygen available in the lower regions of the cut decreases. With less oxygen available, the oxidation reaction rate decreases, and also the oxygen jet has less energy to carry the reaction products out of the kerf. As a result, the most distant part of the cutting stream lags behind the portion nearest to the torch tip. The length of this lag, measured along the line of cut, is referred to as the *drag*. This is shown in Figure O-4.

Drag may also be expressed as a percentage of the cut thickness. A 10% drag means that the far side of the cut lags the near side of the cut by a distance equal to 10% of the material thickness.

An increase in cutting speed with no increase in oxygen flow usually results in a larger drag. This may cause a decrease in cut quality. There is also a strong possibility of loss of cut at excessive speeds. Reverse drag may occur when the cutting oxygen flow is too high or the travel speed is too low. Under these conditions, poor quality cuts usually result. Cutting stream lag caused by incorrect torch alignment is not considered to be drag.

Cutting speeds below those recommended for best quality cuts usually result in irregularities in the kerf. The oxygen stream inconsistently oxidizes and washes away additional material from each side of the cut. Excessive preheat flame results in undesirable melting and widening of the kerf at the top.

Chemistry of Oxyfuel Gas Cutting

The process of oxygen cutting is based on the characteristic of high-purity oxygen to combine rapidly with iron when it is heated to its ignition temperature, above 870°C (1600°F). The iron is rapidly oxidized by the high-purity oxygen and heat is liberated by several reactions.

The balanced chemical equations for these reactions are the following:

(1) $Fe + O \rightarrow FeO$ + heat (267 kJ), first reaction

(2) $3Fe + 2O_2 \rightarrow Fe_3O_4$ + heat (1120 kJ) second reaction

(3) $2Fe + 1.5\ O_2 \rightarrow Fe_2O_3$ + heat (825 kJ), third reaction

The tremendous heat release of the second reaction predominates over that of the first reaction, which is supplementary in most cutting applications. The third reaction occurs to some extent in heavier cutting applications. Stoichiometrically, 2.9 m^3 (104 ft^3) of oxygen will oxidize 1 kg (2.2 lb) of iron to Fe_3O_4.

In actual operations, the consumption of cutting oxygen per unit mass of iron varies with the thickness of the metal. Oxygen consumption per unit mass is higher than the ideal stoichiometric reaction for thicknesses less than approximately 40 mm (1-1/2 in.), and it is lower for greater thicknesses. For thicker sections, the oxygen consumption is lower than the ideal stoichiometric reaction because only part of the iron is completely oxidized to Fe_3O_4. Some oxidized or partly oxidized iron is removed by the kinetic energy of the rapidly moving oxygen stream.

Chemical analysis has shown that, in some instances, over 30% of the slag is unoxidized metal. The heat generated by the rapid oxidation of iron melts some of the iron adjacent to the reaction surface. This molten iron is swept away with the iron oxide by the force of the oxygen stream. The concurrent oxidizing reaction heats the layer of iron at the active cutting front.

The heat generated by the iron-oxygen reaction at the focal point of the cutting reaction (the hot spot) must be sufficient to continuously preheat the material to the ignition temperature. Allowing for the loss of heat by radiation and conduction, there is ample heat to sustain the reaction. In actual practice, the top surface of the material is frequently covered by mill scale or rust. That layer must be melted away by the preheat flames to expose a clean metal surface to the oxygen stream. Preheat flames help to sustain the cutting reaction by providing heat to the surface. They also shield the oxygen stream from turbulent interaction with air.

The alloying elements normally found in carbon steels are oxidized or dissolved in the slag without markedly interfering with the cutting process. When alloying elements are present in steel in appreciable amounts, their effect on the cutting process must be considered. Steels containing minor additions of oxidation resistant elements, such as nickel and chromium, can still be oxygen-cut. However, when oxidation resistant elements are present in large quantities, modifications to the cutting technique are required to sustain the cutting action. This is true for stainless steels.

Oxygen. Oxygen used for cutting operations should have a purity of 99.5% or higher. Lower purity reduces the efficiency of the cutting operation. A 1% decrease in oxygen purity to 98.5% will result in a decrease in cutting speed of approximately 15%, and an increase of about 25% in consumption of cutting oxygen. The quality of the cut will be impaired, and the amount and tenacity of the adhering slag will increase. With oxygen purity below 95%, the familiar cutting action disappears, and it becomes a melt-and-wash action that is usually unacceptable.

Preheating Fuels. Functions of the preheat flames in the cutting operation are the following:

(1) Raise the temperature of the steel to the ignition point

(2) Add heat energy to the work to maintain the cutting reaction

(3) Provide a protective shield between the cutting oxygen stream and the atmosphere

(4) Dislodge from the upper surface of the steel any rust, scale, paint, or other foreign substance that would stop or retard the normal forward progress of the cutting action

A preheat intensity that rapidly raises the steel to the ignition temperature will usually be adequate to maintain cutting action at high travel speeds. However, the quality of the cut will not be the best. High-quality cutting can be carried out at considerably lower preheat intensities than those normally required for rapid heating. On most larger cutting machines, dual range gas controls are provided that limit high-intensity preheating to the starting operation. Then the preheat flames are reduced to lower intensity during the cutting operation, to save fuel and oxygen and to provide a better cut surface.

A number of commercially available fuel gases are used with oxygen to provide the preheating flames. Some have proprietary compositions. Fuel gases are generally selected because of availability and cost. Properties of some commonly used fuel gases are listed in Table O-2. To understand the significance of the information in this table, it is necessary to understand some of the terms and concepts involved in the burning of fuel gas. *See* OXYFUEL GAS WELDING.

Fuel Selection

Combustion intensity or specific flame output for various fuel gases are important considerations in fuel gas selection. Some of the more common fuel gases used are: acetylene, natural gas, propane, hydrogen, propylene and methyl-acetylene propadiene.

Some of the factors to be considered when selecting a particular fuel gas are:

(1) The time required for preheating when starting cuts on square edges and rounded corners and also when piercing holes for cut starts.

(2) The effect on cutting speeds

(3) The effect on productivity

(4) The cost and availability of the fuel gases

(5) Volume of oxygen required per volume of fuel gas to obtain a neutral flame

(6) Safety in transporting and handling of gases

For best performance and safety, the torches and tips should be designed for the particular fuel selected.

Acetylene. Acetylene is widely used as a fuel gas for oxygen cutting and also for welding. Its chief advantages are availability, high flame temperature, and widespread familiarity with its flame characteristics among users.

Combustion of acetylene with oxygen produces a hot, short flame with a bright inner cone at each preheat port. The hottest point is at the end of this inner cone. Combustion is completed in the long outer flame. The sharp distinction between the two flames helps to adjust the oxygen-to-acetylene ratio for the desired flame characteristics.

Depending on this ratio, the flame may be adjusted to reducing (carburizing), neutral, or oxidizing, as shown in Figure A-1. The neutral flame, obtained with a ratio of approximately one part oxygen to one part acetylene, is used for manual cutting. As the oxygen flow is decreased, a light streamer begins to appear.

This indicates a reducing flame, which is sometimes used to rough-cut cast iron.

When excess oxygen is supplied, the inner flame cone shortens and becomes more intense. The flame temperature increases to a maximum at an oxygen-to-acetylene ratio of about 1.5 to 1. An oxidizing flame is used for short preheating times and for cutting very thick sections.

The high flame temperature and heat transfer characteristics of the oxyacetylene flame are particularly important for bevel cutting. These characteristics are also an advantage for operations in which the preheat time is an appreciable fraction of the total time for cutting, such as short cuts.

MPS Gas. MPS is a liquefied, stabilized, acetylene-like fuel that can be stored and handled similarly to liquid propane. MPS is a mixture of several hydrocarbons, including propadiene (allene), propane, butane, butadiene, and methylacetylene. Methylacetylene, like acetylene, is an unstable, high-energy, triple-bond compound. The other compounds in MPS dilute the methylacetylene sufficiently to make the mixture safe for handling. The mixture burns hotter than either propane or natural gas. It also affords a high release of energy in the primary flame cone, another characteristic similar to acetylene. The outer flame gives relatively high heat release, like propane and propylene. The overall heat distribution in the flame is the most even of any of the gases.

A neutral flame is achieved at a ratio of 2.5 parts of torch-supplied oxygen to 1 part MPS. Its maximum flame temperature is reached at a ratio of 3.5 parts of oxygen to 1 part of MPS. These ratios are used for the same cutting applications as the acetylene flame.

Although MPS gas is similar in many characteristics to acetylene, it requires about twice the volume of oxygen per volume of fuel for a neutral preheat flame. Thus, oxygen cost will be higher when MPS gas is used in place of acetylene for a specific job. To be competitive, the cost of MPS gas must be lower than acetylene for the job.

MPS gas does have an advantage over acetylene for underwater cutting in deep water. Because acetylene outlet pressure is limited to 207 kPa (30 psi) absolute, it usually is not applicable at depths below 6 m (20 ft) of water. MPS can be used there and at greater depths, as can hydrogen. For a particular underwater application, MPS, acetylene, and hydrogen should be evaluated for preheat fuel.

Natural Gas. The composition of natural gas varies depending on its source. Its main component is methane (CH_4). The ratio of torch-supplied oxygen to natural gas is 1.5 to 1 for a neutral flame. The flame temperature with natural gas is lower than with acetylene. It is also more diffused and less intense. The characteristics of the flame for carburizing, neutral, or oxidizing conditions are not as distinct as with the oxyacetylene flame.

Because of the lower flame temperature and the resulting lower heating efficiency, significantly greater quantities of natural gas and oxygen are required to produce heating rates equivalent to those of oxygen and acetylene. To compete with acetylene, the cost and availability of natural gas and oxygen, the higher gas consumptions, and the longer preheat times must be considered. The use of tips designed to provide a heavy preheat flame, or cutting machines that allow a high-low preheat setting, may compensate for deficiencies in the lower heat output of natural gas.

The torch and tip designs for natural gas are different from those for acetylene. The delivery pressure for natural gas is generally low and the combustion ratios are different. *See* Table O-2, Properties of Common Fuel Gases.

Propane. Propane is routinely used for oxygen cutting in a number of plants because of its availability and because it has a much higher total heat value (MJ/m^3) than natural gas (*see* Table O-2). For proper combustion during cutting, propane requires 4 to 4-1/2 times its volume of preheat oxygen. This requirement is offset somewhat by its higher heat value. Propane is stored in liquid form and is easily transported to the work site.

Propylene. Propylene, under many different brand names, is used as fuel gas for oxygen cutting. One volume of propylene requires 2.6 volumes of torch-supplied oxygen for a neutral flame, and 3.6 volumes for maximum flame temperature. Cutting tips are similar to those used for MPS.

Advantages and Disadvantages

Advantages. Oxyfuel gas cutting has a number of advantages and disadvantages compared to other metal cutting operations, such as sawing, milling, and arc cutting.

(1) Steels can generally be cut faster by OFC than by mechanical chip removal processes.

(2) Section shapes and thicknesses that are difficult to produce by mechanical means can be severed economically by OFC.

(3) Basic manual OFC equipment costs are low compared to machine tools.

(4) Manual OFC equipment is very portable and can be used in the field.

(5) Cutting direction can be changed rapidly on a small radius during operation.

(6) Large plates can be cut rapidly in place by moving the OFC torch rather than the plate.

(7) OFC is an economical method of plate edge preparation for bevel and groove weld joint designs.

Disadvantages. Following are several important disadvantages of oxyfuel gas cutting of metals:

(1) Dimensional tolerances are significantly poorer than machine tool capabilities.

(2) The process is essentially limited commercially to cutting steels and cast iron, although other readily oxidized metals, such as titanium, can be cut.

(3) The preheat flames and expelled red-hot slag present fire and burn hazards to plant and personnel.

(4) Fuel combustion and oxidation of the metal require proper fume control and adequate ventilation.

(5) Hardenable steels may require preheat, postheat, or both, adjacent to the cut edges to control their metallurgical structures and mechanical properties.

(6) Special process modifications are needed for OFC of high-alloy steels and cast irons.

Equipment

There are two basic types of OFC equipment: manual and machine. The manual equipment is used primarily for maintenance, for scrap cutting, cutting risers off castings and other operations that do not require a high degree of accuracy or a high quality cut surface. Machine cutting equipment is used for accurate, high quality work, and for large volume cutting, such as in steel fabricating shops. Both types of equipment operate on the same principle.

No one should attempt to operate any oxyfuel apparatus until trained in its proper use or under competent supervision. It is important to closely follow the manufacturer's recommendations and operating instructions for safe use. See Appendix ??. For more information on safe practices, refer to American Welding Society, Miami, Florida: *Welding Handbook*, Vol. 1, 8th Edition. American Welding Society, 1987.

Manual Equipment. A setup for manual OFC requires the following:

(1) One or more cutting torches suitable for the preheat fuel gas to be used and the range of material thicknesses to be cut

(2) Required torch cutting tips to cut a range of material thicknesses

(3) Oxygen and fuel gas hoses

(4) Oxygen and fuel gas pressure regulators

(5) Sources of oxygen and fuel gases to be used

(6) Flame strikers, eye protection, flame and heat resistant gloves and clothing, and safety devices

(7) Equipment operating instructions from the manufacturer

Torches. *See* OXYFUEL GAS CUTTING TORCH.

Manual Cutting Tips. Cutting tips are precision-machined copper-alloy parts of various designs and sizes. They are held in the cutting torch by a tip nut. All oxygen cutting tips have preheat flame ports, usually arranged in a circle around a central cutting oxygen orifice. The preheat flame ports and the cutting oxygen orifice are sized for the thickness range of metal that the tip is designed to cut. Cutting tips are designated as standard or high speed. Standard tips have a straight bore oxygen port, and they are usually used with oxygen pressures from 205 to 415 kPa (30 to 60 psi). High-speed tips differ from standard tips in that the exit end of the oxygen orifice flares out or diverges. The divergence allows the use of higher oxygen pressures, typically 415 to 690 kPa (60 to 100 psi), while maintaining a uniform oxygen jet at supersonic velocities. High-speed tips are ordinarily used for machine cutting only. They usually permit cutting at speeds approximately 20% greater than speeds available with standard tips. Both types of tips are shown in Figure O-5.

Gas Pressure Regulators. The ability to make successful cuts also requires a means of precisely regulating the specified gas pressures and volumes. Regulators are pressure control devices used to reduce high source pressures to required working pressures by manually adjusted pressure valves. They vary in design, performance, and convenience features. They are designed for use with specific types of gases and for definite pressure ranges.

Gas pressure regulators used for OFC are generally similar in design to those used for oxyfuel gas welding (OFW). Regulators for most other fuel gases are similar in design to acetylene regulators. For OFC, regulators with higher capacities and delivery pressure ranges than those used for OFW may be required for multi-torch operations and heavy cutting.

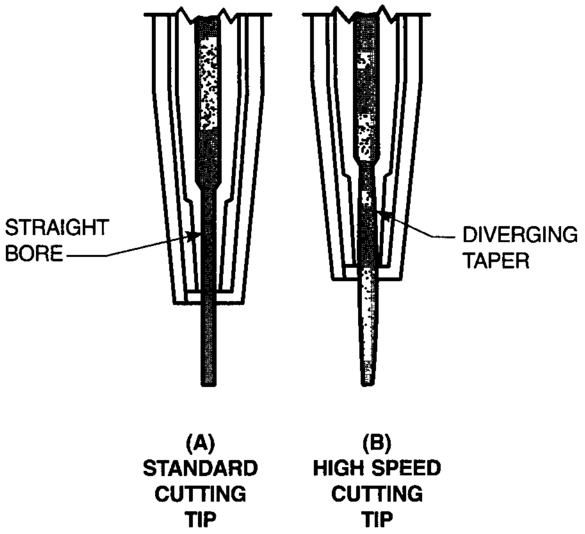


Figure O-5—Standard and High Speed Oxyfuel Gas Cutting Tips

Hoses and Other Equipment. Hoses and such equipment as tip cleaners, wrenches, and strikers used in OFC are the same as those used for OFW.

Safety. Tinted goggles or other appropriate eye protection devices are available in a number of different shades. All appropriate safety devices, including protective clothing, should be used. They are specified in Z49.1, *Safety in Welding, Cutting and Allied Processes,* published by the American Welding Society, Miami, Florida.

Mechanized Equipment

Mechanized OFC will require additional equipment, depending on the application:

(1) A machine to move one or more torches in the required cutting pattern

(2) Torch mounting and adjusting arrangements on the machine

(3) A cutting table to support the work

(4) Means for loading and unloading the cutting table

(5) Automatic preheat ignition devices for multiple torch machines

Mechanized OFC equipment can vary in complexity from simple hand-guided machines to very sophisticated computer-controlled units. The mechanized equipment is analogous to the manual equipment in principle, but differs in design to accommodate higher fuel pressures, faster cutting speeds, and means for starting the cut. Many machines are designed for special purposes, such as those for making vertical cuts, edge preparation for welding, and pipe cutting and beveling. Many variations of mechanized cutting systems are commercially available.

Machine Torches. A typical machine cutting torch consists of a barrel, similar to a manual torch but with heavier construction, and a cutting tip. *See* Figure O-6. *See also* OXYFUEL GAS CUTTING TORCH.

Machine Cutting Tips. Machine cutting tips are designed to operate at higher oxygen and fuel pressures than those normally used for manual cutting. The two-piece divergent bore tip is one type used for operation at high cutting speeds. Divergent bore cutting tips are based on the principles of gas flow through a venturi. High velocities are reached as the gas emerges from the venturi nozzle. Divergent bore cutting tips are precision machined to minimize any distortion of the gases when they exit from the nozzle. They are used for the majority of machine cutting applications because of their superior cutting characteristics for materials up to 150 mm (6 in.) thick. They are not recommended for cutting materials over 250 mm (10 in.) thick.

Cutting Machines. Oxyfuel gas cutting machines are either portable or stationary. Portable machines are usually moved to the work. Stationary machines are fixed in location and the work is moved to the machine.

Portable Machines. Portable cutting machines are primarily used for straight-line cutting, although they can be adapted to cut circles and shapes. Portable machines usually consist of a motor driven carriage with an adjustable mounting for the cutting torch. *See* Figure O-7. In most cases, the machine travels on a track, which performs the function of guiding the torch. The carriage speed is adjustable over a wide range. The degree of cutting precision depends on both the accuracy of the track, or guide, and the fit between the track and the driving wheels of the carriage. Portable machines are of various weights and sizes, depending on the type of work to be done. The smallest machines weigh only a few pounds. They are limited to carrying light-duty torches for cutting thin materials. Large, portable cutting machines are heavy and rugged. They can carry one or more heavy-duty torches and the necessary auxiliary equipment for cutting thick sections.

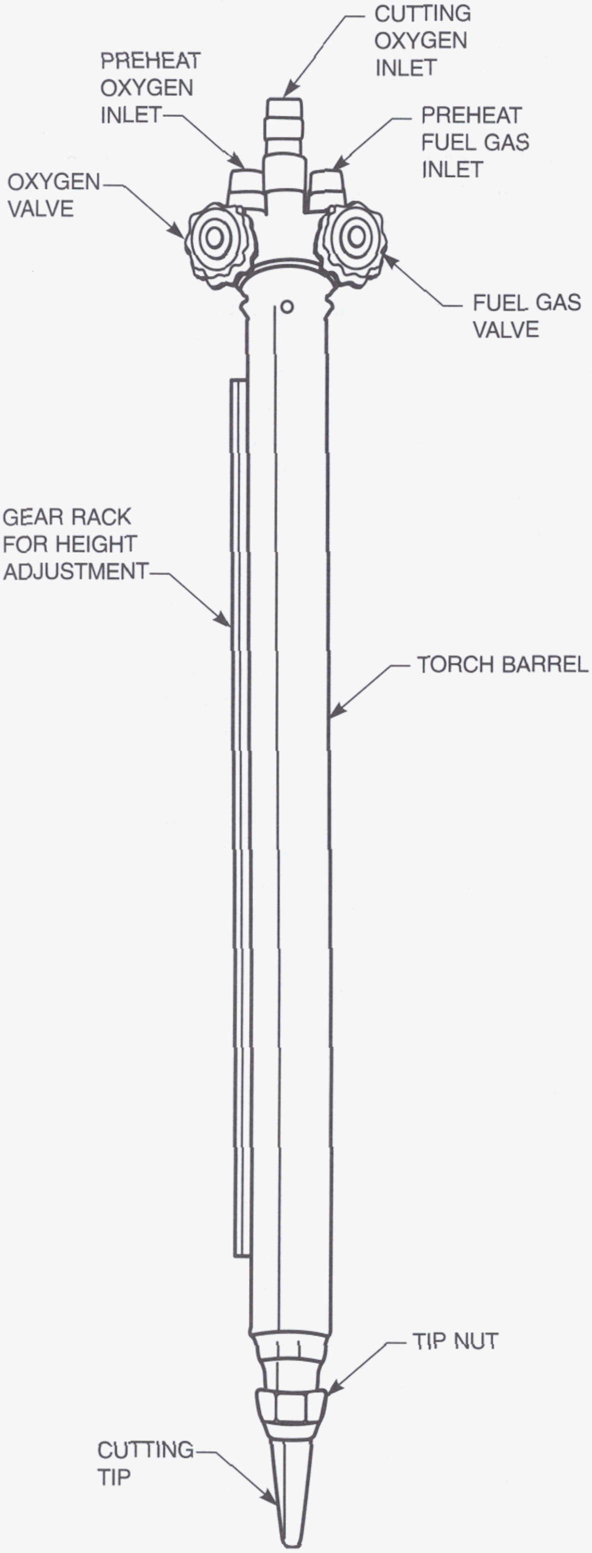


Figure O-6—Three Hose Machine Cutting Torch

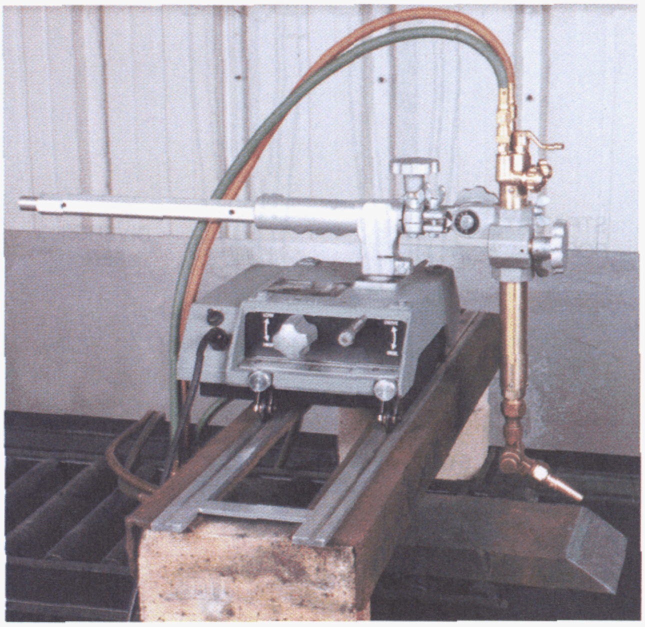


Figure O-7—Machine Cutting Torch Mounted on a Portable Carriage

Generally, the operator must follow the carriage to make adjustments, as required, to produce good quality cuts. The operator ignites the torch, positions it at the starting point, and initiates the cutting oxygen flow and carriage travel. The operator adjusts torch height to maintain the preheat flames at the correct distance from the work surface. At the completion of the cut, the operator shuts off the cutting torch and carriage.

Stationary Machines. Stationary machines are designed to remain in a single location. The raw material is moved to the machine, and the cut shapes are transported away. The work station is composed of the machine, a system to supply the oxygen and preheat fuel to the machine, and a material handling system.

The torch support carriage runs on tracks. The structure either spans the work with a gantry-type bridge across the tracks or it is cantilevered off to one side of the tracks. A gantry machine is shown in Figure O-8. Cutting machines are usually classified according to the width of plate that can be cut (transverse motion). The length that can be cut is the travel distance on the tracks. The maximum cutting length is dictated by physical limitations of gas and electric power supply lines. An operator station with consolidated controls for gas flow, torch movement and machine travel is generally a part of the machine.

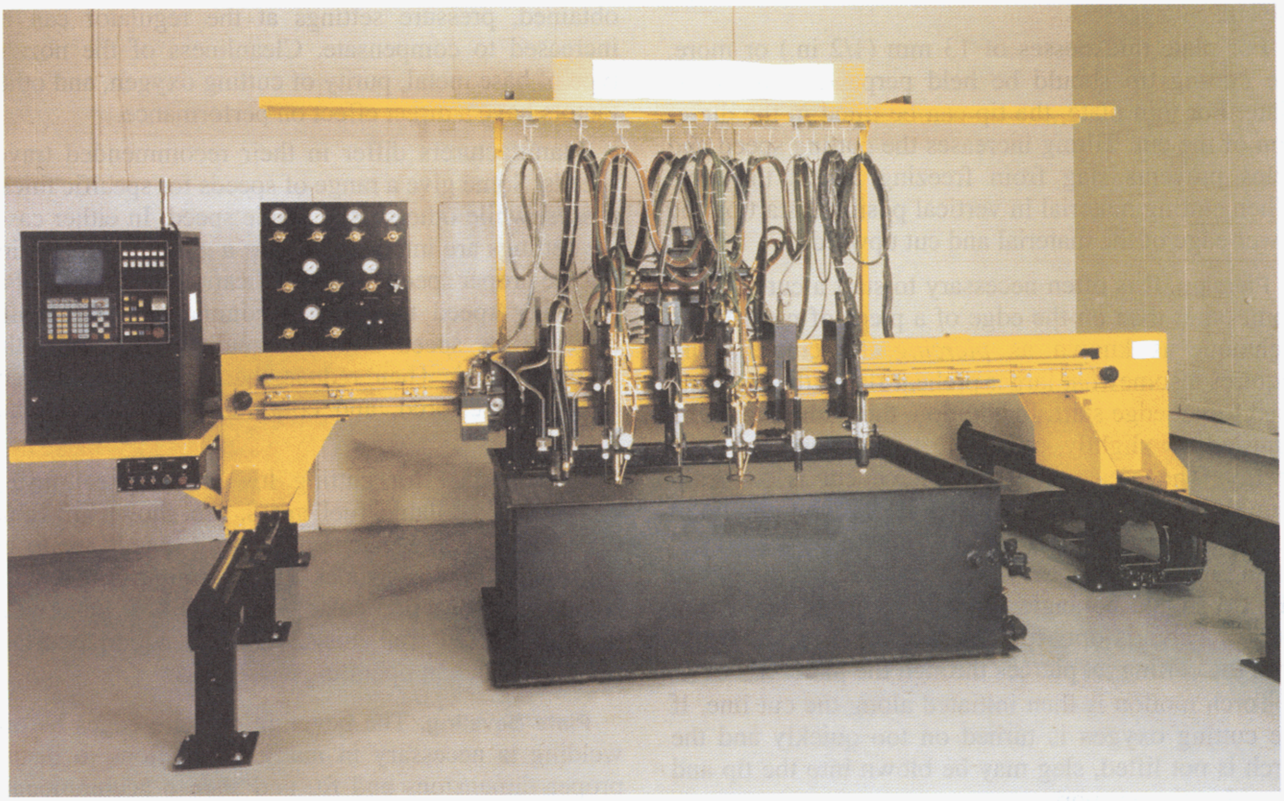


Figure O-8—Gantry Type Shape Cutting Machine with Computer Control

Shape Cutting

A number of torches can be mounted on a shape cutting machine, depending on the size of the machine. The machine can cut shapes of nearly any complexity and size. In multiple torch operations, several identical shapes can be cut simultaneously. The number depends on the part size, plate size and the number of available torches.

It is possible to feed information to the electric drive motors of the carriage and cross arm from any suitable control. One method uses a photoelectric cell tracer that can follow line drawings or silhouettes. Numerical control machines use profile programs placed on punched or magnetic tapes or computer disks. These storage devices, in turn, control the shape cutting by appropriate signals to the cutting machine drive motors.

Operating Procedures

In the operation of OFC equipment, the recommendations of the equipment manufacturer in assembling and using the equipment should always be closely followed. This will prevent damage to the equipment and also insure its proper and safe use.

Procedures

Starting a Cut. Several methods can be used to start a cut on an edge. The most common method is to place the preheat flames halfway over the edge, holding the end of the flame cones 1.5 to 3 mm (1/16 to 1/8 in.) above the surface of the material to be cut. The tip axis should be aligned with the plate edge. When the top corner reaches a reddish yellow color, the cutting oxygen valve is opened and the cutting process starts. Torch movement is started after the cutting action reaches the far side of the edge.

Another method is to put the tip entirely over the material to be cut. The preheat flame is held there until the metal reaches its kindling temperature. The tip is then moved to the edge of the plate so the oxygen stream will just clear the metal. With the cutting oxygen on, the cut is initiated. This method has the advantage of producing sharper corners at the beginning of the cut.

For plate thicknesses of 13 mm (1/2 in.) or more, the cutting tip should be held perpendicular to the plate. For thin plate, the tip can be tilted in the direction of the cut. Tilting increases the cutting speed and helps prevents slag from freezing across the kerf. When cutting material in vertical position, start on the lower edge of the material and cut upward.

Piercing. It is often necessary to start a cut at some point other than on the edge of a piece of metal. This technique is known as *piercing*. Piercing usually requires a somewhat larger preheat flame than the one used for an edge start. In addition, the flame should be adjusted to slightly oxidizing to increase the heat energy. The area where the pierce cut is to begin should be located in a scrap area. Hold the torch tip in one spot until the steel surface turns a yellowish red and a few sparks appear from the surface of the metal. The tip should be angled and lifted up as the cutting oxygen valve is opened. The torch is held stationary until the cutting jet pierces through the plate.

Torch motion is then initiated along the cut line. If the cutting oxygen is turned on too quickly and the torch is not lifted, slag may be blown into the tip and may plug the gas ports.

Machine Cutting. Operating conditions for mechanized oxygen cutting will vary depending on the fuel gas and the style of cutting torch being used. Tip size designations, tip design, and operating data can be obtained from the torch manufacturer.

Proper tip size and cutting oxygen pressure are important in making a quality machine cut. If the proper tip size is not used, maximum cutting speed and the best quality of cut will not be achieved. The cutting oxygen pressure setting is an essential condition; deviations from the recommended setting will greatly affect cut quality. For this reason, some manufacturers specify setting the pressure at the regulator and operating with a given length of hose. When longer or shorter hoses are used, an adjustment in pressure should be made. An alternative is to measure oxygen pressure at the torch inlet. Pressure settings for cutting oxygen are then adjusted to obtain the recommended pressure at the torch inlet, rather than at the regulator outlet.

Other adjustments, such as the preheat fuel and oxygen pressure settings and the travel speed, are also important. Once the regulators have been adjusted, the torch valves are used to throttle gas flows to give the desired preheat flame. If sufficient flow rates are not obtained, pressure settings at the regulator can be increased to compensate. Cleanliness of the nozzle, type of base metal, purity of cutting oxygen, and other factors have a direct effect on performance.

Manufacturers differ in their recommended travel speeds. Some give a range of speeds for specific thicknesses, while others list a single speed. In either case, the settings are intended only as a guide. In determining the proper speed for an application, begin the cut at a slower speed than that recommended. Gradually increase the speed until cut quality falls below the required level. Then reduce the speed until the cut quality is restored, and continue to operate at that speed.

Typical data for cutting low-carbon steel, using commonly available fuel gases, are shown in Table O-3. The gas flow rates and cutting speeds are to be considered only as guides for determining more precise setting for a particular job. When new material is being cut, a few trial cuts should be made to ascertain the most efficient operating conditions.

Plate Beveling. The beveling of plate edges before welding is necessary in many applications to insure proper dimensions and fit, and also to accommodate standard welding techniques. Beveling may be done by using a single torch or multiple torches operating simultaneously. Although single beveling can be done manually, beveling is best done by machine for accurate control of the cutting variables. When cutting bevels with two or three torches, plate riding devices should be used to insure constant tip position above the plate, as shown in Figure O-9.

Cutting Oxidation-Resistant Steels

The absence of alloying materials in pure iron permits the oxidation reaction to proceed rapidly. As the quantity and number of alloying elements in iron increase, the oxidation rate decreases from that of pure iron. Cutting becomes more difficult.

The iron oxides produced have melting points near the melting point of iron. However, the oxides of many of the alloying elements in steels, such as aluminum and chromium, have melting points higher than those of iron oxides. These high-melting oxides, which are refractory in nature, may shield the material in the kerf so that fresh iron is not continuously exposed to the cutting oxygen stream. Thus, the speed of cutting decreases as the amount of refractory oxide-forming elements in the iron increases.

Table O-3
Data For Cutting of Low Carbon Steel

SI Units

Thickness of Steel mm	Diameter of Cutting Orifice, mm	Cutting Speed mm/s	Gas Flow, L/min				
			Cutting Oxygen	Acetylene	MPS	Natural Gas	Propane
3.2	0.51–1.02	6.8–13.5	7.2–21.2	2–4	2–4	4–12	2–5
6.4	0.76–1.52	6.8–11.0	14.2–26.0	2–4	2–5	4–12	2–6
9.5	0.76–1.52	6.4–10.1	18.9–33.0	3–5	2–5	5–12	3–7
13	1.02–1.52	5.1–9.7	26.0–40.0	3–5	2–5	7–14	3–8
19	1.14–1.52	5.1–8.9	47.2–70.9	3–6	3–5	7–17	3–9
25	1.14–1.52	3.8–7.6	51.9–75.5	4–7	4–7	8–17	4–9
38	1.52–2.03	2.5–5.9	51.9–75.5	4–8	4–8	9–17	4–10
51	1.52–2.03	2.5–5.5	51.9–82.6	4–8	4–8	9–19	4–10
76	1.65–2.16	1.7–4.7	61.4–89.6	4–9	4–10	10–19	5–11
102	2.03–2.29	1.7–4.2	113–170	5–10	4–10	10–19	5–11
127	2.03–2.41	1.7–3.4	127–170	5–10	5–10	12–24	5–12
152	2.41–2.67	1.3–3.0	123–236	5–12	5–12	12–24	6–19
203	2.41–2.79	1.3–2.1	217–293	7–14	10–19	14–30	7–15
254	2.41–2.79	0.85–1.7	274–331	7–17	10–19	16–33	7–15
305	2.79–3.30	0.85–1.7	340–401	9–19	15–29	20–75	10–22

U.S. Customary Units

Thickness of Steel in.	Diameter of Cutting Orifice, in.	Cutting Speed in./min.	Gas Flow, ft^3/h				
			Cutting Oxygen	Acetylene	MPS	Natural Gas	Propane
1/8	0.020–0.040	16–32	15–45	3–9	2–10	9–25	3–10
1/4	0.030–0.060	16–26	30–55	3–9	4–10	9–25	5–12
3/8	0.030–0.060	15–24	40–70	6–12	4–10	10–25	5–15
1/2	0.040–0.060	12–23	55–85	6–12	6–10	15–30	5–15
3/4	0.045–0.060	12–21	100–150	7–14	8–15	15–30	6–18
1	0.045–0.060	9–18	110–160	7–14	8–15	18–35	6–18
1-1/2	0.060–0.080	6–14	110–175	8–16	8–15	18–35	8–20
2	0.600–0.080	6–13	130–190	8–16	8–20	20–40	8–20
3	0.065–0.085	4–11	190–300	9–20	8–20	20–40	9–22
4	0.080–0.090	4–10	240–360	9–20	10–20	20–40	9–24
5	0.080–0.095	4–8	270–360	10–25	10–20	25–50	10–25
6	0.095–0.105	3–7	260–500	10–25	20–40	25–50	10–30
8	0.095–0.110	3–5	460–620	15–30	20–40	30–55	15–32
10	0.095–0.110	2–4	580–700	15–35	30–60	35–70	15–35
12	0.110–0.130	2–4	720–850	20–40	30–60	45–95	20–45

Notes:

1. Preheat oxygen consumptions: Preheat oxygen for acetylene = 1.1 to 1.25 × acetylene flow ft^3/h; preheat oxygen for natural gas = 1.5 to 2.5 × natural gas flow ft^3/h; preheat oxygen for propane = 3.5 to 5 × propane flow ft^3/h.
2. Operating notes: Higher gas flows and lower speeds are generally associated with manual cutting, whereas lower gas flows and higher speeds apply to machine cutting. When cutting heavily scaled or rusted plate, use high gas flow and low speeds. Maximum indicated speeds apply to straight line cutting; for intricate shape cutting and best quality, lower speeds will be required.

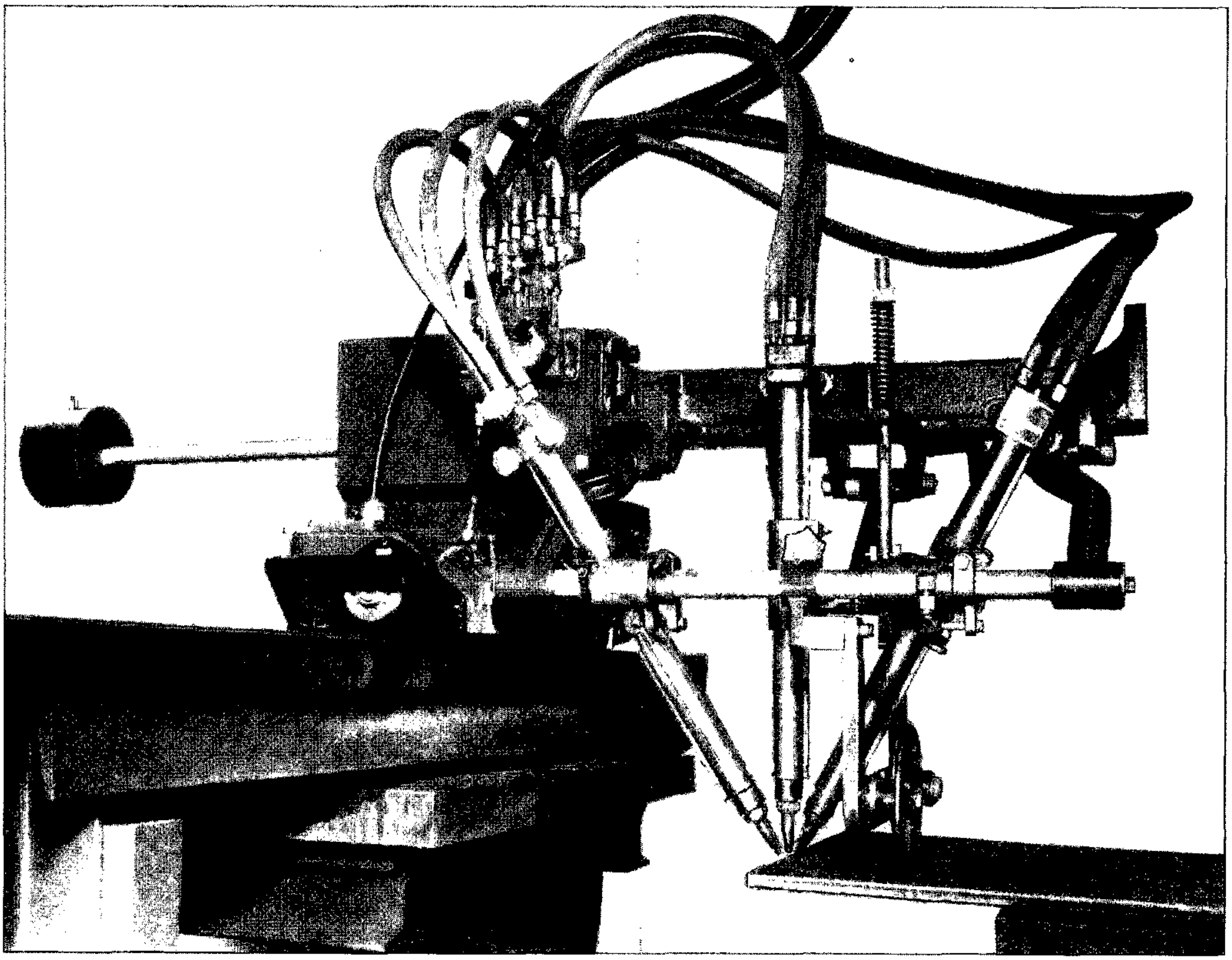


Figure O-9—Plate Riding Device Used When Cutting Bevels with Two or Three Torches

For ferrous metals with high-alloy content, such as stainless steel, the use of plasma arc cutting (PAC) and in some cases air carbon arc cutting (CAC-A) should be considered. If these options are not available or practical, then variations of OFC techniques must be used.

There are several variations for oxygen cutting of oxidation resistant steels, which are also applicable to cast irons. The important ones are the following:

(1) Torch oscillation
(2) Waster plate
(3) Wire feed
(4) Powder cutting
(5) Flux cutting

When the above methods are used to cut oxidation resistant metals, the quality of the cut surface is somewhat impaired. Scale and slag may adhere to the cut faces. Pickup of carbon or iron, or both, usually appears on the cut surfaces of stainless steels and nickel alloy steels. This may affect the corrosion resistance and magnetic properties of the metal. If the corrosion resistance or magnetic properties of the material are important, approximately 3 mm (1/8 in.) of metal should be machined from the cut edges. *See* FLUX CUTTING *and* METAL POWDER CUTTING.

Torch Oscillation. Low-alloy content stainless steels up to 100 mm (4 in.) thick can sometimes be severed with a standard cutting torch and oscillation. The entire thickness of the starting edge must be preheated to a bright red color before the cut is started. This technique should be combined with some of the other cutting methods listed.

Waster Plate. One method of cutting oxidation resistant steels is to clamp a low-carbon steel "waster" plate on the upper surface of the material to be cut. The cut is started in the low-carbon steel material. The heat liberated by the oxidation of the low-carbon steel provides additional heat at the cutting face to sustain the oxidation reaction. The iron oxide from the low-carbon steel helps to wash away the refractory oxides from stainless steel. The thickness of the waster plate must be in proportion to the thickness of the material being cut. Several undesirable features of this method are the cost of the waster plate material, the additional setup time, the slow cutting speeds, and the rough quality of the cut.

Wire Feed. With the appropriate equipment, a small diameter low-carbon steel wire is fed continuously into the torch preheat flames, ahead of the cut. The end of the wire should melt rapidly into the surface of the alloy steel plate. The effect of the wire addition on the cutting action is the same as that of the waster plate. A motor-driven wire feeder and wire guide, mounted on the cutting torch, are needed as accessory equipment. This is a seldom-used method.

Safe Practices

Safe practices for the installation and operation of oxyfuel gas systems for welding and cutting are given in American National Standard Z49.1, latest edition, published by the American Welding Society, Miami, Florida. These practices and those recommended by the equipment manufacturer should always be followed by the person operating the equipment.

Fumes are a potential health hazard. When the process is used in an enclosed or semi-enclosed area, exhaust ventilation should be provided and the operator should be equipped with a respirator. Noise from the operation may exceed safe levels in some circumstances. When necessary, ear protection should be provided for the operator. Fire is a potential hazard and combustible materials should be cleared away from the cutting area for a distance of at least 11 m (35 ft).

Appropriate protective clothing and equipment for any cutting operation will vary with the nature and location of the work to be performed. Some or all of the following may be required:

(1) Tinted goggles or face shields with filter lenses; the recommended filter lenses for various cutting operations are:
    (a) Light cutting, up to 25 mm (1 in.) shade 3 or 4
    (b) Medium cutting, 25 to 150 mm (1 to 6 in.) shade 4 or 5
    (c) Heavy cutting, over 150 mm (6 in.) shade 5 or 6
(2) Flame-resistant gloves
(3) Safety glasses
(4) Flame-resistant jackets, coats, hoods, aprons, etc.
    (a) Woolen clothing, preferably, not cotton or synthetic materials
    (b) Sleeves, collars, and pockets kept buttoned
    (c) Cuffs eliminated
(5) Hard hats
(6) Leggings and spats
(7) Safety shoes
(8) Flame extinguishing protective equipment
(9) Supplemental breathing equipment
(10) Other safety equipment

Reference: American Welding Society, *Welding Handbook*, 8th Edition, Vol. 2. Miami, Florida: American Welding Society, 1991.

OXYFUEL GAS CUTTING TORCH

A device used for directing the preheating flame produced by the controlled combustion of fuel gases and to direct and control the cutting oxygen. See STANDARD WELDING TERMS. *See also* OXYFUEL GAS CUTTING TORCH, Equipment.

OXYFUEL GAS SPRAYING

A nonstandard term for FLAME SPRAYING.

OXYFUEL GAS WELDING (OFW)

A group of welding processes that produces coalescence of workpieces by heating them with an oxyfuel gas flame. The processes are used with or without the application of pressure and with or without filler metal. See STANDARD WELDING TERMS.

Oxyfuel gas welding is an inclusive term used to describe any welding process that uses a fuel gas combined with oxygen to produce a flame having sufficient energy to melt the base metal. The fuel gas and oxygen are mixed in the proper proportions in a chamber which is generally a part of the welding torch assembly. The torch is designed to give the welder complete control of the welding flame to melt the base metal and the filler metal in the joint.

Oxyfuel gas welding is normally done with acetylene as the fuel gas. Other fuel gases, such as methylacetylene propadiene and hydrogen, are sometimes used for oxyfuel gas welding of low-melting metals. The welding flame must provide high localized energy to produce and sustain a molten weld pool. With proper adjustment, the flames can also supply a protective reducing atmosphere over the molten weld pool. Hydrocarbon fuel gases such as propane, butane, natural gas, and various mixtures of these gases are not suitable for welding ferrous materials because the heat output of the flame is too low or the flame atmosphere is oxidizing.

In combination with pressure, oxyfuel gas flames can be used to make upset welds in butt joints without filler metals. This process is called pressure gas welding (PGW). In PGW, abutting surfaces are heated with oxyfuel gas flames and forced together to obtain the forging action needed to produce a sound weld. The process is ideally adapted to a mechanized operation, and practically all commercial applications are either partly or fully mechanized.

Since the OFW processes are primarily manual, it is essential that the welder be adequately trained and highly skilled for specific critical welding jobs such as pipe welding. The skill required by the welding operator for a fully mechanized PGW machine would be lower that than required by the manual welder, since the machine control, when set, performs the complete operation.

Oxyfuel gas welding can be used for joining thick plate, but welding is slow and high heat input is required. Welding speed is adequate to produce economical welds in sheet metal and thin-wall and small diameter piping. Thus, OFW is best applied on material up to about 6 mm (1/4 in.). Pressure gas welding is used to join sections up to 25 mm (1 in.) thick.

Oxyfuel gas welding equipment is versatile and can be used with most construction materials. The equipment involved is easily portable. For these reasons, the cost effectiveness is good. However, when parts are to be made in quantity, other welding processes are usually more suitable. See OXYACETYLENE WELDING.

OXYFUEL GAS WELDING TORCH

A device used in oxyfuel gas welding, torch brazing, and torch soldering for directing the heating flame produced by the controlled combustion of fuel gases. *See* STANDARD WELDING TERMS. *See also* OXYACETYLENE WELDING, Equipment.

OXYGAS CUTTING

A nonstandard term for OXYFUEL GAS CUTTING.

OXYGEN

(Chemical symbol: O). An odorless, tasteless gaseous element; colorless except in its liquid state, when it is a faint blue color. Atomic number, 8; atomic weight, 16; melting point, –218.4°C (–361.1°F); boiling point; –183.0°C (–297.4°F); density, 1.429 grams/liter. The critical temperature is –118°C (–180.4°F), and its critical pressure 49.3 atmospheres (5 MPa [725 psi]).

Oxygen is a non-metallic element that can be found nearly everywhere in nature, either in free state or in combination with other elements. Oxygen combines with all elements except inert gases. It is one of the chief constituents of the atmosphere, and without oxygen, life as we know it would be impossible. Water is a compound of oxygen and hydrogen, in which approximately 89% by weight is oxygen.

Oxygen constitutes about 1/5 (20.99% by volume) of the earth's atmosphere, and it has been roughly estimated to constitute nearly half of the weight of the various rocks of which the earth's crust is composed.

The discovery of oxygen as an element was made in 1774 by two chemists, Priestly and Scheele, working independently and without knowledge of one another's endeavors. Various methods have since been perfected for the commercial production of oxygen. Of practical value today are the chemical, electrolytic, and the liquefaction methods.

In the welding industry the principal value of oxygen is that it will support combustion: it will combine with other substances in the production of flame and the evolution of heat. This property of oxygen has been utilized in the development of oxyfuel gas welding and cutting torches. Regardless of the nature of the combustible gas used in these torches, oxygen is a requisite of operation.

Used with acetylene, and to a lesser extent with other fuel gases, oxygen produces a sufficiently hot flame to cut and weld metals. It is also used, in mixtures with selected carbonaceous matter, as an explosive for quarrying in strip coal mining, and in other mining operations to break up ores in copper and certain other minerals.

Pharmaceutical oxygen is used in medical applications for resuscitation and rehabilitation, and in certain forms of therapy.

OXYGEN ARC CUTTING (AOC)

An oxygen cutting process that uses an arc between the workpiece and a consumable tubular electrode, through which oxygen is directed to the workpiece. See STANDARD WELDING TERMS.

The oxygen arc process is used in cutting, piercing, and gouging. Mild steel is cut by using the arc to raise the temperature of the material to its kindling point in the presence of oxygen. The combustion reaction that occurs is self-sustaining, liberating sufficient heat to maintain the kindling temperature on all sides of the cut. The necessary preheat at the start of cutting is provided by the electric arc. A schematic illustration of the process is shown in Figure O-10.

Applications

Oxygen arc cutting has been used effectively by foundries and scrap yards for cutting mild and low-alloy steels, stainless steel, cast iron, and nonferrous metals in any position. The usefulness of the process varies with the thickness and composition of the material being cut. The edges of metal cut by the oxygen arc torch are somewhat uneven and usually require a light surface preparation to make them suitable for welding.

Oxygen arc cutting electrodes were developed primarily for use in underwater cutting and were later applied to cutting in air. In either application, oxygen arc electrodes can cut ferrous and nonferrous metals in any position.

Equipment

Either constant current a-c or d-c power sources of sufficient capacity can be used for oxygen arc cutting. Direct current electrode negative (DCEN) is preferred for rapid cutting. The specially designed electrode holder used for oxygen-arc cutting conveys electric current to the electrode and delivers oxygen to the cut. This is accomplished by bringing oxygen to the electrode holder and passing it through the bore of the electrode into the arc.

For cutting in air, a fully insulated electrode holder is required. When used for underwater cutting, a fully insulated holder equipped with a suitable flash-back arrester is required.

Tubular steel electrodes are available in 5 and 8 mm (3/16 and 5/16 in.) diameter sizes, 46 cm (18 in.) long, with bore diameter approximately 1.6 mm (1/16 in.) The extruded covering is comparable to a mild steel electrode of AWS classification E6013. Underwater electrodes are steel tubes with a waterproof coating.

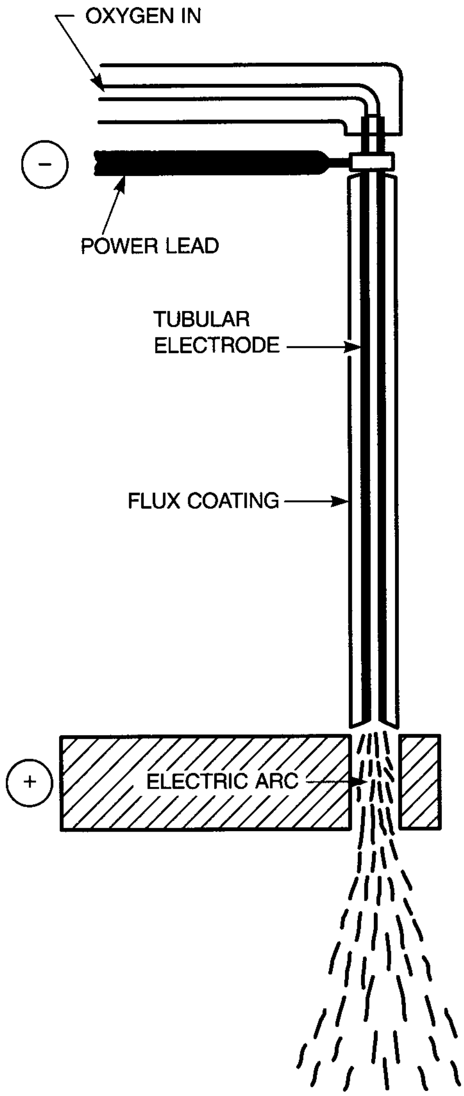


Figure O-10—Schematic of Oxygen-Arc Electrode in Operation

Metallurgical Effects

The oxygen arc method of cutting produces metallurgical effects in the heat-affected zone comparable to those that occur in shielded metal arc welding. The power input approaches that of shielded metal arc welding, but the heat penetration is generally not as deep in AOC because of the faster speed of travel. This produces a somewhat more pronounced quench effect. Metals that do not require a postheat treatment after welding may be severed by this process without detrimental effect. Grades of austenitic stainless steels that are sensitive to corrosion attack when subjected to shielded metal arc welding will be sensitized along the cut when severed by the AOC process.

Oxygen arc cuts in cast iron and medium carbon, low-alloy steels are apt to develop cracks on the face of the cut. The extent and frequency of cracking depend on the composition and hardenability of the steel.

OXYGEN CUTTER

See STANDARD WELDING TERMS. *See also* THERMAL CUTTER.

OXYGEN CUTTING (OC)

A group of thermal cutting processes that severs or removes metal by means of the chemical reaction between oxygen and the base metal at elevated temperature. The necessary temperature is maintained by the heat from an arc, an oxyfuel gas flame, or other source. See STANDARD WELDING TERMS. *See also* OXYFUEL GAS CUTTING, OXYGEN LANCE CUTTING, *and* THERMAL CUTTING.

OXYGEN CUTTING OPERATOR

See STANDARD WELDING TERMS. *See also* THERMAL CUTTING OPERATOR.

OXYGEN CYLINDER

Oxygen cylinders are constructed of seamless drawn steel to contain compressed oxygen. They are annealed, tested, and threaded to accommodate an outlet valve and cylinder cap. Oxygen cylinders are made in several sizes, but the most frequently used cylinder in welding and cutting contains approximately 7 m^3 (250 ft^3) at a pressure of 15 MPa (2200 psig) at 21°C (70°F).

OXYGEN GOUGING

Thermal gouging that uses an oxygen cutting process variation to form a bevel or groove. See STANDARD WELDING TERMS.

Oxygen gouging of steel plate is usually limited to steel plate thicknesses up to 25 mm (1 in.). The OFC process is frequently used on the underside of a welded joint to remove defects that are in the original root pass, or to remove defective weld joints or cracks when repairing previously fabricated metal.

The gouging process usually requires a special gouging tip with extra-heavy preheat capacity and a central oxygen orifice that causes a high level of turbulence in the oxygen stream. This turbulence causes a wide flow of oxygen that can be controlled by the operator to achieve the desired width and depth of gouge. Other factors used to determine the shape of the gouge are speed, tip angle, oxygen pressure, amount of preheat, and tip size. One of the significant advantages of oxygen gouging is that no additional equipment other than that already used in the oxyfuel cutting process is required. *See* OXYFUEL GAS CUTTING.

OXYGEN GROOVING

A nonstandard term for OXYGEN GOUGING.

OXYGEN HOSE

A hose through which oxygen flows from the regulator to the torch. Hoses used in gas welding are manufactured specifically to meet the utility and safety requirements for this service. Oxygen hoses are colored green; the connections each have a plain nut with right-hand threads matching the oxygen regulator outlet and the oxygen inlet fitting on the torch. To avoid error, fuel gas hose connections will not fit the oxygen regulator outlet and the torch inlet fitting for oxygen.

OXYGEN LANCE

A length of pipe used to convey oxygen to the point of cutting in oxygen lance cutting. See STANDARD WELDING TERMS.

OXYGEN LANCE CUTTING

Oxygen lance cutting (LOC) is an oxygen cutting process that uses oxygen supplied through a consumable steel pipe or lance. The preheat required to start the cutting is obtained by other means. See STANDARD WELDING TERMS.

The earliest version of LOC used a plain black iron pipe as a lance, with oxygen flowing through it. An improved version of the lance involves a number of low-carbon steel wires packed into the steel tube. This increases the cutting life and capability of the lance. Commercially available tubes are typically 3.2 m (10-1/2 ft) long and 16 mm (0.625 in.) in diameter.

An oxyfuel gas cutting or welding torch is used to heat the cutting end of the lance to a cherry red, and then the oxygen flow is started. The iron pipe burns in a self-sustaining, exothermic reaction, and the heating torch is removed. When the burning end of the lance is brought close to the workpiece, the work is melted by the heat of the flame. The oxygen lancing operation is shown schematically in Figure O-11.

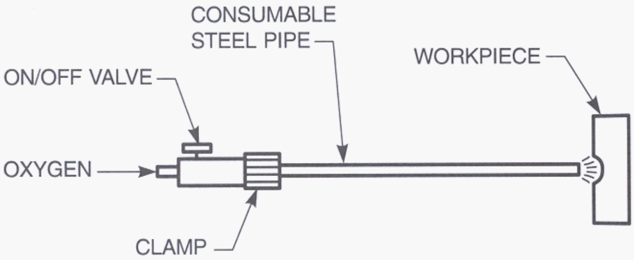


Figure O-11—Schematic View of Oxygen Lance Cutting

Oxygen lance cutting can be used to pierce virtually all materials. It has been used successfully on aluminum, cast iron, steel, and reinforced concrete. Oxygen lancing of a 1 m (40 in.) diameter cast iron roll used in a paper mill is shown in Figure O-12. Cutting oxygen was supplied at 550 to 870 kPa (80 to 120 psi). Holes pierced in the roll are shown in Figure O-13. The variable angle bracket shown in Figure O-13 was found to be helpful in guiding the lance.

Figure O-12—Oxygen Lancing of a 102 cm (40-in.) Diameter Cast Iron Roll from a Paper Mill

A 64 mm (2-1/2 in.) diameter hole can be made in reinforced concrete at a rate of about 100 mm/min (4 in./min). The process has been used to open furnace tap holes and to remove solidified material from vessels, ladles, and molds. It can be used to cut refractory brick, mortar, and slag.

Figure O-13—Holes Pierced in a 102 cm (40-in.) Diameter Cast Iron Roll Using an Oxygen Lance

The LOC process can be used underwater. The lance must be lighted before it is placed underwater, but then piercing proceeds essentially the same as in air. The process produces a violent bubbling action which can restrict visibility.

Arc-Started Oxygen Lancing. A variation of the oxygen lancing process uses an arc to start the iron-oxygen reaction. This equipment uses tubes typically 45 cm (18 in.) long and either 6.4 or 9.5 mm (0.25 or 0.375 in.) in diameter. A 12-volt battery can be used as a power source, with the cutting tube connected to one battery terminal and a copper striker plate connected to the other.

To start the burning operation, the operator starts the oxygen flow and draws the steel tube across the copper plate at a 45° angle. Sparking at the copper plate will ignite the tube. The burning rod can then be used for cutting, piercing, or beveling steel. It can also be used to remove pins, rivets, and bolts.

OXYGEN LANCING

A nonstandard term for OXYGEN LANCE CUTTING.

OXYGEN MACHINING

A process of shaping ferrous metals by oxygen cutting or oxygen grooving. *See* OXYFUEL GAS CUTTING.

OXYGEN PRODUCTION

Most oxygen used in the welding industry is extracted from the atmosphere by liquefaction techniques. Nitrogen can also be separated by liquefaction. In the extraction process, air may be compressed to approximately 20 MPa (3000 psig), although some types of equipment operate at much lower pressure. The carbon dioxide and any impurities in the air are removed; the air passes through coils, and is allowed to expand to a rather low pressure. The air becomes substantially cooled during the expansion, and then it is passed back over coils, further cooling the incoming air, until liquefaction occurs. The liquid air is sprayed on a series of evaporating trays or plates in a rectifying tower.

Nitrogen and other gases boil at lower temperatures than the oxygen and, as these gases escape from the top of the tower, high-purity liquid oxygen collects in a receiving chamber at the base. Some plants are designed to produce bulk liquid oxygen; in other plants, gaseous oxygen is withdrawn for compression into cylinders.

Historical Background

While oxygen can be produced chemically, as in the Brinn and the Jaubert processes, the most efficient and economical means is the liquification process. In the liquid air process, air is liquefied by means of very low temperatures and compression.

The basic idea for the separation of the elements of air by liquefaction was first suggested by Parkinson in 1892, and depends on the difference in the boiling points of the major elements constituting air, approximately –183°C (–297°F) for oxygen, and –196°C (–320.4°F) for nitrogen. Various modifications of this idea have been developed; the principal processes were developed by Linde, Claude, Messer, Heylandt, Pictet, and Hilldebrandt. These very low temperatures are reached by external refrigeration, and the *Joule-Thompson effect*: the fall in temperature produced when a compressed gas is allowed to expand freely through a nozzle, which results in self-cooling of the gas caused by absorption of energy (heat) during the expansion. When the oxygen and nitrogen are allowed to boil off from the liquid air, the resulting gases are very cold. This phenomenon is used in all commercial processes to cool more incoming air for liquefaction. This refrigeration process takes place in a heat interchanger, the principle of which was suggested by Siemens in 1857. Without the saving of power made possible by the heat interchanger, none of the liquefaction processes would be commercially practical.

In 1903 Georges Claude showed that a further cooling could be effected by allowing the compressed gas to expand and at the same time do external recoverable work through the intermediary of an expansion technique. Applying this principle, the need for outside refrigeration was eliminated, and the initial compression requirements were decreased.

In all rectification processes, the separation is accomplished in a rectification column by means of the interaction between a descending stream of liquid and an ascending stream of vapor in direct contact with one another. As it descends, the liquid partially absorbs the constituent having the higher boiling point, and as it ascends, the vapor partially absorbs the constituent having the lower boiling point. When the mixture treated in a rectification column is liquid air, the descending liquid stream ultimately becomes almost pure oxygen, while the percentage of nitrogen in the vapor stream increases as it ascends.

In addition to its value in the production of oxygen, liquid air has a number of interesting commercial uses, such as solidifying mercury vapor in high-vacuum work; the formation of a powerful explosive by soaking charcoal cartridges in it; producing low temperatures for testing materials that are to be used at temperatures far below the freezing temperature; pulverization of various compounds for chemical analysis; purifying chemicals, and for refrigeration-ventilation.

Oxygen and Hydrogen Production by Electrolysis

In the year 1800, Nicholson and Carlisle showed that on conducting an electric current through water by immersing the two terminals of a voltaic pile into it, hydrogen was produced at one of the terminals and oxygen was produced at the other. In the commercial electrolysis of water, the water is made a conductor by the addition of alkalies or acids. The alkalies are almost entirely used commercially because they are cost effective, and because of the resistance of a greater class of materials to their chemical action.

When an electric current is passed through an alkaline solution, the water is decomposed by a primary and secondary reaction, so that the hydrogen is liberated at the negative pole, or cathode, and the oxygen is liberated at the positive pole, or anode. The equipment and functions necessary for the decomposition of water follow:

(1) A container to hold the alkaline or acid solution or water, called the *electrolyte*; an anode, which is submerged in the solution and to which the current from an outside source is led

(2) A cathode, submerged in the solution to receive the current and lead it back to its source

(3) A dividing wall to separate the gases and a means for collecting them separately, and conducting them to some desired point

DC Current. The necessary current must be a direct current so that the evolution of gas will always be at the same point. It is not practical to use alternating current.

The introduction, development and use of hydrogen and oxygen for cutting steel and welding aluminum, and the large demand for hydrogen for other industrial purposes contributed further to the development of the electrolysis method of producing oxygen and hydrogen. The distinctive feature of this method is the simultaneous production of two volumes of hydrogen for every one volume of oxygen.

Modern production of hydrogen involves the steam re-forming of natural gas over a nickel catalyst. *See* HYDROGEN.

OXYGEN REGULATOR

A device designed to reduce and control pressure of oxygen cylinders to a level compatible with the operating system or process. The regulator must handle incoming gas pressure and provide a range of delivery pressures.

Oxygen regulators must be clean and in good working condition. If there is oil, grease, or foreign material on a regulator or other equipment, or if the equipment is damaged, it must not be used prior to being properly cleaned or serviced by a qualified repair technician. *See* OXYACETYLENE WELDING *and* REGULATOR.

OXYHYDROGEN CUTTING (OFC-H)

An oxyfuel gas cutting process variation that uses hydrogen as the fuel gas. See STANDARD WELDING TERMS. *See also* OXYFUEL GAS CUTTING.

OXYHYDROGEN FLAME

The flame produced by combustion of a mixture of one volume of oxygen and two volumes of hydrogen. If the flame is to be used for welding, the proportion should be one volume of oxygen to four volumes of hydrogen to prevent oxidation of the metal. The temperature of the flame is about 2660°C (4820°F). The relatively low heat content of the oxyhydrogen flame restricts its use to certain torch brazing operations and to welding of aluminum, magnesium and lead.

OXYHYDROGEN WELDING (OHW)

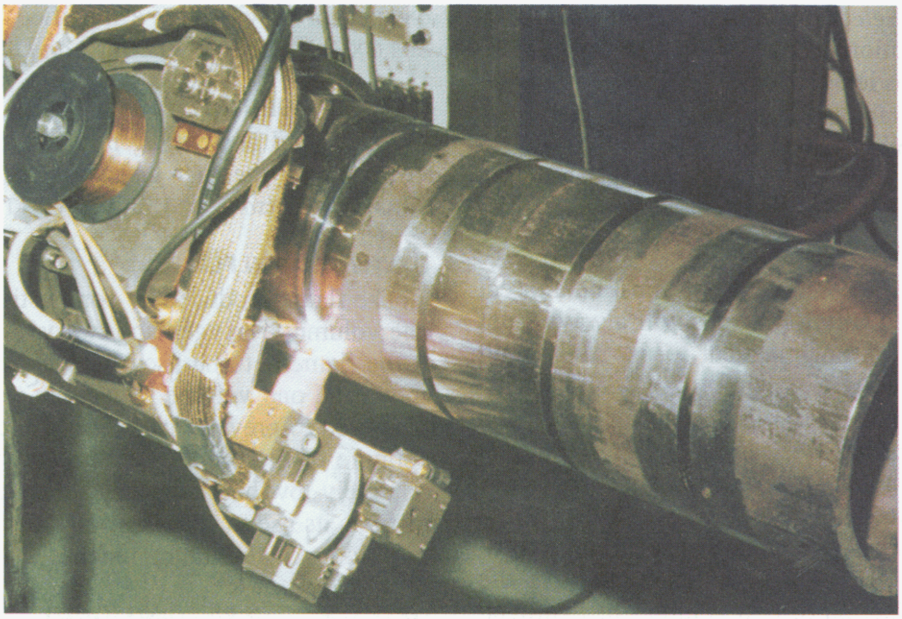
An oxyfuel gas welding process that uses hydrogen as the fuel gas. This process is used without the application of pressure. See STANDARD WELDING TERMS. *See also* OXYFUEL GAS WELDING.

OXYNATURAL GAS CUTTING (OFC-N)

An oxyfuel gas cutting process variation that uses natural gas as the fuel gas. See STANDARD WELDING TERMS.

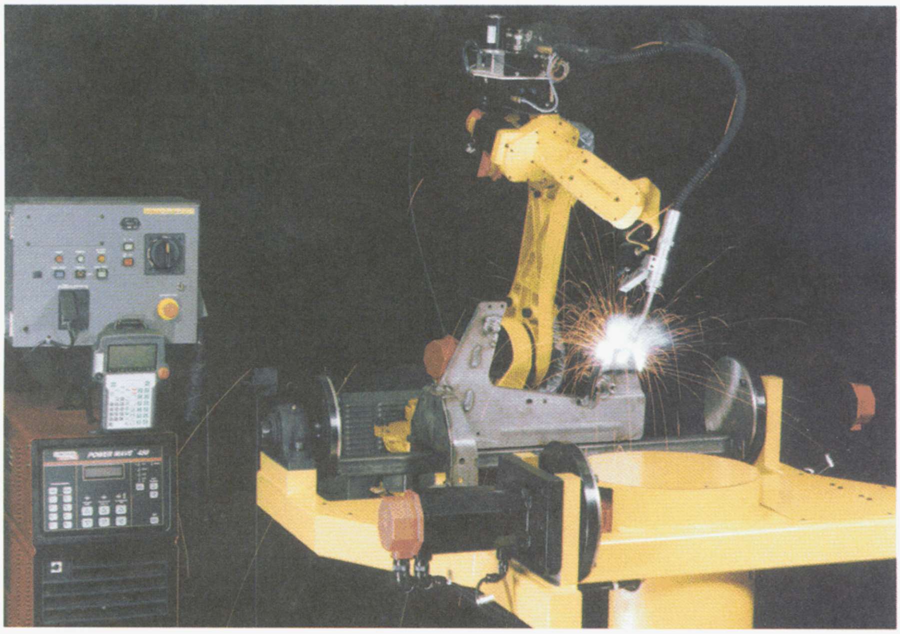
OXYPROPANE CUTTING (OFC-P)

An oxyfuel gas cutting process variation that uses propane as the fuel gas. See STANDARD WELDING TERMS.



High precision oribital welding machine using hot-wire gas tungsten arc welding has the advantage of high deposition rates which shorten welding time

Photo courtesy of Polysoude France and Astro Arc, USA



Robotic arc welding cell designed to maximize accuracy and minimize cycle time

Photo courtesy of Fanuc Robots North America

P

PACK ANNEALING

Annealing a stack of several sheets of metal instead of a single sheet. Pack annealing minimizes oxidation and scale formation on the surfaces of the sheets.

PADDING

This term is no longer in general use; the term *buildup* is generally used when surfacing material deposited has essentially the same chemistry as the base metal. *See* BUILDUP.

PARALLEL BEADS

See BEADING WELD *and* STRINGER BEAD WELDING.

PARALLEL CIRCUIT

An electrical circuit in which the current divides at a connection and flows through two or more devices connected to it.

PARALLEL CONNECTION

The connection of two or more arc welding machines so that higher welding currents are provided than are available from one machine separately.

For parallel operation, the welding machines must be similar and the recommendations of the manufacturers must be closely followed to adjust control settings correctly and to use the equalizer connections. All machines in parallel must be set for the same polarity and open circuit voltage, and current settings should be kept as nearly equal as possible on all the machines.

PARALLEL GAP WELDING

A nonstandard term for series welding with closely spaced electrodes.

PARALLEL SERIES

An electrical circuit in which a number of devices are connected in series with one another, forming a group. Several groups of series circuits can be connected in parallel with one another to form a parallel.

PARALLEL WELDING

A resistance welding secondary circuit variation in which the secondary current is divided and conducted through the workpieces and electrodes in parallel electrical paths to simultaneously form multiple resistance spot, seam or projection welds. See STANDARD WELDING TERMS. *See also* Figure P-1.

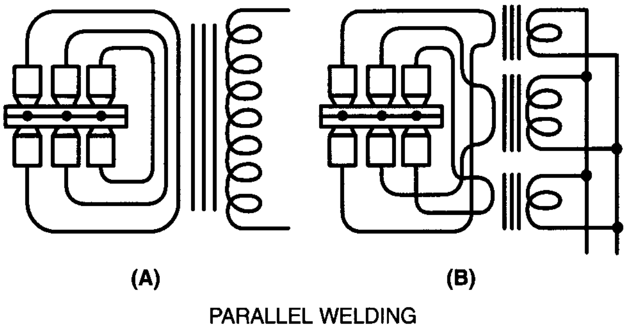


Figure P-1—Typical Arrangements for Multiple Spot Welding

PARAMAGNETIC

A substance which displays a small but positive susceptibility to a magnetic field, varying little with field strength. Examples are aluminum and platinum.

PARENT METAL

A nonstandard term for BASE METAL or SUBSTRATE.

PARTIAL JOINT PENETRATION WELD

A joint root condition in a groove weld in which incomplete joint penetration exists. See STANDARD WELDING TERMS. *See* Figure I-3. *See also* COMPLETE JOINT PENETRATION, COMPLETE JOINT PENETRATION WELD, INCOMPLETE JOINT PENETRATION, *and* JOINT PENETRATION.

PASS

See STANDARD WELDING TERMS. *See also* THERMAL SPRAY PASS *and* WELD PASS.

A pass is a single progression of welding along a joint, resulting in a weld bead or layer.

PASS SEQUENCE

See STANDARD WELDING TERMS. *See also* WELD PASS SEQUENCE.

PASTE BRAZING FILLER METAL

A mixture of finely divided brazing filler metal with a flux or neutral carrier. See STANDARD WELDING TERMS.

PASTE SOLDER

A mixture of finely divided solder with a flux or neutral carrier. See STANDARD WELDING TERMS.

PATCHING SHEET

A sheet of material used to place a patch in a flat, round or warped plate where cracking has occurred or is expected to occur during or after welding, or while in service. *See* Figure P-2. The cross section of the diagram shows that the patch is slightly dished to allow for contraction in the weld. The preferred circular patch shape equalizes stresses around the weld. However, if a circular patch is not practical, a patch shape as nearly circular as possible, such as oval or elliptical, should be used. If the opening is rectangular, corners of the patch and opening should be rounded.

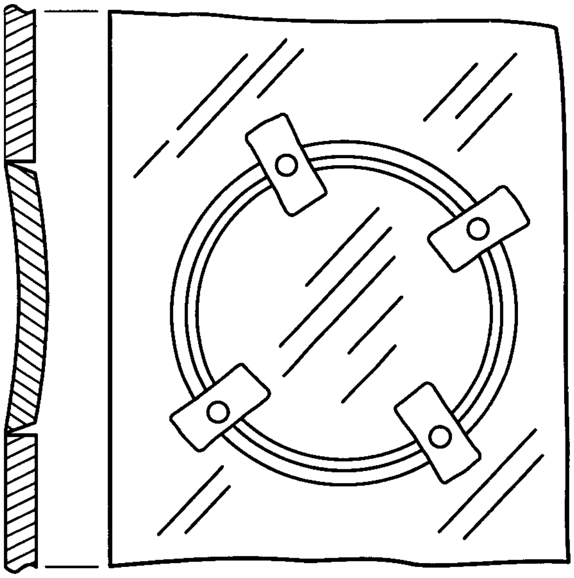


Figure P-2—Patching Sheet

Where equipment for forming a dished patch is not available, the patch can be dished by hammering, which should be done when the plate is hot. The diagram shows a simple method for holding the patch in place. Holes are drilled through at the joint, and bolts are used to clamp lugs on both surfaces of the patch. *See also* CORRUGATED PATCH.

PATENTING

An archaic term for annealing. In wire production, it refers to an annealing treatment applied to medium- or high-carbon steel before drawing the wire, or between drafts. The process consists of heating to a temperature above the transformation range, then cooling to a temperature below the transformation range in air, molten lead or salt. *See* ANNEALING.

PEARLITE

A microstructural aggregate or a mechanical mixture of ferrite and cementite (iron carbide) platelets which normally occurs in steel and cast iron. This lamellar structure can be observed only through a metallographic microscope because the platelets are very thin, on the order of 0.001 mm (0.00004 in.).

Pearlite was given its name by H. M. Howe because its lamellar appearance resembles mother-of-pearl.

See METALLOGRAPHY.

PEEL TEST

A destructive method of testing that mechanically separates a lap joint by peeling. See STANDARD WELDING TERMS.

PEENING

The mechanical working of metals using impact blows. See STANDARD WELDING TERMS.

Peening is accomplished by repeated hammer blows to the surface of the metal. The blows may be administered manually, as with a hammer, or with pneumatic tools. Peening tends to stretch the surface of the cold metal, thus reducing contraction stresses.

PENETRAMETER

A penetrameter, or image quality indicator (IQI), is a device used to measure the quality of radiographic images. Penetrameters consist of a piece of metal of simple geometric shape, with similar absorption characteristics as the weld to be tested. The thickness is generally 2% of the weld thickness. A penetrameter usually has three holes, the diameters of which are 1, 2, and 4 times the thickness of the penetrameter. The penetrameters are placed on a test piece during setup and are radiographed at the same time as the test piece. Sharpness of the penetrameter features in the developed image is a measure of image quality. *See* RADIOGRAPHIC EXAMINATION.

PENETRANT INSPECTION

Penetrant inspection is a non-destructive test method for revealing fine surface discontinuities such as cracks, pores or seams in weld metal or base metal. It is useful for detecting discontinuities in magnetic and nonmagnetic materials where magnetic particle inspection cannot be used.

Penetrant inspection is accomplished by applying a liquid with high wetting capabilities to the surface which can be drawn into surface cavities or openings. The excess penetrant is then removed from the surface, and a liquid-propelled or dry powder developer is applied.If there is a significant discontinuity, the penetrant will be held in the cavity. Blotter action draws the penetrant from the discontinuity to provide a contrasting indication on the surface. This is a relatively reliable and inexpensive method for obtaining information on questionable welds.

The following sequence is normally used in the application of a typical penetrant test. When the order is changed or short cuts are taken, the validity of the test is suspect.

(1) Clean the test surface.

(2) Apply the penetrant.

(3) Wait for the prescribed dwell time.

(4) Remove the excess penetrant.

(5) Apply the developer.

(6) Examine the surface for indications, and record the results.

(7) Clean to remove the residue.

Dye Penetrant

The dye penetrant method uses a bright red dye with high wetting capabilities. To begin this method, the part is cleaned with a cleaning solution to prepare the surface. The dye penetrant is applied by brush, spray, or dipping, and allowed to remain for at least five minutes. (Detection of very small cracks may require two or three such applications). After applying the dye penetrant, excess penetrant is removed with a cleaning solution, and the developer is sprayed on or applied with a brush. As the developer dries, the penetrant is drawn to the surface, and the discontinuities are revealed.

Fluorescent Penetrant

In fluorescent penetrant examination, a highly fluorescent liquid with good wetting or penetrating properties is applied to the surface of the part to be inspected. The liquid is drawn into very small surface openings by capillary action. Excess liquid is removed from the surface and a developer in the form of a fine powder, or water suspension of a fine powder, is applied to the surface. The developer draws the penetrant from the pores and cracks and makes them more visible under ultraviolet light.

Before the fluorescent penetrant test is started, the part must be thoroughly clean, because any dirt, grease, or paint could close the discontinuities to the penetrant. The penetrant may be applied by spraying, dipping or brushing. The time the penetrant must remain on the surface will vary from a few minutes to several hours, depending on the thickness of the workpiece, but 5 to 15 minutes is usually required.

After the penetrating time, the excess penetrant must be removed carefully to avoid removing more than the surface penetrant. Water-wash penetrants can be washed with a low-pressure water spray. Some commercial penetrants require a solvent wash or an emulsifier. The emulsifier is applied to the surface and allowed to remain for one to four minutes before washing with the water spray. The parts are then dried by wiping, air blower, or hot air oven.

The dry developer is applied to the dried parts with a powder gun, spray bulb, or by dipping the part into the developer powder. The penetrant is drawn from the discontinuities, making the discontinuities visible in ultraviolet light. If a wet developer is used, drying after washing is not necessary. The wet developer in the form of a colloidal suspension is applied by spraying or dipping. The developer should remain on the surface for at least half the penetrating time. After this, the part is dried by hot air.

When viewed under ultraviolet light, the indications of discontinuities are brilliantly fluorescent, revealing the depth and length of discontinuities by the amount of penetrant which bleeds out. Contrast is enhanced when viewed in a darkened location, which allows the finer indications to be observed.

Historical Background. The old "oil and whiting" method might be considered the forerunner of penetrant inspection. A light oil was applied to a surface, wiped off, then the surface was coated with chalk. The oil showing through the chalk pointed up the location of cracks.

Standard Practices and References

For additional information, refer to ASTM E165, *Standard Practice for Liquid Penetrant Inspection*, and ASTM E433, *Standard Reference Photographs for Liquid Penetrant Inspection.* These documents are published by American Society for Testing and Materials, Philadelphia, Pennsylvania.

PENETRATION

A nonstandard term when used for DEPTH OF FUSION, JOINT PENETRATION, or ROOT PENETRATION. *See* STANDARD WELDING TERMS.

PERCENT FERRITE

A nonstandard term when used for FERRITE NUMBER.

PERCUSSION WELDING (PEW)

A welding process that produces coalescence with an arc resulting from a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the electrical discharge. See STANDARD WELDING TERMS.

The electrical energy is stored in a capacitor or group of capacitors at a relatively high voltage and discharged directly, or through a transformer, to the part to be welded. Discharge is initiated by closing a mechanical or electronic switch.

Percussion welding is the process used in the electronics industry for joining wires, contacts, leads, and similar items to a flat surface. However, if the item is a metal stud that is welded to a structure for attachment purposes, it is called *capacitor discharge stud welding.*

In applying the process, the two parts are initially separated by a small projection on one part, or one part is moved toward the other. At the proper time, an arc is initiated between them. This arc heats the faying surfaces of both parts to welding temperature. Then, an impact force drives the parts together to produce a welded joint. There are basically two variations of the percussion process: capacitor discharge and magnetic force.

Although the steps may differ in certain applications because of process variations, the essential sequence of events in making a percussion weld is as follows:

(1) Load and clamp the parts into the machine.

(2) Apply a low force on the parts or release the driving system.

(3) Establish an arc between the faying surfaces (a) with high voltage to ionize the gas between the parts or (b) with high current to melt and vaporize a projection on one part.

(4) Move the parts together percussively with an applied force to extinguish the arc and complete the weld.

(5) Turn off the current.

(6) Release the force.

(7) Unclamp the welded assembly.

(8) Unload the machine.

Operation. Welding heat is generated by an arc between the two parts to be joined. The current density is very high, and this melts a thin layer of metal on the faying surfaces in a few milliseconds. Then the molten surfaces are brought together in a percussive manner to complete the weld.

Capacitor Discharge

With the capacitor discharge method, power is furnished by a capacitor storage bank. The arc is initiated by the voltage across the terminals of the capacitor bank (charging voltage) or a superimposed high-voltage pulse. Motion may be imparted to the movable part by mechanical or pneumatic means.

Magnetic Force

For magnetic force welding, power is supplied by a welding transformer. The arc is initiated by vaporizing a small projection on one part with high current from the transformer. The vaporized metal provides an arc path. The percussive force is applied to the joint by an electromagnet that is synchronized with the welding current. Magnetic force percussion welds are made in less than one-half cycle of 60 Hz. Consequently, the timing between the initiation of the arc and the application of magnetic force is critical.

Advantages of Percussion Welding

The extreme brevity of the arc in both versions of percussion welding limits melting to a very thin layer on the faying surfaces. Consequently, there is very little upset or flash on the periphery of the welded joint, only enough to remove impurities from the joint. Heat-treated or cold-worked metals can be welded without annealing them. Filler metal is not used and there is no cast metal at the weld interface. A percussion welded joint usually has higher strength and electrical conductivity than a brazed joint. Unlike brazing, no special flux or atmosphere is required.

A particular advantage of the capacitor discharge method is that the capacitor charging rate is easily controlled and low compared to the discharge rate. The line power factor is better than with a single-phase a-c machine. Both these factors contribute to good operating efficiency and low power line demand.

Percussion welding can tolerate a slight amount of contamination on the faying surfaces because expulsion of the thin molten layer tends to carry any contaminants out of the joint. Figure P-3 shows several electrical contact designs joined by magnetic force percussion welding.

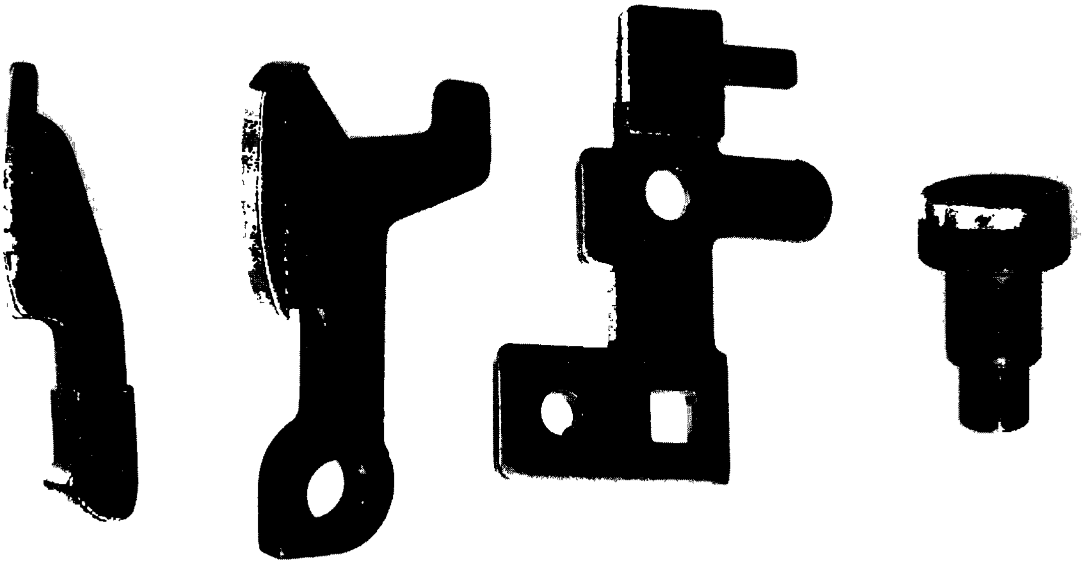


Figure P-3—Typical Electrical Contacts Joined by Magnetic Force Percussion Welding

Limitations

The percussion welding process is limited to butt joints between two like sections, and to flat pads or contacts joined to flat surfaces. In addition, the total area that can be joined is limited, since control of an arc path between two large surfaces is difficult.

Joints between two like sections can usually be accomplished more economically by other processes. Percussion welding is usually confined to the joining of dissimilar metals not normally considered weldable by other processes, and to the production of joints where avoidance of upset is imperative. Another limitation of this process is that two separate pieces must be joined. It cannot be used to weld a ring from one piece.

Safety

Mechanical. The welding machine should be equipped with appropriate safety devices to prevent injury to the operator's hand or other parts of the body. Initiating devices, such as push buttons or foot switches, should be arranged and guarded to prevent them from being actuated inadvertently.

Machine guards, fixtures, or operating controls should prevent the hands of the operator from entering between the work-holding clamps or the parts to be welded. Dual hand controls, latches, presence-sensing devices, or any similar device may be employed to prevent operation in an unsafe manner.

Electrical. All doors and access panels on machines and controls should be kept locked or interlocked to prevent access by unauthorized personnel. When the equipment utilizes capacitors for energy storage, the interlocks should interrupt the power and discharge all the capacitors through a suitable resistive load when the panel door is open. A manually operated switch or other positive device should also be provided in addition to the mechanical interlock or contacts. Use of this device will assure complete discharge of the capacitors.

A lock-out procedure should be followed prior to working with the electrical or hydraulic systems.

Personal Safety Equipment. Eye protection with suitable shaded lenses should be worn by the operator.

When the welding operations produce high noise levels, operating personnel should be provided with ear protection. Metal fumes produced during welding operations should be removed by local ventilating systems. Additional information on safe practices for welding may be found in the American National Standard Z49.1, *Safety in Welding and Cutting* (latest edition), available from the American Welding Society.

Reference: American Welding Society, *Welding Handbook*, Vol. 2, 8th Edition Miami, Florida: 1991.

PERCUSSIVE WELDING

A nonstandard term for PERCUSSION WELDING.

PERIODIC DUTY

A requirement of electrical service that demands operation for alternate periods of loads and rest in which the load conditions are well defined, with recurrent magnitude, duration and character.

PERMANENT MAGNET

A ferromagnetic material which can be magnetized permanently by applying a magnetic field to the material. A permanent magnet retains its magnetization and magnetic poles for a long period of time after the magnetizing field is removed.

PERMANENT MOLD

A form consisting of two or more parts which is used repeatedly to make castings of the same shape. Castings are made by pouring liquid metal into the mold cavity. After the cast metal solidifies, the mold is taken apart and can be reassembled and used again.

PERMANENT SET

The shape retained after plastic deformation of materials following drawing, bending and forming operations, after the stress that produced the deformation has been removed.

PERMEABILITY

(1) Sand Molds: The characteristic of the molding material which permits gases to pass through it.

(2) Powder Metallurgy: The property which indicates the rate at which a liquid or gas will pass through a sintered powdered metal compact.

(3) Magnetism: a term used to express the relationship between magnetic induction and magnetizing force. Stated another way, it is the affinity of a substance to conduct or carry magnetic lines of force.

PHASE

In a-c power, a phase is the cyclically recurring wave form of a current or voltage wave form. Phase also refers to the branches of an electrical circuit.

An a-c welding machine operates from single-phase electrical power. A d-c welding machine usually operates from three-phase electrical power, and utilizes a rectifier circuit to obtain d-c output for welding.

PHOS-COPPER

A brazing alloy filler metal made up of copper and 5 to 10% phosphorus. Phos-copper begins to melt at 714°C (1317°F) and is completely molten at about 832°C (1530°F). Phos-copper is considered to be a self-fluxing brazing alloy in which the phosphorous prevents oxide formation on the copper surfaces. However, if gas-tight or liquid-tight joints are required, or brass, bronze or other alloys are being joined, a paste flux is recommended. The paste is mixed with water and applied with a brush.

Phos-copper may be used to join copper and copper alloys, and has limited use for brazing silver, tungsten and molybdenum. These alloys should not be used for ferrous and nickel base alloys or on copper base alloys with more than 10% nickel to avoid formation of brittle, intermetallic phosphide compounds. Brazed phos-copper joints can be used for continuous service up to 150°C (300°F). Lap joints are recommended, but butt joints can be used where strength properties are less stringent. Recommended joint clearances are 0.03 to 0.13 mm (0.001 to 0.005 in.).

Brazing. The procedure for brazing with phos-copper depends on the material to be brazed and the brazing process, but the following are general procedures:

(1) Clean all joint surfaces thoroughly.

(2) If flux is needed, apply a paste flux mixed with water to all joint surfaces.

(3) Heat the joint to between 800 and 830°C (1475 and 1525°F), using a neutral flame if heating with an acetylene or other gas torch.

(4) Apply phos-copper rod or wire to the heated joint, ensuring that it flows into the joint gap.

If phos-copper ribbon is to be used instead of wire or rod, it should be inserted into the joint before heating, then heated to 830°C (1525°F), or until the braze has melted and flowed throughout the joint. Excess amounts of the phos-copper braze alloy in fillet joints, for example, should be avoided.

PHOSPHOR BRONZE

A bronze with a high degree of hardness, elasticity, and toughness, that contains a small amount of phosphorus. This group of copper, tin and phosphorus alloys contains from 1.3 to 10% tin and 0.03 to 0.35% phosphorus. These alloys may be brazed, soft soldered, and flash welded. They may also be *welded* with resistance spot welding and gas metal arc welding processes. Oxyfuel gas welding and shielded metal arc welding of the phosphor-bronze alloys produce only fair results.

A free-machining variety of phosphor bronze contains 3.5 to 4.5% lead, 3.5 to 4.5% tin, 1.5 to 4.5% zinc and 0.01 to 0.50% phosphorus. The free-machining alloys can be soldered, brazed, or flash welded, but other welding processes are not recommended.

Coated or uncoated welding rods are available for several of these alloys. Melting range for these alloys is 1035 to 1075°C (1900 to 1970°F) for the lower tin alloys, and 845 to 1000°C (1550 to 1830°F) for the higher tin alloys.

PHOSPHORUS

(Chemical symbol: P) A highly reactive, toxic, nonmetallic element used in steel, glass, and pyrotechnics. In the free state phosphorus has three allotropic forms; yellow, red and black. However, it is almost always found in combination with other elements such as minerals or metal ores. Atomic number, 15; atomic weight, 31.02; specific gravity, 12.16; and melting point, 44.2°C (111.6°F).

Phosphorus is usually found in steel and cast iron as an impurity. It is therefore the practice of steel makers to reduce the phosphorus level to 0.05%, or lower if possible. Higher amounts cause embrittlement and loss of toughness; however, small amounts of phosphorus in low-carbon steel produce a slight increase in strength and corrosion resistance.

PHOTOMICROGRAPH

A photographic reproduction of an object magnified more than ten times. In metallurgy, it usually refers to a polished and etched metal surface photographed through a microscope to show the grain structure and other microstructural constituents. As an example, photomicrographs are made of sections cut from a weld or a piece of metal to show the metallurgical structure. *See* METALLOGRAPHY.

PHYSICAL PROPERTIES

Characteristics of a material that can be measured without application of force. Examples of physical properties of metal that may require consideration in designing or fabricating a weldment are thermal and electrical conductivity, melting temperature, thermal expansion and contraction, and density. *See* METALLURGY. *See also* PHYSICAL TESTING.

PHYSICAL TESTING

Testing methods by which physical properties of materials are determined. This term may also be used for a test procedure in which mechanical properties are determined. *See* TESTING.

PICKLING

The chemical cleaning of steel surfaces by dissolving or loosening scale with acid. Sulfuric, hydrochloric, nitric and hydrofluoric acids in various combinations with water are used. Sulfuric-hydrochloric acid mixtures are used for plain carbon steels and low-alloy steels. Most pickling solutions include organic inhibitors, which minimize pitting and hydrogen pickup. Time in the pickling solution must be limited to minimize hydrogen pickup.

Stainless steels, nickel base alloys, titanium alloys, and copper alloys require more aggressive pickling solutions, which include nitric and hydrofluoric acids. The appropriate pickling specifications for a given alloy may be obtained from the producer of the alloy, or the ASM *Metals Handbook*, published by ASM International, Materials Park, Ohio.

PICKUP

This term usually refers to dilution of weld metal with metal melted from the base metal. To make a good weld, the joint edges of the base metal must be melted and intentionally mixed with the weld metal. This melted weld metal "picks up" metal from the base metal.

This term also applies to resistance welding, in which the electrode tips partially melt and weld to the base metal, and pick up metal from the other. This type of pickup results in degraded welds and can be avoided by correct control of the welding parameters, and by reshaping worn electrode tips to their original dimensions.

PIERCING

Producing a hole in metal by forcing a pointed bar through it. As an example, seamless steel tubing is usually made from a steel billet which has been pierced longitudinally and on center with a pointed probe.

The term *piercing* also applies to starting an oxyfuel gas or plasma arc cut at some point other than the edge of a piece of metal.

PIERCING, OXYGEN

See OXYGEN LANCE.

PIG IRON

Crude iron cast in oblong blocks, or "pigs." Pig iron is produced in a blast furnace by heating iron ore and coke with a limestone flux. Pig iron is high in carbon and impurities and must be refined to produce steel, wrought iron or ingot iron.

PILED PLATE CUTTING

See STACK CUTTING *and* OXYFUEL GAS CUTTING.

PILOT ARC

A low current arc between the electrode and constricting nozzle of a plasma arc torch to ionize the gas and facilitate the start of the welding arc. See STANDARD WELDING TERMS.

PINCH EFFECT

Pinch effect is the radial force or "pinch" on a conductor carrying an electrical current. For a given diameter wire, the effect is proportional to the square of the current. In gas metal arc welding (GMAW), the separation of molten drops of metal from the electrode is controlled by an electrical phenomenon called the *electromagnetic pinch effect.* Pinch effect on the welding wire is one of the most important factors controlling metal transfer. The shape, size and rate of transfer are governed by this phenomenon.

PINHOLES

Minute gas cavities sometimes found in weld deposits. *See* POROSITY.

PINTSCH GAS

A combustible gas, no longer used, produced by the destructive distillation of petroleum or some of its distillates. It is the oldest of the commercially compressed combustible gases, and greatly influenced the development of the compressed gas industry.

PIPE

A cavity formed incidentally in metal (especially ingots) during the solidification of the last portion of liquid metal. Contraction of the metal causes this cavity or pipe. The pipe in an ingot must be removed before rolling to prevent defects such as laminations, or cold shuts, that will reduce the strength of the product.

PIPING POROSITY

A form of porosity having a length greater than its width that lies approximately perpendicular to the weld face. See STANDARD WELDING TERMS.

PIPELINE REPAIRING, Under Pressure

Oil and gas pipelines become damaged in service as a result of severe rust pitting. Salt water and other chemicals in creek beds and in the ground cause rusting on the outside of the pipe. Sulphide gas inside the pipe causes corrosion and pitting. Leaks occurring when the pits penetrate the pipe wall must often be repaired while crude oil, gas or other petroleum products are being pumped through the pipe at pressures up to 3400 kPa (500 psi). These repairs can be difficult and hazardous, especially when flammable liquids are being carried.

Sometimes a large area of pitting will be repaired by "sleeving," in which a section from a slightly larger diameter pipe is cut to cover the pitted portion of pipe. The edges of the sleeve are fillet welded all around to the outer surface of the pipe.

In some cases, a section must be cut out and replaced, requiring that pumps be shut down, the pipeline section be bled of any liquid, and the section to be repaired purged with inert gas. The defective section is cut out and a replacement section of the same diameter and wall thickness is welded into the line.

PIPE, Thawing

Arc welding machines have been used effectively for thawing frozen metal water pipes, either underground or through the basement walls of a building. Leads from a welding machine are attached to the pipe on each side of the frozen section and the current is turned on until the ice begins to melt and the water pressure pushes the slush ice out of the pipe. One lead may be connected to a pipe inside the basement and the other lead to a shut-off valve outside by the curb.

If an entire main is frozen, cables may be connected to fire plugs on each end of the frozen section. C-clamps can be used to connect the ends of the cables to the pipe. It is critical that the connections to the pipe are tight and that no overheating takes place. These connections should be checked frequently while the current is flowing. The welding machine and cables should also be checked and adjusted to avoid overloading.

Copper and brass pipes have less electrical resistance than iron or steel and require higher current and longer times to thaw. Currents up to 500 amperes may be required depending on the pipe diameter. Particular care should be used with lead pipe to prevent melting the lead or joints; current of 75 amperes may be adequate for many cases, and should not exceed 150 amperes.

Details of specific instances of pipe thawing may be obtained from manufacturers of arc welding equipment.

PIPELINE WELDING

The American Petroleum Institute (API) sets specifications for welding procedures and qualifications for personnel employed on pipeline welding in its "*Standard for Welding Pipelines and Related Facilities*" (API Standard 1104). This document is available from the American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005-8029.

API Code 1104

Before production welding is started, a procedure specification must be established and qualified to demonstrate that welds having acceptable mechanical properties and soundness will result from the procedure. The quality and properties of the weld are determined by destructive testing. When tensile tests are performed, the tensile strength of the weld, including the fusion zone, should be equal to or greater than the minimum specified tensile strength of the pipe material.

The API Standard 1104 does not include welding procedures for joining steel pipelines; however, the API 1104 Committee has collected and cataloged successfully used procedures, and the Committee Secretary provides them on request as guides for those wishing to use them as a starting point for qualification.

These API Procedure Specifications are identified by the position of the pipe (horizontal or vertical), whether rolled during welding or maintained in a fixed position, and the range of diameter and wall thickness for which the procedure is considered suitable. These are basically suggestions which the skilled welder can use, with proper material and equipment, to gain qualification.

When API 1104 is applied to any pipeline project, it is mandatory that the method used in making, testing and inspecting welded joints is in complete conformance with the requirements of the Standard. The fabricator is expected to provide details of the procedure which are to be used on each particular pipe size.

Historical Background

First Pipelines. Pipelines were used to transport natural gas long before Edwin Drake drilled his first oil well. Hollow logs were used for this purposed in Fredonia, New York, in 1821. By 1862, cast iron pipe was used on a 6.4-km (4-mile), 50 mm (2-in.) line at Titusville, Pennsylvania. Soon after, wrought iron pipe came into the picture, with its various lengths joined by screwed couplings.

A search followed to find a way to make a tighter and stronger joint than the screw-type coupling provided. Attempts were made to weld pipelines with the oxyacetylene process; the first of these was an 18-km (11-mile) line laid in 1911 near Philadelphia. In 1914, a 55-km (34-mile) pipeline was constructed near Enid, Oklahoma, followed by a longer line in the bay area of San Francisco, which supplied gas for the 1915 Pan American Exposition.

However, the real breakthrough in welding came in 1922, when the Prairie Pipeline Company welded a 20-cm (8-in.) diameter, 225-km (140-mile) line carrying crude oil from Mexico to Jacksboro, Texas, using oxyacetylene welding. The advantages of welding over screwed couplings were clearly demonstrated when the final cost of the project was 35% less than it would have been if couplings had been used. The cost of the weld, labor and material was only $2.00 for each joint.

Pipeline Builders. After the surveyor's crew had identified the right-of-way, the "brush crew" came on the scene to clear away brush and trees. Then the trenching crew dug the trench for the pipeline. Sections of pipe were then dropped alongside the trench. The line-up and tacking crew came ahead of the construction gang. Aided by a tractor and hoist, they placed the pipe lengths on ball-bearing dollies to permit rolling. At four points in the circumference of the pipe, the tack welder made a tack weld, joining as many lengths of pipe as the contour of the land required. This long tack-welded section, lined up on the dollies, was left by the line-up and tacking crew for the "firing line" crew, the welders.

Several welders comprised the crew which completed the welding of the long tack-welded sections. Helpers turned the pipe with chain pipe wrenches, enabling the welders to weld at the top of the pipe, in the flat downward position.

PIPE RINGS (Backing Rings)

See PIPE WELDING, Backing Rings.

PIPE TEMPLATES

See PIPE WELDING, Accessories.

PIPE WELDING

Welding is the most important and most common method of joining all kinds of pipe, from cross-country line pipe to piping used in power plants, refineries and chemical processing plants. Much of this piping operates at high internal pressure, at temperature extremes or in corrosive environments. It is obvious that the welding used to join piping for these various applications must be of the highest quality and integrity.

Pipe welding is a specialized occupation different from plate welding. Welders must pass special tests on pipe welding to qualify for welding pipe in production or on an installation job. Performance tests have been established by the American Petroleum Institute (API) and the American Society of Mechanical Engineers (ASME). These societies have also established specifications for pipe composition and properties, and the American Welding Society has established filler metal specifications.

Pipe Steels and Welding Electrodes

The API publishes standards covering all aspects of pipe welding procedures, operator qualifications, joint design, testing, inspection and specifications for types of pipe steel.

In the early days of pipe welding, lap joints, or Bell and Spigot type joints (Figure P-4), were used with fillet welds instead of butt joints, because only bare or lightly coated electrodes which produced marginal weld properties were available at that time. Now, however, with the availability of a variety of coated electrodes and filler wires which provide the necessary weld properties, butt welds are used almost exclusively. Specifications for pipe steels range from 240 MPa (35 ksi.) min. yield, 414 MPa (60 ksi.) min. tensile for API Grade B X-42; to 448 MPa (65 ksi.) min. yield, 552 kPa (80 ksi.) min. tensile for API Grade B X-65. The higher strength steels allow the use of thinner pipe walls, and improved coatings are available to protect the pipe from corrosion caused by the soil.

Welder Qualification

API pipe welders must make butt welds to specification on API pipe of the same material they are to weld on the job. Four longitudinal specimens are cut from equally spaced locations around the pipe to include the weld at the midpoint of each. The specimens must be ground or machined to provide a uniform width across the weld and into the base metal. These specimens are tested in tension. The welder is qualified if three of the four, and in some cases, all four, break in the base material. This assures that the weld has at least the strength of the base metal. Welding and testing must be witnessed by an AWS-certified welding inspector. While on the job, the welding inspector may call for cutting out a pipe weld for subsequent cutting into four specimens and testing. The possibility of testing at any time helps assure that the welder is careful at all times.

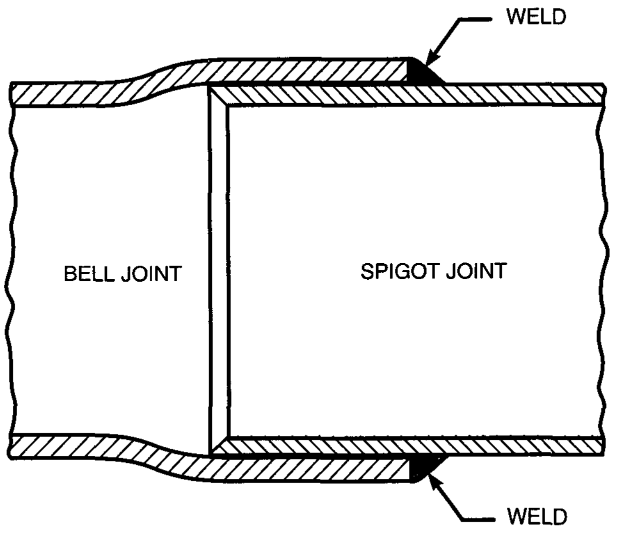


Figure P-4—Bell and Spigot Pipe Joint

Utility Piping

Local building codes must be consulted when welding, soldering, brazing or mechanically joining connections are used in commercial, industrial and residential buildings.

Piping is used in buildings to conduct water for plumbing and sprinkler systems, steam and gas, and for sewer, waste and vent connections. Copper tubing, which is joined by soft soldering (using lead-free solder), or brass pipe, which is joined by threaded connections or brazing, may be used for water piping. Steam heating systems which operate below 103 kPa (15 psi) may use wrought iron or steel piping, which can be welded. *See* BRAZING, SOLDERING, *and* COPPER ALLOY WELDING.

Forged Fittings for Welding

Forged steel fittings are made with beveled edges which match the beveled edges of pipes and form V-grooves when butted to the beveled pipe ends. The wall thickness of the fittings matches the wall thickness of the pipe, and presents an unrestricted flow path for the fluid. For low-pressure steam lines in buildings, pipe may be cut and beveled with an oxyfuel gas cutting torch, but the cut surfaces must be ground to remove scale and roughness. Cutting machines which produce a clean, uniform cut and bevel on pipe should be used when available.

Some city ordinances require pipes to be joined by threading. Where welding is allowed in local codes, cast iron and galvanized pipes may be brazed. Black wrought iron and steel pipe can be arc welded. Galvanized pipe is brazed in basically the same manner as other galvanized steels. *See* GALVANIZED IRON.

Nuclear Power Plants

Piping systems in nuclear power plants operate at approximately 315°C (600°F) under high pressure. These parameters, along with the need to prevent any leakage of radioactive fluids, require high weld integrity. Welders must be nuclear-qualified. To assure complete root penetration and fusion, the root pass is usually made by the manual gas tungsten arc welding (GTAW) process, and the remainder of the groove is filled by the manual shielded metal arc welding (SMAW) process. Submerged arc welding is used for shop welding of pipe where pipe sections can be rotated under the welding head.

Type 304 stainless steel is used extensively in primary piping for nuclear power systems to minimize corrosion and corrosion residue, which may become radioactive in the reactor coolant stream. High ferrite 308 filler rods are used to avoid hot cracking in the weld deposit. Extreme care must be used in the handling of carbon steel and stainless steel electrodes to prevent moisture pickup in the coating. Oven storage facilities should be provided at the job site.

Backing Rings

A backing ring is a device placed against the back side of a pipe joint to support the weld metal or bridge an excessive gap between pipe ends. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal.

Consumable Inserts

A consumable insert is a piece of metal formed into a ring which is fitted into the inside surface of the pipe or tube prior to welding. It should be essentially the same composition as the pipe or tube. The ring serves two purposes: (1) to help align the two pipes to be joined, and (2) to assure complete root penetration and fusion.

Several insert cross sections are available, as shown in Figure P-5. One type of flat ring is designed to fit inside both rings at the joint, another fits in the joint between the pipe ends, and others fit inside the pipes and in the joint. These rings are split and are cut to fit the inside diameter of the pipe. All are tack-welded to both pipe ends to be joined, providing alignment and filler material for the root weld pass, which is made by the GTAW process. Inert gas shielding of the root area of the joint is necessary for best results.

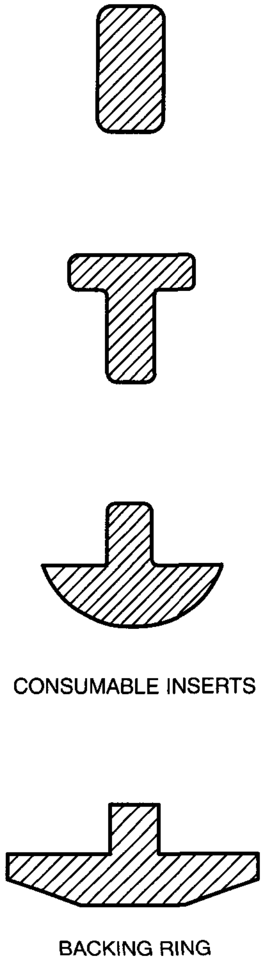


Figure P-5—Cross Sectional Views of Typical Consumable Inserts and a Backing Ring

Flat rings may have nubs formed or tack-welded to the outer surface to serve as spacers to establish the joint gap. The other shapes automatically establish the joint gap, align the pipes, and provide filler metal.

Stress Relieving

Stress relieving of pipe weld joints is recommended for lines operating at less than 200°C (400°F). All high-pressure steel pipe welds should be stress relieved at a temperature of about 620°C (1150°F) for one hour for each inch of wall thickness, then slow-cooled to room temperature. Stress relieving can be done (1) in a furnace, or (2) with a wrap-around electrical resistance heating pad connected to a transformer with a rating of about 200 kVA.

When welding thick-walled pipe, several small passes prove to be more satisfactory than using a few large passes. Depositing thin layers of weld bead helps prevent porosity and produces a finer grain structure, as a result of the thermal effect of each successive pass on previous passes. Each bead is cleaned with a light chipping hammer and a wire brush to remove all slag particles.

Pipe Welding Processes

All of the standard arc welding processes are suitable for welding pipe, although the shielded metal arc welding (SMAW) process is used for the majority of pipe welds. Oxyacetylene welding was formerly used for welding pipe of less than 100 mm (4 in.) diameter. The advantage of this process is that base metal can be heated without applying filler metal, and heat can be applied independently of the rate of filler metal addition, particularly for making root passes. At present, however, many root passes are made by the GTAW process, followed by one or more shielded metal arc passes to fill the joint. This is true for welding stainless steel and especially nuclear piping, where stainless steel and high-nickel alloys are used. Gas tungsten arc welding is used more frequently for filler passes in these materials, especially for critical highly stressed applications.

Pipes made of the so-called exotic metals, such as titanium, zirconium and tantalum must be arc welded by an inert gas process, GTAW or GMAW, with inert gas shielding of the weld root. The plasma arc welding (PAW) process uses an inert gas shield, and in many cases can be used in place of the GTAW process.

Submerged arc welding (SAW) is used frequently for pipe welding in fabricating shops, where it is considered to be the most efficient pipe welding process available. It is applied mainly to large-diameter pipes where it is possible to clamp sections of pipe together and rotate them so that all welding is done in the flat position. Its greatest use is in the double lengthening of line pipe, where two or more sections of pipe are shop-welded into longer sections.

When welding steel piping with the GMAW process, CO_2 or argon-CO_2 gas mixtures are used. Argon is the primary shielding gas used when welding stainless steel, nickel base alloys and aluminum.

Accessories

Many types of clamps, jigs and fixtures are available for holding pipe in position for welding. Rollers allow pipe sections to be rotated together so that the entire joint can be welded from the top in the flat position. It is best that the ends of pipe be cut and joint preparation be done by machining to provide the cleanest and most accurate fit. Oxyacetylene cutting torches or plasma arc cutting torches can be used to cut bevels on pipe that is rotated under the torch. If the rotating equipment is not available or an irregular cut is required, it may be necessary to do the cutting with a hand-held torch.

Pipe Clamps. Clamps are used to hold pipe ends together in proper alignment for tack welding. A typical bar clamp is shown in Figure P-6. These devices feature quick-release handles for holding a wide range of pipe diameters. Sets of rollers, as shown in Figure P-7, can be used to rotate the pipe as it is being welded. Usually four sets of rollers are required to support two sections of straight pipe.

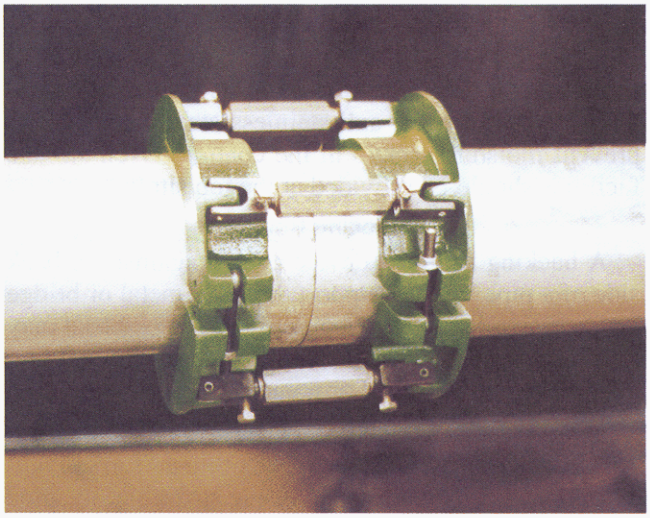


Figure P-6—A Typical Bar Clamp Used to Hold Pipe Ends Together for Tack Welding

Photo courtesy of Walhonde Tools, Inc.

Miter Joints. The design of miter joints produces a sharp bend in right angle connections unless the joint is made with more than one weld. Miter joints are not recommended and should be avoided, not only because they are difficult and expensive to lay out and

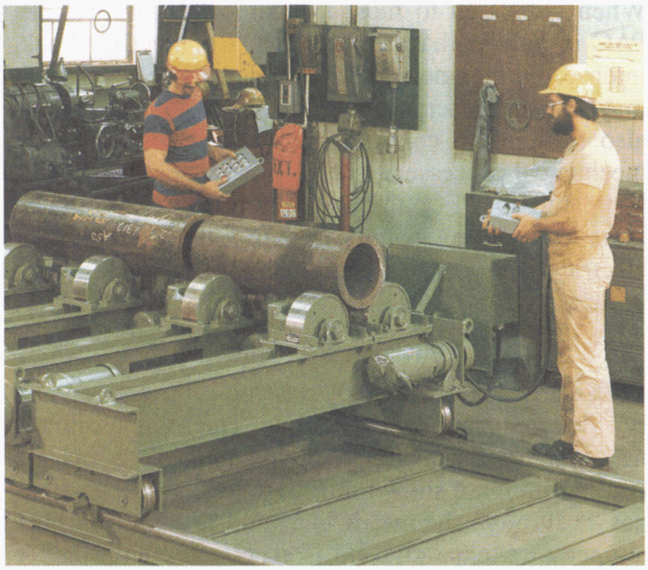


Figure P-7—Turning Rolls Used to Rotate Pipe for Welding

Photo courtesy of Koike Aronson, Inc.

weld, but also because they result in sharp bends that cause turbulence and added resistance to flow. Stresses from thermal expansion and contraction and other loads on the system can be excessive and concentrated at the miter joint welds. Weld fittings are available for every situation where a miter connection would be used and are much simpler to install. *See also* ORBITAL TUBE WELDING.

PIPING CODE

See PRESSURE PIPING CODE.

PIPING, Building

See PIPE WELDING.

PIPING, Power Plant

See PIPE WELDING, Nuclear Power Plants.

PIPING, Pressure

See PIPE WELDING.

PIPING, Refrigeration

ASME B31.5, Refrigeration Piping, covers piping systems for refrigerant and brine at temperatures as low as –196°C (–320°F), whether erected on the premises or factory assembled. Coverage does not include (1) self-contained or unit refrigeration systems subject to requirements of Underwriters Laboratories or any other nationally recognized testing laboratory, (2) water piping, or (3) piping designed for external or internal pressure not exceeding 103 kPa (15 psig) regardless of size. *See* PIPE WELDING.

PIT

A depression in the surface of a metal.

PLAIN CARBON STEEL

See STEEL, Carbon.

PLANISHING

See ROLL PLANISHING.

PLASMA

See STANDARD WELDING TERMS. *See also* ARC PLASMA.

PLASMA ARC

The arc plasma forms as a result of the electrical heating of any gas to a very high temperature so that its atoms are ionized and conduct electricity.

The plasma arc torch consists of an electrode surrounded by a constricting nozzle which forms a plenum chamber around the electrode. The plasma gas flows through this chamber and is heated and ionized by an electric current between the electrode and the nozzle or the work. The heating causes the gas to expand greatly and exit a small orifice at the end of the nozzle at high velocity. A pilot arc or high-frequency spark is required to start the main arc.

The plasma gas exits from the nozzle at very high speeds and temperatures; up to 16 000°C (30 000°F) and 6000 m/s (20 000 ft/s). The energy of the arc is concentrated in a small area and thereby produces very rapid heating of the workpiece it impinges.

There are two forms of plasma arc torch operation: transferred arc and non-transferred arc. In the transferred arc mode, the arc current flows between the electrode and the work. This mode of operation is used for welding and cutting. In the non-transferred arc version, the current flows from the electrode to the torch nozzle. The arc within the nozzle heats the plasma gas which exits the nozzle at high speed. This mode of operation is used for plasma spraying powder, where no electrical connection is made with the work. The extreme heat of the arc is absorbed partly by the water-cooled nozzle and partly by the plasma gas on ionization. When the ionized gas strikes the workpiece, it gives up its energy to supply heat to the workpiece as it returns to the normal gaseous state.

PLASMA ARC CUTTING (PAC)

An arc cutting process that uses a constricted arc and removes the molten metal with a high velocity jet of ionized gas issuing from the constricting orifice. See STANDARD WELDING TERMS.

Plasma arc cutting produces fast, high-quality cuts that often require no further finishing. It accomplishes this by passing an electric current through a column of gas, causing it to ionize and become a plasma. The resulting plasma produces temperatures up to 16 000°C (30 000°F). This causes the gas to expand and results in high-velocity flow through the torch orifice. When this high-temperature plasma arc stream strikes a workpiece, it melts the metal rapidly, and the high-velocity jet blows it away. The process makes clean cuts and forms little or no dross or slag on most metals, requires no preheat, and produces a minimum heat-affected zone, with little or no distortion.

While oxyfuel gas cutting is limited to metals which combine with oxygen at elevated temperatures, plasma arc cutting is not limited to this chemical reaction: it is only limited to materials which are electrical conductors.

Historical Background

PAC was invented in the mid 1950s and became commercially successful shortly after its introduction to industry. The ability of the process to sever any electrically conductive material made it especially attractive for cutting nonferrous metals that could not be cut by the oxyfuel cutting (OFC) process. It was initially used for cutting stainless steel and aluminum. As the cutting process was developed, it was found that it had advantages over other cutting processes for cutting carbon steel as well as nonferrous metals.

Advantages and Limitations

Advantages. When compared to mechanical cutting processes, the amount of force required to hold the workpiece in place and move the torch (or vice versa) is much lower with the "non-contact" plasma arc cutting process. Compared to OFC, the plasma cutting process operates at a much higher energy level, resulting in faster cutting speed. In addition to its higher speed, PAC has the advantage of instant start-up without requiring preheat. Instantaneous starting is particularly advantageous for applications involving interrupted cutting, such as severing mesh.

Limitations. There are notable limitations to PAC. When compared to most mechanical cutting means, PAC introduces hazards such as fire, electric shock, intense light, fumes and gases, and noise levels that may not be present with mechanical processes. It is also difficult to control PAC as precisely as some mechanical processes for close tolerance work. When compared to OFC, the PAC equipment tends to be more expensive, requires a fairly large amount of electric power, and introduces electrical shock hazards.

Principles of Operation

The arc is constricted by passing it through an orifice downstream of the electrode. The basic terminology and the arrangement of the parts of a plasma cutting torch are shown in Figure P-8. As plasma gas passes through the arc, it is heated rapidly to a high temperature, expands, and is accelerated as it passes through the constricting orifice toward the workpiece. The intensity and velocity of the plasma is determined by several variables including the type of gas, its pressure, the flow pattern, the electric current, the size and shape of the orifice, and the distance to the workpiece. Plasma arc cutting circuitry is shown in Figure P-9. The process operates on direct current, straight polarity. The orifice directs the super-heated plasma stream from the electrode toward the workpiece. When the arc melts the workpiece, the high-velocity jet blows away the molten metal to form the kerf, or cut. The cutting arc attaches to or "transfers" to the workpiece, and is referred to as a *transferred arc*.

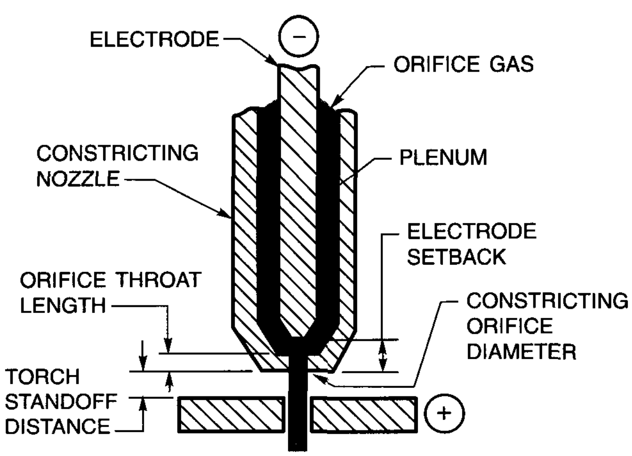


Figure P-8—Plasma Arc Torch Terminology

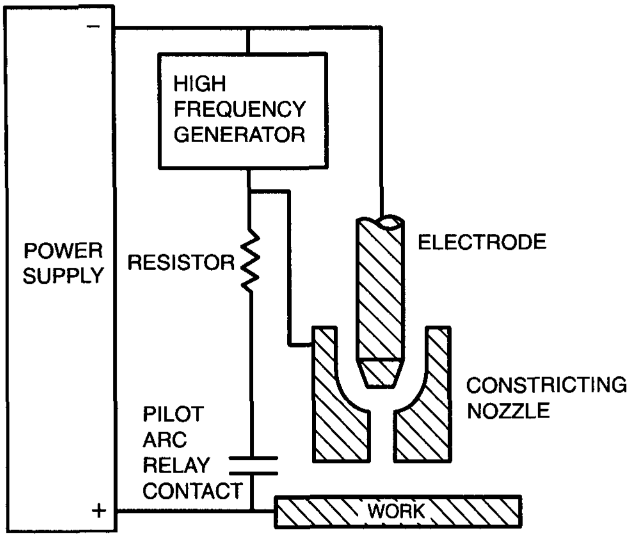


Figure P-9—Basic Plasma Arc Cutting Circuitry

The gases used for plasma arc cutting include nitrogen, argon, air, oxygen, and mixtures of nitrogen/hydrogen and argon/hydrogen.

The most common pilot arc starting technique is to strike a high-frequency spark between the electrode and the torch tip. A pilot arc is established across the resulting ionized path. When the torch is close enough to the workpiece so the plume or flame of the pilot arc touches the workpiece, an electrically conductive path from the electrode to the workpiece is established. The cutting arc will follow this path to the workpiece.

Equipment

Torches. The plasma cutting process is used with either a hand-held torch or a mechanically-mounted torch. There are several types and sizes of each, depending on the thickness of metal to be cut. Some torches can be dragged along in direct contact with the workpiece, while others require that a standoff be maintained between the tip of the torch and workpiece.

Certain plasma arc torch parts must be considered to be consumable. The tip and electrode are the most vulnerable to wear during cutting, and cutting performance deteriorates as they wear. The timely replacement of consumable parts is required to achieve good quality cuts.

Power Supplies. Plasma arc cutting requires a constant current or drooping volt-ampere characteristic, relatively high-voltage, direct-current power supply. To achieve satisfactory arc starting performance, the open circuit voltage of the power supply is generally about twice the operating voltage of the torch. Operating voltages will range from 50 or 60 volts to over 200 volts so PAC power supplies will have open circuit voltages ranging from about 150 to over 400 volts.

Newer types of plasma cutting power supplies include electronic phase control and various types of "switch mode," or inverter, power supplies. The switch mode power supplies utilize high-speed, high-current semiconductors to control the output. They can either regulate the output of a standard DC power supply, the so-called "chopper" power supply, or they can be incorporated in an inverter-type power supply. As new types of semiconductors become commercially available, it can be expected that improved versions of this type of power supply will appear. Switch mode supplies have the advantage of higher efficiency and smaller size, and are attractive for applications where portability and efficiency are important considerations.

Motion Equipment. A variety of motion equipment is available for use with mechanized plasma cutting torches. This equipment can range from straight-line tractors to numerically-controlled or direct computer-controlled cutting machines with parts nesting capabilities, etc. Plasma cutting equipment can also be adapted to robotic actuators for cutting other than flat plates.

Environmental Controls. The plasma cutting process is inherently a noisy and fume-generating process. Several different devices and techniques are available to control and contain the hazards. One commonly used approach to reduce noise and fume emissions is to cut over a water table and surround the arc with a water shroud. This method requires a cutting table filled with water up to the work-supporting surface, a water shroud attachment for the torch, and a recirculating pump to draw water from the cutting table and pump it through the shroud. In this case, a relatively high 55 to 75 L/min (15 to 20 gpm) water flow is used.

Another method, underwater plasma cutting, is also in common use. With this method, the working end of the torch and the plate to be cut are submerged under approximately 75 mm (3 in.) of water. While the torch is underwater but not cutting, a constant flow of compressed air is maintained through the torch to keep water out.

The primary requirements in water table design are adequate strength for supporting the work, sufficient scrap capacity to hold the dross or slag resulting from cutting, procedure for removing the slag, and ability to maintain the water level in contact with the work. When the table is used for underwater cutting, it is necessary to provide a means of rapidly raising and lowering the water level. This can be accomplished by pumping the water in and out of a holding tank, or by displacing it with air in an enclosure under the surface of the water.

A cutting table for mechanized or hand plasma cutting is usually equipped with a down-draft exhaust system. This is vented to the outdoors in some cases, although fume removal or filtering devices may be required to meet air pollution regulations.

Applications

The first commercial application of plasma arc cutting was the mechanized cutting of manway holes on aluminum railroad tank cars at the Graver Tank plant in Edgemoor, Delaware. In five minutes the plasma arc torch produced a beveled, ready-to-weld joint, in a 16 mm (5/8 in.) thick shell that previously took five hours to prepare. The process has since been used on a wide variety of aluminum applications. Table P-1 shows typical conditions for mechanized cutting of aluminum plate.

Typical conditions for mechanized cutting of stainless steel plate are shown in Table P-2.

Manual plasma arc cutting is widely used in automobile body repair for cutting high-strength low-alloy (HSLA) steel. Instant starting and high travel speeds reduce heat input to the high-strength, low-alloy steel and help maintain its strength.

The chief application of mechanized plasma arc cutting of carbon steel is for thicknesses up to 13 mm (1/2 in.). The higher cost of plasma arc equipment compared to oxyfuel cutting (OFC) equipment can be justified by the former's higher cutting speeds. Conditions for mechanized plasma arc cutting of carbon steel plate are shown in Table P-3.

The plasma process has been used for stack cutting of carbon steel, stainless steel, and aluminum. The plates to be stack-cut should preferably be clamped together, but PAC can tolerate wider gaps between plates than OFC.

Plate and pipe edge beveling is done by using techniques similar to those for OFC. One to three PAC torches are used, depending on the joint preparation required.

Cut Quality

Factors to consider in evaluating the quality of a cut include surface smoothness, kerf width, kerf angle, dross adherence, and squareness of the top edge. These factors are affected by the type of material being cut, the equipment being used, and the cutting conditions.

Plasma cuts in plates up to approximately 75 mm (3 in.) thick may have a surface smoothness very similar to that produced by oxyfuel gas cutting.

Kerf widths of plasma arc cuts are 1-1/2 to 2 times the width of oxyfuel gas cuts in plates up to 50 mm (2 in.) thick. For example, a typical kerf width in 25 mm (1 in.) stainless steel is approximately 5 mm (3/16 in.). Kerf width increases with plate thickness. A plasma cut in 180 mm (7 in.) stainless steel made at approximately 3 mm/s (4 in./min) has a kerf width of 28 mm (1-1/8 in.).

The plasma jet tends to remove more metal from the upper part of the kerf than from the lower part. This results in beveled cuts wider at the top than at the bottom. A typical included angle of a cut in 25 mm (1 in.) steel is four to six degrees. This bevel occurs on one side of the cut when orifice gas swirl is used. The bevel angle on both sides of the cut tends to increase with cutting speed.

Dross is the material that melts during cutting and adheres to the bottom edge of the cut face. With mechanized equipment, dross-free cuts can be produced on aluminum and stainless steel up to approximately 75 mm (3 in.) thickness and on carbon steel up to approximately 40 mm (1-1/2 in.) thickness. With carbon steel, selection of speed and current are more critical. Dross is usually present on cuts in thick materials.

Top edge rounding will result when excessive power is used to cut a given plate thickness or when the torch standoff distance is too large. It may also occur in high-speed cutting of materials less than 6 mm (1/4 in.) thick. Examples of high-definition (square edge, dross-free) plasma arc cuts in carbon and stainless steel are shown in Figure P-10.

Metallurgical Effects

During PAC, the material at the cut surface is heated to its melting temperature and ejected by the force of the plasma jet. This produces a heat-affected zone along the cut surface, as with fusion welding operations. The heat not only alters the structure of the metal in this zone, but also introduces internal tensile stresses from the rapid expansion, upsetting, and contraction of the metal at the cut surface.

The depth to which the arc heat will penetrate the workpiece is inversely proportional to cutting speed. The heat-affected zone on the cut face of a 25 mm

Table P-1
Typical Conditions for Plasma Arc Cutting of Aluminum Plate

Thickness		Speed		Orifice Diam*		Current	
mm	in.	mm/s	in./min	mm	in.	(dcsp), A	Power kW
6	1/4	127	300	3.2	1/8	300	60
13	1/2	86	200	3.2	1/8	250	50
25	1	38	90	4.0	5/32	400	80
51	2	9	20	4.0	5/32	400	80
76	3	6	15	4.8	3/16	450	90
102	4	5	12	4.8	3/16	450	90
152	6	3	8	6.4	1/4	750	170

*Plasma gas flow rates vary with orifice diameter and gas used from about 47 L/min. (100 ft^3/h) for a 3.2 mm (1/8 in.) orifice to about 120 L/min. (250 ft^3/h) for a 6.4 mm (1/4 in.) orifice. The gases used are nitrogen and argon with hydrogen additions from 0 to 35%. The equipment manufacturer should be consulted for each application.

Table P-2
Typical Conditions for Plasma Arc Cutting of Stainless Steel

Thickness		Speed		Orifice Diam*		Current	
mm	in.	mm/s	in./min	mm	in.	(dcsp), A	Power kW
6	1/4	86	200	3.2	1/8	300	60
13	1/2	42	100	3.2	1/8	300	60
25	1	21	50	4.0	5/32	400	80
51	2	9	20	4.8	3/16	500	100
76	3	7	16	4.8	3/16	500	100
102	4	3	8	4.8	3/16	500	100

*Plasma gas flow rates vary with orifice diameter and gas used from about 47 L/min. (100 ft^3/h) for a 3.2 mm (1/8 in.) orifice to about 94 L/min. (200 ft^3/h) for a 4.8 mm (3/16 in.) orifice. The gases used are nitrogen and argon with hydrogen additions from 0 to 35%. The equipment manufacturer should be consulted for each application.

Table P-3
Typical Conditions for Plasma Arc Cutting of Carbon Steel

Thickness		Speed		Orifice Diam*		Current	
mm	in.	mm/s	in./min	mm	in.	(dcsp), A	Power kW
6	1/4	86	200	3.2	1/8	275	55
13	1/2	42	100	3.2	1/8	275	55
25	1	21	50	4.0	5/32	425	85
51	2	11	25	4.8	3/16	550	110

*Plasma gas flow rates vary with orifice diameter and gas used from about 94 L/min. (200 ft^3/h) for a 3.2 mm (1/8 in.) orifice to about 104 L/min. (300 ft^3/h) for a 4.8 mm (3/16 in.) orifice. The gases used are usually compressed air, nitrogen with up to 10% hydrogen additions, or nitrogen with oxygen added downstream from the electrode (dual flow). The equipment manufacturer should be consulted for each application.

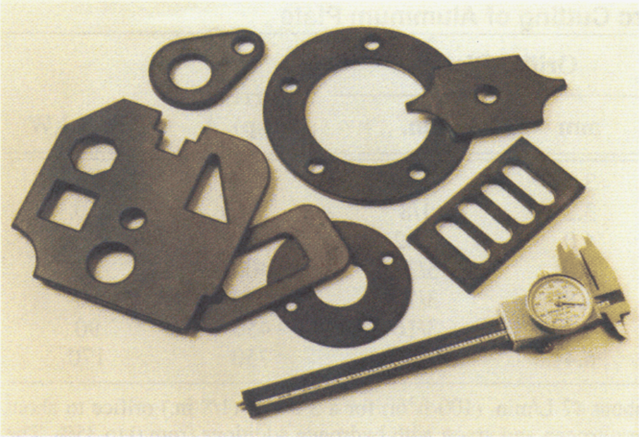


Figure P-10—High Definition (Square Edge) Plasma Arc Cuts in Carbon Steel Made Using Oxygen as the Cutting Gas

Photo courtesy of Hypertherm, Inc.

(1 in.) thick stainless steel plate severed at 21 mm/s (50 in./min) is 0.08 to 0.13 mm (0.003 to 0.005 in.) deep. This measurement was determined from microscopic examination of the grain structure at the cut edge of a plate.

Because of the high cutting speed on stainless steel and the quenching effect of the base plate, the cut face passes through the critical 650°C (1200°F) temperature very rapidly. Thus, there is virtually no chance for chromium carbide to precipitate along the grain boundaries, so corrosion resistance is maintained. Measurements of the magnetic properties of Type 304 stainless steel made on base metal and on plasma arc cut samples indicate that magnetic permeability is unaffected by arc cutting.

Metallographic examination of cuts in aluminum plates indicates that the heat-affected zones in aluminum are deeper than those in stainless steel plate of the same thickness. This results from the higher thermal conductivity of aluminum. Micro-hardness surveys indicate that the heat effect penetrates about 5 mm (3/16 in.) into a 25 mm (1 in.) thick plate. Age-hardenable aluminum alloys of the 2000 and 7000 series are crack-sensitive at the cut surface. Cracking appears to result when a grain boundary eutectic film melts and separates under stress. Machining to remove the cracks may be necessary on edges that will not be welded.

Hardening will occur in the heat-affected zone of a plasma arc cut in high-carbon steel if the cooling rate is very high. The degree of hardening can be reduced by preheating the workpiece to reduce the cooling rate at the cut face.

Various metallurgical effects may occur when long, narrow, or tapered parts, or outside corners are cut. The heat generated during a preceding cut may reach and adversely affect the quality of a following cut.

Safety

The potential hazards of plasma arc cutting and gouging are similar to those of most arc welding and cutting. The following information concerns the less obvious hazard categories of electrical shock, fume and gas generation, noise, and radiation.

Emergency first aid should be available. Prompt, trained emergency response may reduce the extent of injury due to accidental electrical shock. Only trained personnel should be permitted to operate or maintain the equipment. In addition to the manufacturer's instructions, the following may be of assistance:

(1) ANSI C-2, the National Electrical Safety Code

(2) ANSI Z49.1, Safety in Welding and Cutting

(3) 29CFR1910, OSHA General Industry Standards

(4) NFPA Standard 51B, *Fire Prevention in the Use of Cutting and Welding Processes.*

The equipment should not be operated until the manufacturer's instructions have been read and understood. In addition, other potential physical hazards such as those due to the high-pressure gas and water systems must be considered.

Some cutting gas mixtures contain hydrogen. Inadvertent release of such gases can result in explosion and fire hazards. The equipment should not be operated when gas leaks are suspected. The manufacturer should be contacted if there is a question about the equipment operation with certain gases.

Electrical. Voltages used in plasma cutting equipment range from 150 to 400 V direct current. Electric shock can be fatal. The equipment must be properly grounded and connected as recommended by the manufacturer.

Some additional safety items are listed below:

(1) Keep all electrical circuits dry. Moisture may provide an unexpected path for current flow. Equipment cabinets that contain water and gas lines as well as electrical circuits should be checked periodically for leaks.

(2) All electrical connections should be kept mechanically tight. Poor electrical connections can generate heat and start fires.

(3) Cable insulated for high voltage should be used. Make sure cables and wires are kept in good repair. Consult the manufacturer's instructions for proper cable and wire sizes.

(4) Do not touch live circuits. Keep equipment access doors closed.

(5) The risk of electrical shock is probably the greatest when replacing used torch parts. Operators must make sure that the primary power to the power supplies and the power to the control circuitry is disconnected when replacing torch parts.

(6) Operators and maintenance personnel should be aware that plasma arc cutting equipment, due to the higher voltages, presents a greater hazard than conventional welding equipment.

Fumes and Gases. Plasma arc cutting produces fumes and gases which can harm the operator's health. The composition and rate of generation of fumes and gases depend on many factors including arc current, cutting speed, material being cut, and gases used. The fume and gas by-products will usually consist of the oxides of the metal being cut, ozone, and oxides of nitrogen.

These fumes must be removed from the work area or eliminated at the source by using an exhaust system. Codes may require that the exhaust be filtered before being vented to the atmosphere.

There is a possibility of hydrogen detonation beneath the workpiece when cutting aluminum or magnesium plate on a water table. This can be caused by hydrogen released by the interaction of molten aluminum or magnesium and water. The hydrogen can accumulate in pockets under the workpiece and ignite when the cutting arc is near the pocket. Before cutting aluminum or magnesium on a water table, the equipment manufacturer should be contacted for recommended practices.

Noise. The amount of noise generated by a PAC torch operated in the open depends primarily on the cutting current. A torch operating at 400 A typically generates approximately 100 dBA measured at about six feet. At 750 A the noise level is about 110 dBA. Much of the noise is in the frequency range of 5000 to 20 000 Hz. Such noise levels can damage hearing. Hearing protection should be worn when the noise level exceeds specified limits. These values may vary locally and are specified by OSHA for most industrial environments.

The water-shroud technique is commonly used to reduce noise in mechanized cutting applications. The water effectively acts as a sound-absorbing enclosure around the torch nozzle. The water directly below the plate keeps noise from coming through the kerf opening.

Radiation. The plasma arc emits intense visible and invisible (ultraviolet and infrared) radiation. In addition to potential harm to the eyes and skin, this radiation may produce ozone, oxides of nitrogen, or other toxic fumes in the surrounding atmosphere.

It is necessary to wear eye and skin protection when exposure to radiation is unavoidable. The recommended eye protection is shown in Appendix 18. The likelihood of radiation exposure may be reduced by the use of mechanical barriers such as walls and welding curtains. The water shroud will also act as a light-absorbing shield, especially when dye is added to the water in the table. When the use of dye is contemplated, contact the equipment manufacturer for information on the type and concentration to use. It is advisable to provide operator eye protection, even when using these dyes, because of the possibility of unexpected interruption of water flow through the water shroud. *See* PLASMA ARC *and* PLASMA ARC WELDING.

PLASMA ARC CUTTING TORCH

A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of shielding gas and orifice gas. See STANDARD WELDING TERMS.

PLASMA ARC GOUGING

Plasma arc gouging is an adaptation of the plasma cutting process. For gouging, arc constriction is reduced, resulting in a lower arc stream velocity. The temperature of the arc and the velocity of the gas stream are used to melt and expel metal in a similar manner to other gouging processes. A major difference compared to other gouging processes is that the gouge is bright and clean, particularly on nonferrous material such as aluminum and stainless steel. Virtually no post-cleaning is required when the plasma gouged surface is to be welded. A plasma arc gouging operation on stainless steel plate is shown in Figure P-11.

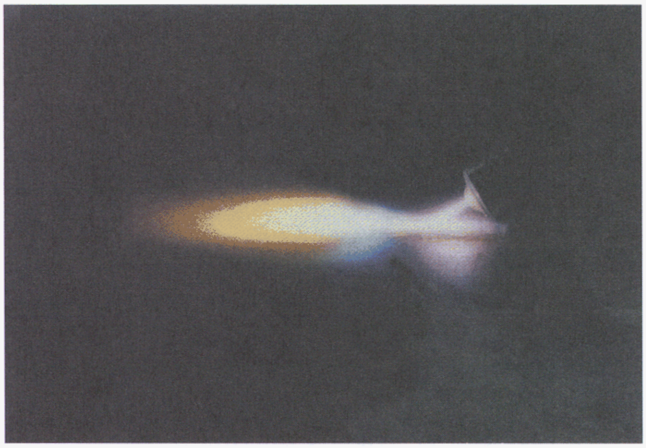


Figure P-11—Plasma Arc Gouging of Stainless Steel Plate

Equipment

The basic equipment for plasma gouging is the same as for plasma cutting. Most plasma cutting equipment can be used for plasma gouging provided that the volt-ampere output curve of the power source is steep enough and the voltage high enough to sustain the long arc used for plasma gouging.

The torch utilizes a gouging tip which is designed to give a softer, wider arc and proper stream velocity. The torch used is the same as a plasma cutting torch and may be either single- or dual-gas flow and air or water cooled.

Gases

The recommended plasma gas for all gouging is argon plus 35 to 40% hydrogen. The gas can be supplied from cylinders or prepared using a gas-mixing device. Helium may be substituted for the argon-hydrogen mixture, but the resulting gouge will be shallower. The secondary or cooling gas, when used, is argon, nitrogen, or air. Selection is based on brightness of gouge desired, fume generation, and cost.

Air is sometimes used for the plasma gas on air operating systems but is generally limited to carbon steel gouging. Most manual air cutting systems are limited to 100 A output and this restricts the size and speed of plasma gouging.

Operating Procedure

The technique for plasma gouging is essentially the same as for other gouging methods. The torch is angled approximately 30° from the horizontal. Gouge depth is determined by speed of travel. It is important not to attempt removal of too much metal in a single pass.

Applications

Plasma gouging can be used on all metals. It is particularly effective on aluminum and stainless steel, where the gouges produced are clean and devoid of any carbon contamination. *See* PLASMA ARC, PLASMA ARC WELDING, *and* PLASMA ARC CUTTING.

PLASMA ARC WELDING (PAW)

An arc welding process that uses a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from the ionized gas issuing from the torch, which may be supplemented by an auxiliary source of shielding gas. The process is used without the application of pressure. See also HOT WIRE WELDING.

Historical Background

One of the earliest plasma arc systems was a gas vortex stabilized device introduced by Schonherr in 1909. In this unit, gas was blown tangentially into a tube through which an arc was struck. The centrifugal force of the gas stabilized the arc along the axis of the tube by creating a low pressure axial core. Arcs up to several meters in length were produced, and the system proved useful for arc studies.

Gerdien and Lotz built a water vortex arc-stabilizing device in 1922. In this device, water injected tangentially into the center of a tube was swirled around the inner surface and ejected at the ends. When an arc struck between carbon electrodes was passed through the tube, the water concentrated the arc along its axis, producing higher current densities and temperatures than were otherwise available. The Gerdien and Lotz invention had no practical metalworking applications because of the rapid consumption of its carbon electrodes and the presence of water vapor in the plasma jets.

While working on the arc melting of refractory metals in 1953, R. M. Gage, U.S. Patent No. 2 806 124, observed the similarity in appearance between a long electric arc and an ordinary gas flame. Efforts to control the heat intensity and velocity of the arc led to the development of the modern plasma arc torch.

The first practical plasma arc metal-working tool was a cutting torch introduced in 1955. This device was similar to a gas tungsten arc welding torch in that it used a tungsten electrode and a "plasma" gas. However, the electrode was recessed in the torch, and the arc was constricted by passing it through an orifice in the torch nozzle. The usual circuitry for gas tungsten arc welding was supplemented in the plasma arc cutting torch with a pilot arc circuit for arc initiation.

Principles of Operation

The plasma arc process can be considered as an extension of the gas tungsten arc welding process. However, the plasma arc processes have a much higher arc energy density and higher gas velocity as a result of the arc plasma being forced through a constricting nozzle. *See* Figure P-12 for a comparison of the gas tungsten arc and plasma arc welding torch configurations. A plasma arc welding torch consists of a central tungsten electrode, a constricting nozzle with a small orifice and an outer gas nozzle which supplies shielding gas to the material being welded.

As the orifice gas passes through the plenum chamber of the plasma torch, it is heated by the arc, expands and exits through the constricting orifice at high velocity. Since too powerful a gas jet can cause turbulence in the weld puddle, orifice gas flow rates are generally held to within 0.25 to 5 L/min (0.5 to 10 cu ft/hr). The orifice gas alone is not normally adequate to shield the weld pool from atmospheric contamination, therefore auxiliary shielding gas is provided through an outer gas nozzle. Typical shielding gas flow rates are in the range of 10 to 30 L/min (20 to 60 cu ft /hr).

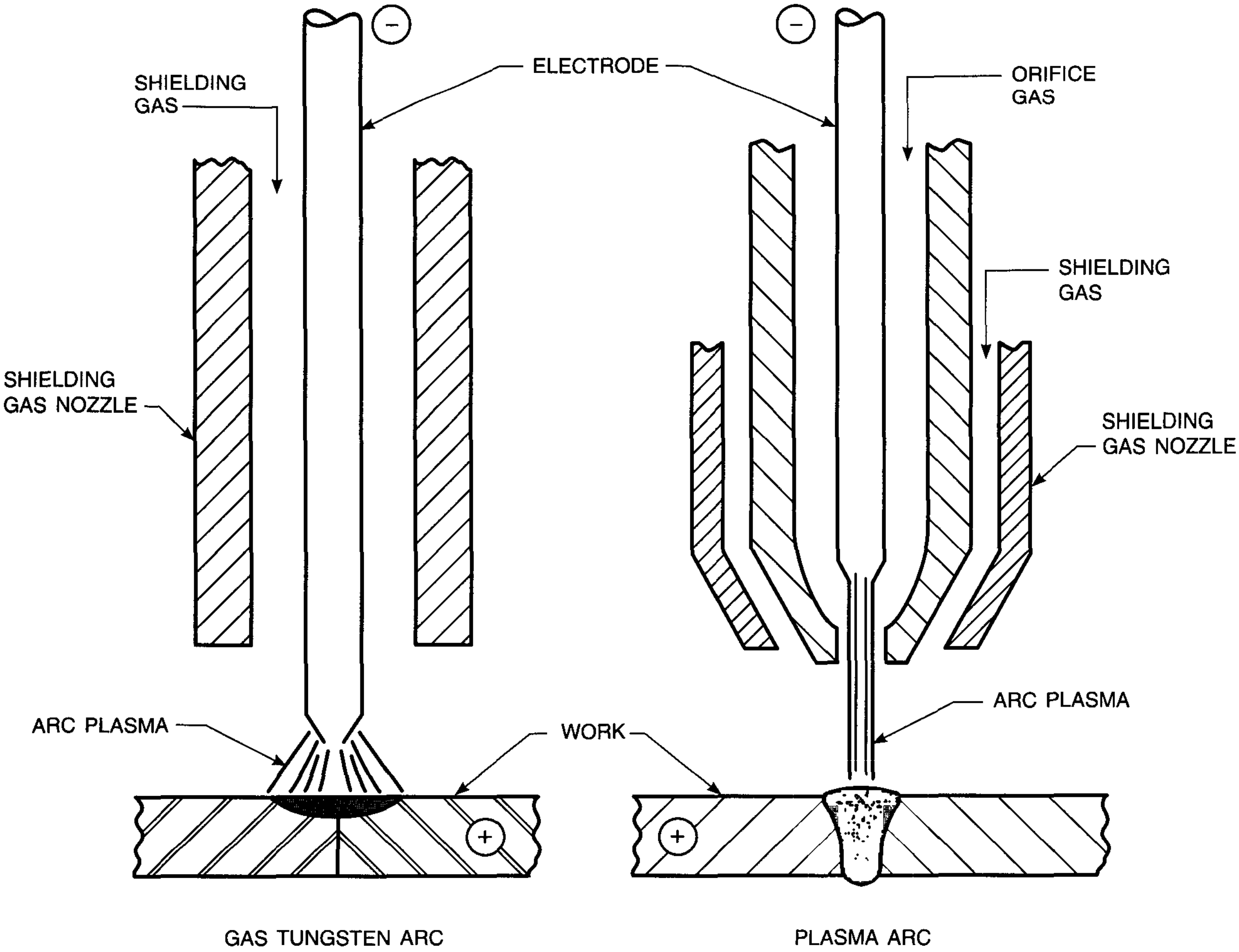


Figure P-12—Comparison of Gas Tungsten Arc and Plasma Arc Processes

The degree of arc collimation, arc force, energy density on the workpiece and other characteristics are primarily functions of the following:

(1) Plasma current

(2) Orifice diameter and shape

(3) Type of orifice gas

(4) Flow rate of orifice gas

The fundamental differences among the plasma arc metalworking processes, arise from the relationship of these four factors. They can be adjusted to provide very high or very low thermal energies. The very high flow rates may result in turbulence and perhaps remove the melted metal from a groove. Therefore, the high energy densities, small orifice diameters and high jet velocities are used for cutting. For welding, a low plasma jet velocity is necessary to prevent expulsion of the molten metal from the groove. This is accomplished by using larger orifice diameters, lower plasma gas flow rates, and lower currents than normally used for cutting.

Polarity

Plasma arc welding is normally done with direct current electrode negative (DCEN), pure tungsten or tungsten alloy electrodes, argon plasma gas and a transferred arc. Current range for plasma arc welding is from 0.1 to 500 amperes, depending on the torch size and material thickness. Steel, stainless steel, nickel base alloys and titanium alloys can be welded with DCEN.

Direct current electrode positive (DCEP) is used to a limited extent for welding aluminum and magnesium to make use of the surface oxide removal feature (sputtering) of this polarity. Arc current is usually limited to a maximum of 100 amperes to prevent rapid deterioration of the electrode.

Sine wave alternating current with continuous high-frequency stabilization can also be used for welding aluminum and magnesium, but the maximum is still limited to about 100 amperes. Surface oxide removal occurs during the positive half cycles of alternating current.

Square-wave alternating current with unbalanced positive and negative current half cycles, also called variable polarity plasma arc (VPPA), is highly efficient for welding aluminum and magnesium alloys and permits use of higher average weld current than sine wave ac. This is possible because the duration of the negative portion is considerably longer than the positive portion, thus developing most of the heat at the work, where it is needed. The short positive pulse is sufficient for removing surface oxides and does not cause excessive heating of the electrode. Good results were obtained with 15 to 20 milliseconds DCEN and 2 to 5 milliseconds DCEP. Shorter DCEP times were not effective; longer times caused electrode deterioration. A typical VPPA waveform is shown in Figure P-13.

Keyhole Welding Technique

Plasma arc welding can be performed in either the melt-in or keyhole mode. The melt-in mode is similar to the gas tungsten arc process but the arc has greater stiffness and heat concentration, permitting narrower

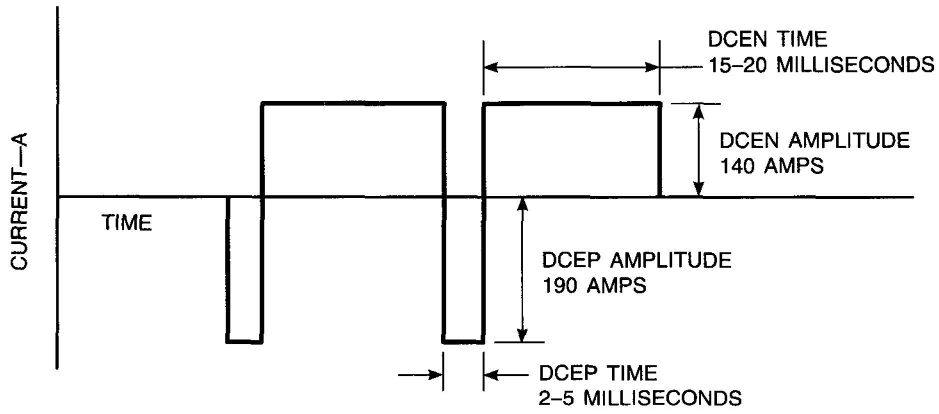


Figure P-13—A Typical Variable Polarity Plasma Arc Waveform

beads and less distortion than GTAW. In the keyhole mode, a stiffer, higher current density arc is used, which produces a small hole completely through the joint being welded. Figure P-14 is a pictorial representation of the keyhole in plasma arc welding. The keyhole technique is generally performed in the downhand position on material thicknesses ranging from 1.6 to 9.5 mm (1/16 to 3/8 in.). However, using appropriate welding conditions on certain metal thicknesses, keyhole welding can be done in any position. The principal advantage of keyhole welding is making welds in a single pass. As the plasma arc moves along the joint, the melted metal flows back into the hole to make the weld. If the arc moves too rapidly, the result will be cutting instead of welding.

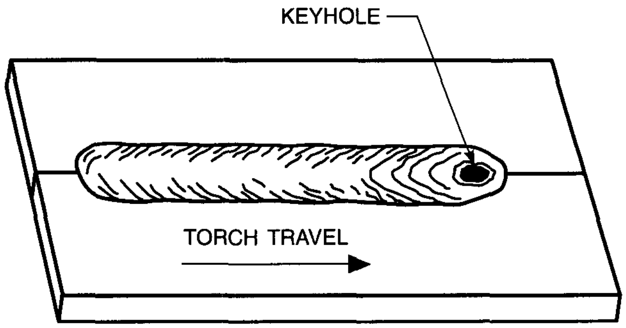


Figure P-14—Pictorial Representation of the Keyhole in Plasma Arc Welding

Advantages and Limitations

Advantages. The low-current and high-current (melt-in) modes have the following advantages over gas tungsten arc welding:

(1) Energy concentration is greater, with the result that:

(a) Welding speeds are higher in some applications.

(b) Lower current is needed to produce a given weld and results in less shrinkage. Distortion may be reduced by as much as 50%.

(c) Penetration can be controlled by adjusting welding variables.

(2) Arc stability is improved.

(3) Arc column has greater directional stability.

(4) Narrower beads (higher depth-to-width ratio) for a given penetration, resulting in less distortion.

(5) Need for fixturing is less for some applications.

(6) Where the addition of filler metal is desirable, this operation is much easier since torch standoff distance is generous and the electrode cannot touch the filler or puddle. This also results in less downtime for tungsten repointing and eliminates tungsten contamination of the weld.

(7) Reasonable variations in torch standoff distance have little effect on bead width or heat concentration at the work; this makes out-of-position welding much easier.

Limitations. Some of the limitations associated with low-current and high-current (melt-in) plasma arc welding include:

(1) Due to the narrow constricted arc, the process has little tolerance for joint misalignment.

(2) Manual plasma welding torches are generally more difficult to manipulate than a comparable GTAW torch.

Equipment

The basic equipment for plasma arc welding is shown in Figure P-15. Plasma arc welding is done with both manual and mechanized equipment.

A complete system for manual plasma arc welding consists of a torch, control console, power source, orifice and shielding gas supplies, source of torch coolant, and accessories such as gas flow timers and remote current control. Equipment is available for operation in the current range of 0.1 to 225 A, DCEN.

Mechanized equipment must be used to achieve the high welding speeds and deep penetration advantages associated with high-current plasma arc welding. A typical mechanized installation consists of a power source, control unit, machine welding torch, torch stand or travel carriage, coolant source, high-frequency power generator, and supplies of shielding gases. Accessory units such as an arc voltage control and filler wire feed system may be used as required. Machine welding torches are available for welding with currents up to 500 A, DCEN.

Accessory Equipment

Wire Feeders. As with the GTAW process, conventional filler wire feed systems can be used with the PAW process. The filler metal is added to the leading edge of the weld pool or the keyhole at a predetermined feed rate. A wire feed system may alleviate occurrences of undercut or underfill when welding thicker materials.

Hot wire feed systems may also be used and should be fed into the trailing edge of the weld pool. Initiation

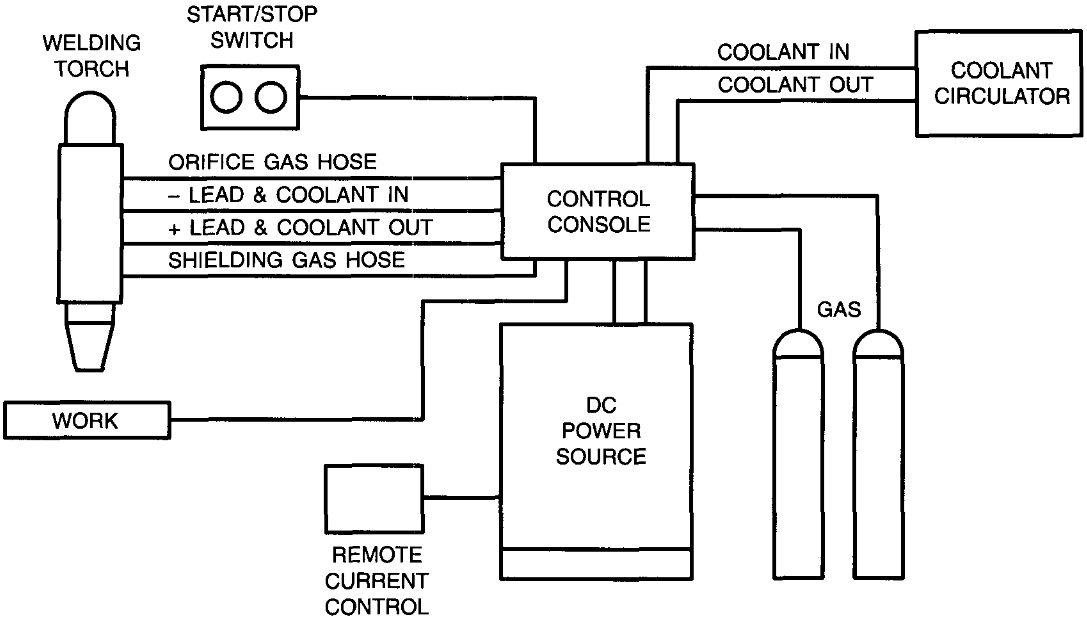


Figure P-15—Typical Equipment for Plasma Arc Welding

and termination of wire feed may be controlled and programmed with automatic welding equipment.

Positioning Equipment. Positioning equipment for PAW is similar to that used for GTAW. Depending on the application, either the workpiece may be manipulated or the torch motion can be controlled. Workpiece manipulation generally involves a rotary positioner with the capability of tilt control. Moving the torch while the workpiece remains stationary requires a carriage on tracks or a side beam carriage for following linear joints. Combining the movement of the torch and workpiece as a system would require the use of computer programming for coordinating the operations.

Materials

Base Metals. The plasma arc welding process can be used to join all metals weldable by the GTAW process. Most material thicknesses from 0.3 to 6.4 mm (0.01 to 0.25 in.) can be welded in one pass with a transferred arc. All metals except aluminum and magnesium and their alloys are welded with DCEN. Square-wave ac is used to effectively remove refractory oxides when welding aluminum and magnesium. Alternating current welding reduces the current capacity of the electrode unless the power source is capable of minimizing the duration of the positive electrode cycle. One pass keyhole welds can be made in aluminum alloys up to 12.7 mm (1/2 in.) thick. Metallurgical effects of the heat from the plasma and gas tungsten arc welding processes are similar, except the smaller diameter plasma arc will usually melt less base metal, resulting in narrower and deeper penetration. Preheat, postheat, and gas shielding procedures are similar for both processes. Each base material has its requirements that maximize weld quality.

Consumables

Filler Metals. Filler metals used to weld the work base materials are the same as those used with the GTAW and GMAW processes. They are added in rod form for manual welding or wire form for mechanized welding. Table P-4 lists the AWS specifications for appropriate filler metals.

Electrodes. The electrode is the same as used for gas tungsten arc welding. Pure tungsten rods and tungsten with small additions of thoria, zirconia, lanthanum, or ceria may be used for DCEN welding.

Electrodes are made to ANSI/AWS A5.12, *Specification for Tungsten Arc Welding Electrodes.* Pure tungsten electrodes are generally selected for a-c welding.

Table P-4
AWS Specifications for Filler Metals Used for Plasma Arc Welding

AWS Specification	Filler Metals
A5.7	Copper and copper alloy welding rods
A5.9	Corrosion resistant chromium and chromium nickel steel bare electrodes
A5.10	Aluminum and aluminum alloy welding rods and bare electrodes
A5.14	Nickel and nickel alloy bare welding rods and electrodes
A5.16	Titanium and titanium alloy bare welding rods and electrodes
A5.18	Mild steel electrodes for gas metal arc welding
A5.19	Magnesium alloy welding rods and bare electrodes
A5.24	Zirconium and zirconium alloy bare welding rods and electrodes

Gases. The choice of gases to be used for plasma arc welding depends on the metal to be welded. For many PAW applications, the shielding gas is often the same as the orifice gas. Typical gases used to weld various metals are shown in Table P-5, Gas Selection Guide for High Current Plasma Arc Welding. The shielding gases are generally inert. Active shielding gas can be used if it does not adversely affect the weld properties.

Safety Recommendations

For detailed safety information, refer to the manufacturer's instructions and the latest edition of ANSI Z49.1, *Safety in Welding and Cutting*. For mandatory federal safety regulations established by the U.S. Labor Department's Occupational Safety and Health Administration, refer to the latest edition of OSHA Standards, *Code of Federal Regulations,* Title 29 Part 1910, available from the Superintendent of Documents, U.S. Printing Office, Washington, D.C. 20402.

Reference: American Welding Society. *Welding Handbook*, Vol.2, 8th Edition, Miami, Florida: American Welding Society.

PLASMA ARC WELDING TORCH

A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas and orifice gas. See STANDARD WELDING TERMS. *See also* PLASMA ARC WELDING.

PLASMA SPRAYER

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYER.

PLASMA SPRAYING (PSP)

A thermal spraying process in which a nontransferred arc is used to create an arc plasma for melting and propelling the surfacing material to the substrate. See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING.

PLASMA SPRAYING OPERATOR

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING OPERATOR.

PLASTIC DEFORMATION

Permanent changes in the shape, structure and properties of a metal or material caused by the action of an applied stress greater than the elastic limit of the material. Plastic deformation is an inherent consequence of cold working.

PLASTIC FLOW

See CREEP.

PLASTIC MATERIALS, WELDING

Among weldable thermoplastics, polyvinyl chloride and polyethylene are the most frequently joined. Thermoplastics or plastics that soften when heated can be welded using a filler rod of the same composition as the base material. Applications of welded plastics have been used in the chemical and food industries, in laundries, breweries, in home and industrial plumbing, and other industries.

The process requires a torch using either electricity or an oxyfuel gas flame to heat air or an inert gas, which will then be used to heat the filler rod and the base material. Temperature of the compressed gas stream may be regulated by gas flow rate and by varying the torch-to-work spacing. Although the filler rod should preferably be of the same chemistry as the base material, a rod which is slightly more plasticized than the base material will give greater control over weld contour. However, welds made with plasticized filler rod show a slight reduction in resistance to chemicals.

Welds in plastic resemble types produced by electric arc welding. For a fillet weld, no joint preparation is necessary. For a butt weld, the two pieces are beveled by sawing, filing, or grinding.

Table P-5
Gas Selection Guide for High Current Plasma Arc Welding[a]

Metal		Thickness mm	Thickness in.	Welding Technique: Keyhole	Welding Technique: Melt-In
Carbon steel (aluminum killed)	under	3.2	1/8	Ar	Ar
	over	3.2	1/8	Ar	75% He—25% Ar
Low alloy steel	under	3.2	1/8	Ar	Ar
	over	3.2	1/8	Ar	75% He—25% Ar
Stainless steel	under	3.2	1/8	Ar, 92.5% Ar—7.5% H_2	Ar
	over	3.2	1/8	Ar, 95% Ar—5% H_2	75% He—25% Ar
Copper	under	2.8	3/32	Ar	75% He—25% Ar
	over	2.8	3/32	Not recommended[b]	He
Nickel alloys	under	3.2	1/8	Ar, 92.5% Ar—7.5% H_2	Ar
	over	3.2	1/8	Ar, 95% Ar—5% H_2	75% He—25% Ar
Reactive metals	under	6.4	1/4	Ar	Ar
	over	6.4	1/4	Ar—He (50 to 75% He)	75% He—25% Ar

a. Gas selections are for both orifice and shielding gases.

b. The underbead will not form correctly. The technique can be used for copper-zinc alloys only.

The prepared surfaces should be clean and roughened with a scraper to improve the weld bond. A sealing pass on the reverse side of the butt weld will ensure higher tensile strength.

One essential difference between metal welding and plastic welding lies in the joining of filler rod and parent material. Complete fusion of the two is characteristic of arc welding. With plastics, however, a simple bonding process takes place, since only the actual meeting surfaces melt. The other parts remain relatively unaffected and rigid. The slight pressure required to force the filler rod into the joint combines melted surfaces into one homogeneous mass. In this manner, a bonded, integral weld is produced.

The torch should be used to pre-heat surfaces or edges to be welded, as well as the filler rod, to produce uniform coalescence. The filler rod cannot adhere properly if surfaces have not been sufficiently preheated and melted. Torch-to-work spacing must be controlled to avoid overheating, which causes darkening of the material, and too much sub-surface melting.

The process can be used in the downhand, vertical and overhead positions. The tensile strength of butt welds in plastic should approach 90% of the tensile strength of the base material. Figures for fillet welds are somewhat lower than this. A weld will attain full strength in two to six hours, depending on the size of the weldment and the type of weld. To determine the soundness of a weld and the thoroughness of surface bonding, the operator may attempt to pull the end of the welding rod from the welded piece after the weld has completely cooled. In a good weld, the filler rod will tear off at the end of the weld; a poorly made weld will allow the rod to be pulled out of the joint.

PLASTICITY

A state of ductility or malleability; a capability of continuous or permanent deformation or change in shape without rupture.

PLATE

A term usually applied to metal in sheet form that is over 3.2 mm (1/8 in.) thick. This is not a hard and fast designation; however, metal up to and including 3.2 mm (1/8 in.) thick is referred to as sheet metal and anything thicker is referred to as plate.

PLATE EDGE PREPARATION

The cutting or beveling of plate edges preparatory to welding. *See* EDGE PREPARATION.

PLATEN FORCE

In flash and upset welding, the force available at the movable platen to cause upsetting. This force may be static or dynamic.

PLATEN, Resistance Welding

A member with a substantially flat surface to which dies, fixtures, backups, or electrode holders are attached, and that transmits the electrode force or upset force. One platen usually is fixed and the other moveable. See STANDARD WELDING TERMS. *See also* RESISTANCE WELDING.

PLATEN SPACING

The distance between adjacent surfaces of the platens in a resistance welding machine. See STANDARD WELDING TERMS. *See also* THROAT HEIGHT.

PLATINUM

(Chemical symbol, Pt). A grayish-white precious metallic element which is not easily oxidized. It is ductile, malleable, and non-corrosive, and is difficult to fuse. It is used extensively for electrical contacts, thermocouples, laboratory equipment and jewelry. It can be alloyed with palladium, iridium and other metals such as copper and nickel. Atomic weight, 195; atomic number, 78; melting point, 1755°C (3191°F); specific gravity, 21.4.

PLATINUM-IRIDIUM

An alloy of platinum and iridium used extensively for electrical contacts. Alloying platinum with iridium increases hardness over that of pure platinum.

PLENUM

See STANDARD WELDING TERMS. *See also* PLENUM CHAMBER.

PLENUM CHAMBER

The space between the electrode and the inside wall of the constricting nozzle of the plasma arc torch or thermal spraying gun. See STANDARD WELDING TERMS. *See also* Appendix 10.

PLOWSHARE WELDING

See FARM IMPLEMENT REPAIR *and* HARDFACING.

PLUG

In piping, a threaded fitting that screws into a pipe fitting to close the system. In electrical usage, a connection to the receptacle of a power source.

PLUG WELD

A weld made in a circular hole in one member of a joint fusing that member to another member. A fillet-welded hole is not to be construed as conforming to this definition. See STANDARD WELDING TERMS. *See* Figure P-16.

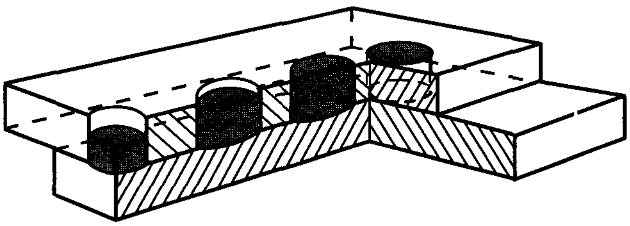


Figure P-16—Typical Plug Welds

PLUG WELD SIZE

The diameter of the weld metal in the plane of the faying surfaces. See STANDARD WELDING TERMS.

POINT WELDING

A term sometimes used to refer to projection welding and the projections or "points" embossed in sheet for concentrating the weld current. *See* PROJECTION WELDING *and* RESISTANCE WELDING.

POKE WELDING

A nonstandard term for PUSH WELDING.

POLARITY

See STANDARD WELDING TERMS. *See also* DIRECT CURRENT ELECTRODE NEGATIVE (DCEN) *and* DIRECT CURRENT ELECTRODE POSITIVE (DCEP).

When welding with direct current it is important that the work and electrode are connected to the correct terminals of the power supply. In the early days of arc welding, bare electrodes were almost always used with the holders connected to the negative terminal and the work connected to the positive terminal of the power supply. This was known as *straight polarity* but the standard term is now *direct current electrode negative* (DCEN).

Heavily coated electrodes may be connected and operated on either polarity, but most types are connected to the positive terminal with work connected to the negative terminal. This was formerly known as *reverse polarity*, but now the standard term is *direct current electrode positive* (DCEP).

Normally, about two thirds of the arc heat is developed at the positive terminal and one third at the negative terminal. The heavily coated electrodes used in shielded metal arc welding (SMAW) require that the most heat be developed at the positive wire electrode, where it is needed to melt the wire. For gas tungsten arc welding (GTAW), the most heat is developed at the positive workpiece, where it is needed to melt the metal in the joint. The negative tungsten electrode does not melt, even though it is ground to a fine point. When welding aluminum using DCEP, which is required to clean the aluminum oxide from the surface, a much larger diameter electrode with a hemispherical tip is used to help dissipate the extra heat and prevent the electrode from melting.

When alternating current is used, there is little difference in the heat developed at either pole because the polarity changes every half cycle. Alternating current is advantageous for welding aluminum because it provides a cleaning action with less heat developed at the electrode.

POLE

One of two opposing terminals of an electric generator or direct current welding power supply. They are termed positive and negative terminals. The ends of a magnet are also called poles.

POLYMER

A chemical compound or mixture of compounds consisting essentially of repeatedly linked structural units, each a light, relatively simple molecule. Polymerization is a chemical reaction in which two or more molecules combine to form larger molecules.

Synthetic organic polymers are used in adhesive bonding to join metal assemblies. *See* POLYMERIC COMPOSITE.

POLYMERIC COMPOSITE

Polymeric composites consist of reinforcing fibers bound together by the cohesive and adhesive characteristics of a resin composite matrix. The purpose of the matrix is to transfer the load to and between fibers. The matrix keeps the reinforcing fibers in the proper orientation and position so that they can carry the intended loads and also helps distribute the loads more uniformly throughout the material.

Polymeric composite materials were developed because no single, homogeneous material could be found that had all of the desired properties for a given application. They were developed initially for aerospace applications.

Some of the common materials used as fibers are steel, tungsten, E-glass, S-glass, silicon carbide whiskers (small monocrystalline materials), boron, graphite, Kevlar, and aluminum oxide. The most common types of resins are epoxy resins, polyamide resins, polyester resins, and thermoplastic resins.

Polymeric composites can be classified according to reinforcement forms, such as *particulate-reinforced, fiber-reinforced*, or *laminate composites*.

Welding Composites

Welding is accomplished through diffusion and entanglement of the matrix molecules. There are two general groups of polymeric matrices: *thermosetting-matrix* and *thermoplastic-matrix*. Thermosetting-matrix composites cannot be welded because of the cross-linking of the polymer chains; they can be joined only by mechanical fastening or adhesive bonding, or both. However, in thermoplastic matrix composites, the polymer chains are held together by secondary chemical bonds that weaken and break when heated, freeing the chains to move and diffuse. Therefore, thermoplastic composites can be welded or fusion bonded.

Most welding processes that are suitable for joining thermoplastics can also be used to fusion bond composites. The processes for welding plastics and composites can be classified in two groups. The first group uses an external heat source, such as hot plate welding, hot gas welding, resistively or inductively heated implants, and infrared or laser welding. Processes in the second group use internal heat generation and include dielectric and microwave heating, friction heating (spin welding), vibration welding, and ultrasonic welding.

Gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), laser beam welding (LBW), electron beam welding (EBW), resistance welding (RW), friction welding (FW), and diffusion welding and brazing can be used to weld composite matrices.

Following are five steps involved in welding composites:

(1) Surface preparation to remove contaminants

(2) Heating and melting of the thermoplastic matrix on the weld surfaces

(3) Pressing to promote flow and wetting

(4) Intermolecular diffusion and entanglement of the polymer chains

(5) Cooling and resolidification of the thermoplastic

The as-welded properties of GTAW in fiber-reinforced Ti/W are shown in Table P-6.

Table P-6
As-Welded GTAW Properties of Fiber-Reinforced Titanium/Tungsten Composites

Tungsten Fiber, %	Specimen Type	Specific Modulus Msi	Specific Modulus GPa	Yield Strength (0.2% Offset) ksi	Yield Strength (0.2% Offset) MPa	Tensile Strength ksi	Tensile Strength MPa	Elongation, %
0	Base	14.3	99	69.2	477	88.7	612	29.0
0	Butt Weld	16.7	115	73.0	503	92.8	640	17.5
0	Bead-on-sheet	15.5	107	82.4	568	101.6	701	14.0
4.5	Base	21.8	150	82.4	568	102.3	705	15.8
4.4	Butt weld	17.0	117	80.9	558	101.5	700	11.7
4.5	Bead-on-sheet	20.3	140	106.8	734	129.6	894	4.5
9.8	Base	21.2	146	95.2	656	103.5	714	3.4
9.9	Bead-on-sheet	17.2	119	105.9	730	131.3	905	4.0

Common Matrix Alloys. Because of their origins in the aerospace industry, most metal-matrix composites (MMCs) emphasize high performance with light weight. As a result, most development time and resources have been put into low-density alloys. Magnesium has the lowest density among the commonly used light metals, however, it creeps at low temperatures, has relatively low strength, and is prone to corrosion. Titanium is more than twice as strong as aerospace grade aluminum alloys. Its exceptional temperature and corrosion resistance make titanium a favored choice for demanding environments, where its high cost is justifiable.

Aluminum is the most widely used matrix material because it is easy to process, inexpensive, light in weight, and can be alloyed to fairly high strengths. It retains useful strength at moderate temperatures and has excellent corrosion resistance.

Common Reinforcements. The choice of reinforcement material generally depends on the desired properties of the composite, its compatibility with the matrix material, and the MMC processing route. Among the reinforcement materials used for metal-matrix composites are silicon carbide, aluminum oxide, titanium carbide, and boron carbide, graphite, and titanium diboride.

Because more aluminum metal-matrix composites are produced than all the other alloys combined, the Aluminum Association developed a standard designation system for MMCs that has been adopted by the American National Standards Institute. ANSI 35.5-1993 provides that aluminum-matrix MMCs be identified with designations in the following format:

matrix/reinforcement/volume%form

where

matrix = metal or alloy designation of matrix
reinforcement = chemical formula for reinforcement
volume% = volume percentage (without the % sign)
form = f, fiber or filament
c, chopped fiber
w, whiskers
p, particulate

Safety. Regardless of the material being welded, standard welding safety practices should be followed at all times. Welding should take place in a well-ventilated area and operators should use appropriate eye protection and safety equipment. For general welding safety procedures, refer to ANSI/ASC Z49.1, *Safety in Welding, Cutting and Allied Processes.*

For additional information and a list of supplementary references on polymeric composites, see American Welding Society, *Welding Handbook*, Vol. 3, American Welding Society, Miami, Florida, 1996.

POOL

See WELD POOL.

POPPING

See BACKFIRE *and* FLASHBACK.

POROSITY

Cavity-type discontinuities formed by gas entrapment during solidification or in a thermal spray deposit. See STANDARD WELDING TERMS.

Porosity reduces the strength of a weld. In fusion welds, it is caused by dissolved gases that are usually present in the molten weld metal. If the dissolved gases are present in amounts greater than their solubility limits, the excess is forced out of solution in the form of bubble or gas pockets as the weld metal solidifies. The gases which may be present in the molten weld pool include hydrogen, oxygen, nitrogen, carbon monoxide, carbon dioxide, water vapor, hydrogen sulphide, and rarely, argon, and helium. Hydrogen is the major cause of porosity in weld metal.

The welding process, procedure and base metal type directly affect the quantities and types of gases that are present in the molten weld pool. The welding process and welding procedure control the solidification rate, which in turn affects the amount of weld metal porosity. Proper welding procedures for a given combination of welding process and base metal should produce welds that are essentially free of porosity.

The common causes of porosity in fusion welds and suggested methods of preventing it are summarized in Table P-7.

Table P-7
Common Causes of and Remedies for Porosity

Cause	Remedies
Excessive hydrogen, nitrogen, or oxygen in welding atmosphere	Use low-hydrogen welding process; filler metals high in deoxidizers; increase shielding gas flow
High solidification rate	Use preheat or increase heat input
Dirty base metal	Clean joint faces and adjacent surfaces
Dirty filler wire	Use specially cleaned and packaged filler wire, and store it in clean area
Improper arc length, welding current, or electrode manipulation	Change welding conditions and techniques
Volatization of zinc from brass	Use copper-silicon filler metal; reduce heat input
Galvanized steel	Use E6010 electrodes and manipulate the arc heat to volatilize the zinc ahead of the molten weld pool
Excessive moisture in electrode covering or on joint surfaces	Use recommended procedures for baking and storing electrodes Preheat the base metal
High sulfur base metal	Use electrodes with basic slagging reactions

POROSITY TEST

A test which can determine the presence of porosity in any particular weld or welded assembly. Radiography is the most effective and reliable non-destructive test method, but it cannot detect porosity smaller than a minimum size. Radiographs taken from two different angles can establish the depth of the porosity from a surface. *See* RADIOGRAPH.

Fine porosity and other fine voids which extend to a free surface can be detected by a dye penetrant or fluorescent penetrant which is applied to a surface, soaks into voids and finally bleeds out of the voids after the excess is removed.

Another type of porosity test is used to test the ability of a welder to produce welds which are satisfactory for oil, water, or gas containers. A test weld joint can be clamped over a pressure box against a rubber gasket and the box pressurized with air. Liquid soap is applied to the weld joint, and porosity or voids are indicated by the appearance of bubbles on the surface.

POSITION

See STANDARD WELDING TERMS. *See also* WELDING POSITION.

POSITIONAL USABILITY

A measure of the relative ease of application of a welding filler metal to make a sound weld in a given position and progression. See STANDARD WELDING TERMS.

POSITIONER

A mechanical device that supports and moves a weldment to the desired position for welding and other operations. In some cases, a positioner may move a weldment as welding progresses along a joint. A welding fixture may be mounted on a positioner to place the fixture and the weldment in the most advantageous positions for loading, welding, and unloading.

Positioning can be done with one, two, or three different motions. One motion is rotation about one axis. This is normally accomplished with turning rolls, headstock and tailstock arrangements, or turntables, all of which rotate the assembly about a single axis.

Two-motion positioning is a combination of rotation and tilting. It is normally accomplished with a positioner that has a tilting table as well as rotation. A typical two-motion positioner is shown in Figure P-17. Three-motion position is accomplished by adding vertical movement with an elevating device in the machine base, thus providing rotation, tilt, and elevation.

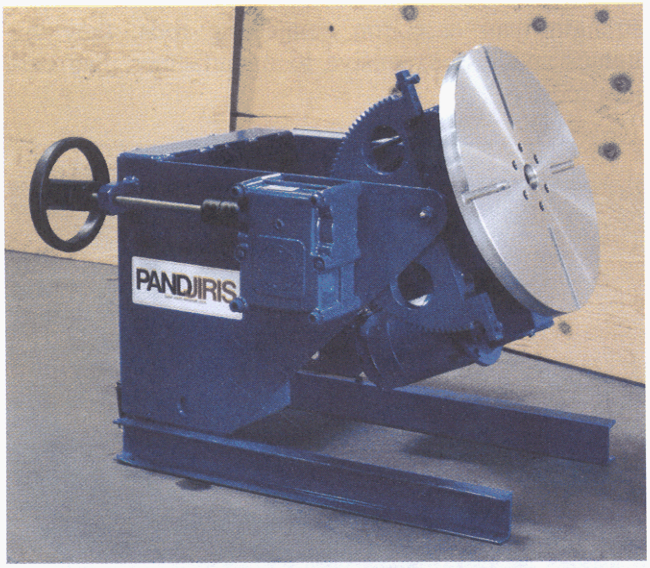


Figure P-17—Positioner with a Rotating and Tilting Turntable

Photo courtesy of Pandjiris, Inc.

The positioner tables contain slots and holes which can be used for anchoring parts to the table. On the smaller positioners, adjustment of the table angle is accomplished by hand-wheels and gears; rotation may be by a hand wheel and gear but is usually by an electric gear drive. Angle and rotation adjustments on large positioners are accomplished by electric motor gear drive.

Parts to be welded and entire jigs and fixtures can be attached to the plane tables, tipped to any angle, and rotated as required.

Positioners are widely used for positioning weldments in the flat or downhand position to improve weld quality, increase production, reduce costs and promote safety in the shop for both production and repair welding operations. Quality is improved because the operator has greater control over the weld pool. Costs are reduced because filler metal can be deposited faster in the flat position, and because less skill is required of welding operators.

POSITION OF WELDING

See STANDARD WELDING TERMS. *See also* WELDING POSITION.

POSITIVE ELECTRODE

An electric conductor through which a direct current enters or leaves a positive welding circuit; it is termed DCEP (direct current electrode positive). *See* POLARITY.

POSTFLOW TIME

The time interval from current shut off to either shielding gas or cooling water shut off. See STANDARD WELDING TERMS. *See also* Appendix 19.

POSTHEATING

The application of heat to an assembly after welding, brazing, soldering, thermal spraying, or thermal cutting. See STANDARD WELDING TERMS.

POSTWELD HEAT TREATMENT

Any heat treatment after welding.

POSTWELD INTERVAL, Resistance Welding

The total elapsed time from the end of the weld interval to the end of hold time. See STANDARD WELDING TERMS. *See also* Figure I-1.

POT ANNEALING

The annealing of steel by heating, usually at a subcritical temperature, in a closed metal box or pot to protect it from oxidation. Slow heating and cooling rates are involved. The process is sometimes called *box annealing*.

POT METAL

See WHITE METAL WELDING.

POTASSIUM

(Chemical symbol: K). A silvery-white, lustrous, highly reactive metallic element used in the production of certain types of photoelectric cells; also used instead of mercury in some types of high-temperature thermometers.

Potassium reacts instantly to air or oxygen, forming a coat of oxide. Potassium is lighter than water and will float in it, reacting violently with it to release hydrogen. Potassium is usually obtained by the electrolysis of caustic potash. Atomic weight: 39; melting point: 65.5°C (149.9°F); specific gravity: 0.859.

POTASSIUM SILICATE

See SODIUM SILICATE.

POTENTIAL

The pressure, voltage or electromotive force that causes an electric current to flow through a complete circuit.

POWDER ALLOY

A nonstandard term for ALLOY POWDER.

POWDER BLEND

A heterogeneous mixture of two or more alloy, metal, or nonmetal powders. See STANDARD WELDING TERMS. *See also* ALLOY POWDER.

POWDER COMPOSITE

Two or more different materials combined to form a single particle, formed by either chemical coating or mechanical agglomeration. See STANDARD WELDING TERMS.

POWDER CUTTING

A nonstandard term for FLUX CUTTING and METAL POWDER CUTTING.

POWDER FEEDER

A device for supplying powdered surfacing material to a thermal spraying gun or cutting torch. See STANDARD WELDING TERMS.

POWDER FEED GAS

A nonstandard term for CARRIER GAS.

POWDER FEED RATE

The quantity of powder fed to a thermal spraying gun or a cutting torch per unit of time. See STANDARD WELDING TERMS.

POWDER FLAME SPRAYING

A flame spraying process variation in which the surfacing material is in powder form. See STANDARD WELDING TERMS. *See also* FLAME SPRAYING.

POWDER METALLURGY

The art and science of producing metal powders and using metal powders to produce serviceable metal objects. The process involves heating, or sintering, a compact formed by compression of metal powder under high pressure. The powder may be a single metal powder, a mixture of two or more metal powders, or alloy powders. Compositions and properties not attainable by the conventional method of melting and casting have been produced through powder metallurgy.

Figure P-18 is a photograph of two powder-forged connecting rods used in automobile engines. Developed in the mid 1980s, these powder forged connecting rods are in use in approximately seventy five million automobiles. Powder-forged units like these have higher dimensional tolerance and higher fatigue strength than cast iron connecting rods; they are lighter and less expensive to manufacture than cast iron rods.

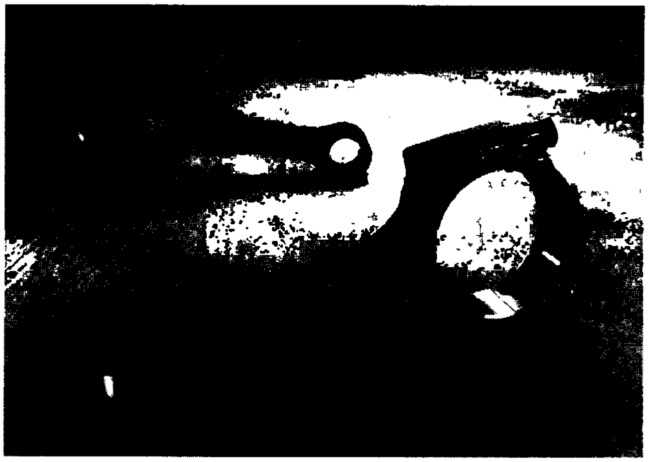


Figure P-18—Two Powder Forged Connecting Rods

Photo courtesy of the Metal Powder Industries Federation

POWER

Electrical energy; in direct current circuits it is equal to E × I (volts × amperes). The electric unit of power is the watt.

POWER CIRCUIT

Wires or other conductors which carry current to electric welding machines and other devices using electric current.

POWER FACTOR

The ratio of true power (watts) to the apparent power (volts times amperes). The power factor is equal to the cosine of the angle of lag between the alternating current and voltage waves.

POWER LOSS

The energy or power lost in an electric circuit due to the resistance of the conductors. It is often referred to as the I^2R loss.

POWER SOURCE

An apparatus for supplying current and voltage suitable for welding, thermal cutting, or thermal spraying. See STANDARD WELDING TERMS. *See also* VOLT-AMPERE CURVE.

PRECIPITATION HARDENING

A method of strengthening an alloy in which a constituent precipitates from a supersaturated solid solution. It is important in the hardening of nonferrous metals and is a method of developing high strength and hardness in some steels. *See* AGE HARDENING.

PRECOATING

Coating the base metal in the joint by dipping, electroplating, or other applicable means prior to soldering or brazing. See STANDARD WELDING TERMS.

The term *tinning* is popularly used for the term *precoating*. Tinning is most commonly used to describe the process of coating a metal with tin (although other metals such as lead may be used instead of tin) or a tin alloy (e.g., solder). In brazing, a thin layer of fluxed filler metal is spread ahead of the main deposit to form a coating which provides a strong bond between base metal and bronze.

PREECE TEST

The Preece test is a procedure to determine the thinnest areas of zinc in newly galvanized components. It is not used on weathered or old components or to determine the relative weight of a coating. The test involves immersion of a test sample in a copper sulfate solution in intervals of one minute in order to dissolve the zinc coating. After each immersion and cleaning the sample is visually evaluated to see if the zinc is removed. When the copper is plated out on the steel, the test is completed and the relative thickness of the coating is known.

The Preece test is no longer in common use; electronic and magnetic instruments are used to determine the thickness of the zinc coating. Reference: ASTM A239.

PREFLOW TIME

The time interval between start of shielding gas flow and arc starting. See STANDARD WELDING TERMS. *See also* Figure L-13.

PREFLUXING

A means of fluxing cast iron prior to brazing to promote "tinning," or precoating. The free graphite in cast iron impedes wetting by the braze material. Surface free graphite can be removed by an oxidizing agent such as potassium chlorate. This is spread on the surface to be brazed just ahead of the braze pool on that part of the base metal which has been heated to a red heat. As soon as the oxidizing agent ceases to foam from the heating, the part is ready to be tinned in the usual manner.

PREFORM

Brazing or soldering filler metal fabricated in a shape or form for a specific application. See STANDARD WELDING TERMS.

PREHEAT

The heat applied to the base metal or substrate to attain and maintain preheat temperature. See STANDARD WELDING TERMS.

Preheat is the application of heat to the workpiece prior to welding, brazing or cutting. There are three basic reasons for preheating:

(1) To equalize temperature in the workpiece. Welding heats a local area of the workpiece, causing local expansion and a tendency to warp or distort. This expansion also causes local stresses which could result in rupture of a weldment. Preheating lowers the yield strength of most metals and allows stresses to be relieved or reduced. Preheating reduces the temperature difference between the base metal and the area welded.

(2) To reduce the amount of heat needed to make a weld or braze. When a cold part is to be welded or brazed, it requires a higher arc current or hotter gas torch flame to start welding than when the part is preheated to a temperature of 150 to 200°C (300 to 400°F). Obviously, the preheating should be done by some lower cost fuel than used for welding.

(3) To prevent hardening and cracking when a part is cooled too rapidly through the transformation range, particularly for cast iron and most carbon steels. Pre-

heating reduces the temperature differential so that heat flow from the weld area is reduced and the cooling rate is slower.

Preheating may be applied locally by oxyfuel torch, by electrical resistance techniques or by induction heating. Entire components may be heated in a furnace or oven that is large enough to hold the part.

Preheat temperature depends upon the material, the workpiece size and shape, and the welding process to be used. Cast iron requires a red heat and brass and bronze a dull red heat. Steels require a preheat of between 90 and 300°C (200 and 600°F), depending on carbon and alloy content and material thickness. Excessive preheats will remove any benefits of prior heat treatment. Aluminum should be preheated carefully, because too high a temperature will remove any prior aging or cold work benefits, or even cause partial melting. Temperature-indicating crayons are usually used to determine the temperature of the workpiece.

PREHEATING BY INDUCTION

Preheating by induction will take place when a voltage or electromotive force is induced in a workpiece by exposing it to an alternating current magnetic field. The induced voltage will cause current to flow in the workpiece, heating it by its resistance to the flow of current. Usually, a water-cooled copper coil is placed close to the workpiece or area to be heated or wrapped around the part. If 60 Hz ac is to be used, the coil can be connected to a step-down transformer of adequate kVA rating. If higher frequency is to be used, then a high-frequency generator of adequate kVA rating will be needed.

One major advantage of preheating by induction is that it can be applied to very large items or systems such as pressure piping, boilers and valves for power plants. These items are made from high-carbon, high-alloy steels designed for high-temperature service. They require preheat for welding and could not be welded satisfactorily without preheat. Induction heating rapidly develops the heat within the workpiece as well as at the surface.

PREHEAT CURRENT, Resistance Welding

An impulse or series of impulses that occur prior to and are separated from the welding current. See STANDARD WELDING TERMS. *See also* Figure I-1.

PREHEAT TEMPERATURE, Brazing and Soldering

The temperature of the base metal in the volume surrounding the point of brazing or soldering immediately before brazing or soldering is started. See STANDARD WELDING TERMS.

PREHEAT TEMPERATURE, Thermal Cutting

The temperature of the base metal in the volume surrounding the point of thermal cutting immediately before thermal cutting is started. See STANDARD WELDING TERMS.

PREHEAT TEMPERATURE, Thermal Spraying

The temperature of the substrate in the volume surrounding the point of thermal spraying immediately before thermal spraying is started. In a multipass thermal spraying, it is also the temperature immediately before the second and subsequent passes are started. See STANDARD WELDING TERMS.

PREHEAT TEMPERATURE, Welding

The temperature of the base metal in the volume surrounding the point of welding immediately before welding is started. In a multipass weld, it is also the temperature immediately before the second and subsequent passes are started. See STANDARD WELDING TERMS.

PREHEAT TIME, Resistance Welding

The duration of preheat current flow during the preweld interval. See STANDARD WELDING TERMS. *See also* Figure I-1.

PRE-IGNITION

Overheating at some point within a welding torch which causes the unwanted burning of mixed gases (oxygen and a fuel gas). *See* FLASHBACK, BACKFIRE, *and* FLAME PROPAGATION RATE.

PREQUALIFIED WELDING PROCEDURE SPECIFICATION

A welding procedure specification that complies with the stipulated conditions of a particular welding code or specification and is therefore acceptable for use under that code or specification without a requirement for qualification testing. See STANDARD WELDING TERMS.

PRESSURE CONTACT WELD

A term sometimes applied to resistance butt welding. *See* RESISTANCE WELDING.

PRESSURE-CONTROLLED WELDING

A resistance welding process variation in which a number of spot or projection welds are made with several electrodes functioning progressively under *the control of a pressure-sequencing device. See* STANDARD WELDING TERMS. *See also* RESISTANCE WELDING.

PRESSURE, ELECTRICAL

The voltage which forces a current through an electric circuit. It is also called *potential difference.*

PRESSURE GAS WELDING (PGW)

An oxyfuel gas welding process which produces a weld simultaneously over the entire faying surfaces. The process is used with the application of pressure and without filler metal. See STANDARD WELDING TERMS.

The two variations of pressure gas welding are the closed joint and open joint methods. In the closed joint method, the clean faces of the parts to be joined are butted together under moderate pressure and heated by gas flames until a predetermined upsetting of the joint occurs. In the open joint method, the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. Both methods are easily adapted to mechanized operation.

Pressure gas welding can be used for welding low- and high-carbon steels, low- and high-alloy steels, and several nonferrous metals and alloys. In the closed joint method, since the metal along the interface does not reach the melting point, the mode of welding is different from that of fusion welding. In general, welding takes place by the action of grain growth, diffusion, and grain coalescence along the interface under the impetus of high temperature (about 1200°C [2200°F] for low-carbon steel) and upsetting pressure. The welds are characterized by a smooth surfaced bulge or upset, as shown in Figure P-19, and by the general absence of cast metal at the weld line. In the open joint method, the joint faces are melted, but molten metal is squeezed from the interface to form flash when the joint is upset. These welds resemble flash welds in general appearance.

Applications

Pressure gas welding has been successfully applied to plain carbon steel, low-alloy and high-alloy steels, and to several nonferrous metals, including nickel-copper, nickel-chromium, and copper-silicon alloys. It has been very useful for joining dissimilar metals. In general, pressure gas welding has a minimum effect on the mechanical and physical properties of the base metals. Pressure gas welding has been used with low-alloy and high-carbon steels for fabricating assemblies subject to high service stresses.

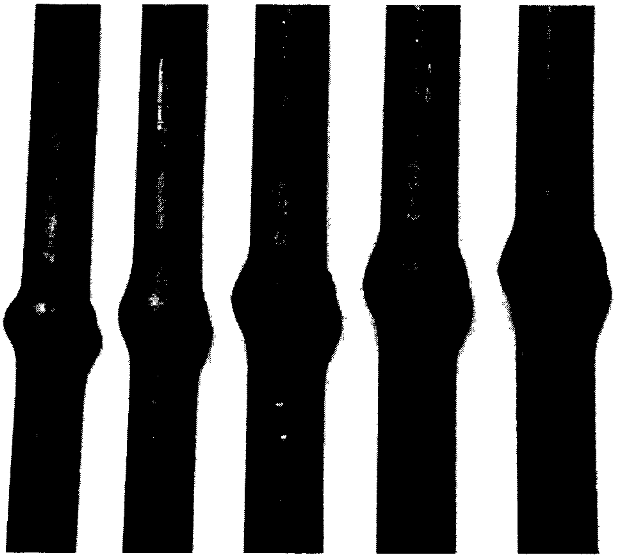


Figure P-19—Typical Pressure Gas Welds in 25 mm (1 in.) and 32 mm (1-1/4 in.) Diameter Steel Bars

While pressure gas welding still has applications in the welding of railroad rails, this process has been largely superseded by flash welding. Automatic welding of pipe, a former application, is accomplished using automatic gas metal arc welding. The basic elements of the pressure gas welding assisted in the development of similar processes, such as flash and friction welding that use other sources of energy.

Equipment

Machines. The apparatus for pressure gas welding is comprised of the following:

(1) Equipment for applying upsetting force

(2) Suitable heating torches and tips designed to provide uniform and controlled heating of the weld zone

(3) Necessary indicating and measuring devices for regulating the process during welding

PRESSURE GAUGE

Pressure gauges are used to measure gas or liquid pressure. Most gauges are the Bourdon tube type, which consist of a flattened metal tube bent into a circular shape, sealed at one end and connected to the fluid to be measured at the other end. The sealed end is linked to a mechanism which moves the indicating needle. When pressure is applied to the tube it tends to straighten slightly, moving the needle upscale. The actuating mechanisms are usually mounted in a brass or steel cup or housing, which also supports the dial and cover glass. These gauges are named for the inventor, Bourdon.

Figure P-20 shows a pressure gauge with the front cover glass and dial removed. This particular one is known as an independent movement type, in which the entire mechanism is mounted independently of the case on the socket (8), which is held securely in place on the case by two holding screws (9). This arrangement protects the mechanism from damage while handling and connecting to a system.

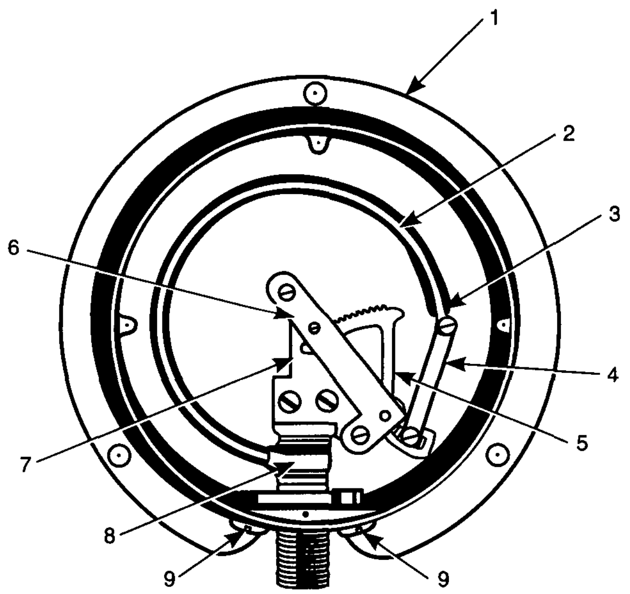


Figure P-20—Mechanism of a Pressure Gauge

The nomenclature of the constituent parts is as follows:

(1) Case, (2) Tube, (3) End Piece, (4) Link, (5) Sector, (6) Pinion Post, or Pinion; (7) Movement: collectively parts 5 and 6, including front and back movement plates, spacing bars and screws; (8) Socket or Connection, (9) Socket Screws.

Actuating Principle. Pressure admitted through socket (8) into tube (2) causes the tube to straighten slightly. The motion of the free end (3) is connected by link (4) to sector (5), which is engaged with pinion (6) causing it to rotate. The indicator hand, or needle, is mounted on the pinion shaft and indicates the pressure. Travel of the hand can be calibrated by adjusting the position of the lower link screw in the slotted sector arm.

Tube. The tube material, cross section dimensions, and wall thickness depend on the diameter of the gauge case and fluid pressure range to be measured. Generally, the wall thickness increases as the pressure increases. The dimensions of the tube must be such that the material is never stressed beyond its elastic limit at the maximum operating pressure. If this happened, the hand of the dial would not return to the zero position when the pressure is released. General practice is to design and calibrate a gauge for double its maximum average working pressure. For example, a gauge intended for a maximum working pressure of 690 kPa (100 psi) would be designed and calibrated for 1380 kPa (200 psi). This design principle will avoid over-stressing a gauge in service.

Standard Equipment

The following types of gauges are normally employed with oxyfuel welding and cutting equipment and for inert gas welding and cutting:

21 MPa (3000 psi) for oxygen, nitrogen, hydrogen, argon, helium

345 kPa (50 psi) for low-pressure oxygen, argon, helium

345 kPa (50 psi) for acetylene

1380 or 2070 kPa (200 or 300 psi) for cutting oxygen

Care of Gauges

Gauges should be given the care afforded to any precision instrument.

(1) To avoid the possibility of an explosion, never permit oil to get into any oxygen apparatus.

(2) Never apply pressures to gauges suddenly. Open valves on cylinders slowly.

(3) Do not apply pressures to the full scale of the dial.

(4) Do not apply full tank pressures with the regulating screw on reducing valves which are screwed all the way in. Increase the pressure on low-pressure gauges slowly.

(5) When installing gauges to apparatus, do not attach a wrench on the pipe threads; use the square above the pipe threads.

(6) Handle gauges with care. The mechanism can be damaged or destroyed if they are bumped, jammed or allowed to fall on the floor.

(7) A gauge that is giving incorrect readings can be a hazard. Do not try to repair a defective gauge. Take it to an authorized gauge repair shop.

PRESSURE PIPING CODE (ASME-B31)

The American Society for Mechanical Engineers (ASME) Code for Pressure Piping (B-31) sets forth engineering requirements deemed necessary for safe design and construction of piping systems. While safety is the basic consideration, this factor alone will not necessarily govern the final specifications for any piping system. The designer is cautioned that the Code is not a design handbook; it does not do away with the need for the engineer and competent engineering judgment.

To the greatest possible extent, Code requirements for design are stated in terms of basic design principles and formulas. These are supplemented as necessary with specific requirements to assure uniform application of principles and to guide selection and application of piping elements. The Code prohibits designs and practices known to be unsafe and contains warnings where caution, but not prohibition, is warranted. The specific design requirements of the Code usually revolve around a simplified engineering approach to a subject. It is intended that a designer capable of applying more complete and rigorous analysis to special or unusual problems should have latitude in the development of such designs and the evaluation of complex or combined stresses. In such cases the designer is responsible for demonstrating the validity of approach which is taken.

The Code for Pressure Piping includes the following:

(1) Material specifications and component standards including dimensional requirements and pressure ratings which have been accepted for Code usage

(2) Requirements for design of components and assemblies, including pipe supports

(3) Requirements and data for evaluation and limitation of stresses, reactions, and movements associated with pressure, temperature changes and other forces

(4) Guidance and limitations on the selection and application of materials, components and joining methods

(5) Requirements for the fabrication, assembly and erection of piping

(6) Requirements for examination, inspection and testing of piping

The Code for Pressure Piping is organized and operated under the direction of ASME Committee B31, under procedures of the American Society of Mechanical Engineers (ASME), which has been accredited by the American National Standards Institute. The Committee is a continuing one, and keeps all Code Sections current with new developments in materials, construction and industrial practice. Addenda are issued periodically. New editions are published at intervals of three to five years.

The ASME B31 Code for Pressure Piping consists of seven sections. Each section prescribes the minimum requirements for the design, materials, fabrication, erection, testing and inspection of a particular type of piping system.

B31.1, Power Piping. This section covers power and auxiliary service systems for electric generation stations; industrial and institutional plants; central and district heating plants; and district heating systems. This section excludes boiler external piping, which is defined by Section I of the ASME Boiler and Pressure Vessel Code. Boiler piping requires a quality control system and third party inspection similar to those required for boiler fabrication. Otherwise the materials, design, fabrication, installation and testing for boiler external piping must meet the requirements of B31.1. A fabricator is not required to provide a quality control system and third party inspection for the other piping systems covered by B31.

B31.2, Fuel Gas Piping. This section covers piping systems for fuel gases including natural gas, manufactured gas, liquefied petroleum gas (LPG) and air mixtures above the upper combustible limits, LPG in the gaseous phase, or mixtures of these gases. These piping systems, both in and between buildings, extend from the outlet of the consumer's meter set assembly (or point of delivery) to and including the first pressure-containing valve upstream of the gas utilization device.

B31.3 Chemical Plant and Petroleum Refinery Piping. This section covers all piping within the property limits of facilities engaged in processing or handling of chemicals, petroleum or related products. Examples are chemical plants, petroleum refineries, loading terminals, natural gas processing plants (including liquefied natural gas facilities), bulk plants, compounding plants and tank farms. This section applies to piping systems that handle all fluids, including fluidized solids and to all types of service including raw, intermediate and finished chemicals; oil and other petroleum products; gas, steam, air, water, and refrigerants, except as specifically excluded.

Piping for air and other gases, which is not within the scope of existing sections of this Code, may be designed, fabricated, inspected and tested in accordance with the requirements of this section of the

Code. The piping must be in plants, buildings and similar facilities that are not otherwise within the scope of this section.

B31.4, Liquid Petroleum Transportation Piping System. This section covers piping for transporting liquid petroleum products between producers' lease facilities, tank farms, natural gas processing plants, refineries, stations, terminals and other delivery and receiving points. Examples of such products are crude oil, condensate, gasoline, natural gas liquids and liquefied petroleum gas.

B31.5, Refrigeration Piping. This section applies to refrigerant and brine piping for use at temperatures as low as –196°C (–320°F) whether erected on the premises or factory assembled. It does not include (1) self-contained or unit refrigeration systems subject to the requirements of Underwriters Laboratories or any other nationally recognized testing laboratory, (2) water piping, or (3) piping designed for external or internal pressure not exceeding 103 kPa (15 psig), regardless of size. Other sections of the Code may provide requirements for refrigeration piping in their respective scopes.

B31.8, Gas Transmission and Distribution Piping Systems. This section addresses gas compressor stations, gas metering and regulating stations, gas mains and service lines up to the outlet of the customers meter set assembly. Gas storage lines and gas storage equipment of the closed pipe type that are either fabricated or forged from pipe or fabricated from pipe and fittings are also included.

B31.9, Building Services Piping. This section applies to piping systems for services in industrial, commercial, public, institutional and multi-unit residential buildings. It includes only those piping systems within the buildings or property limit.

When no section of the ASME Code for Pressure Piping specifically covers a piping system, at the discretion of the user, the user may select any section of the Code determined to be generally applicable. However, it is cautioned that supplementary requirements of the section chosen may be necessary to provide for a safe piping system for the intended application. Technical limitations of the various sections, legal requirements and possible applicability of other codes or standards are some of the factors to be considered by the user in determining the applicability of any section of this code.

All sections of the Code for Pressure Piping require qualification of the welding procedures and performance of welders and welding operators to be used in construction. Some sections require these qualifications to be performed in accordance with Section IX of the ASME Boiler and Pressure Vessel Code, while in others it is optional. The use of API Std 1104, *Standard for Welding Pipelines and Related Facilities* or AWS D10.9, *Specification for Qualification of Welding Procedures and Welders for Piping and Tubing* is permitted in some sections as an alternative to Section IX. Each section of the Code should be consulted for the applicable qualification documents and detailed requirements for joint designs, welding procedures, heat treatment, quality control and operator qualification.

Weld Filler Metals

All filler metal, including consumable insert material, should comply with the requirements of Section IX, ASME Boiler and Pressure Vessel Code. A filler metal not incorporated in Section IX may be used if a procedure qualification test is first successfully made in accordance with Section IX. Filler metals with less than 0.05% carbon content should not be used for high temperature applications (above 450°C [850°F]) in low-alloy steels due to reduced creep rupture properties.

Backing Rings

The design and dimensions of backing rings vary according to the application; therefore if backing rings are to be used, the applicable subsection of the Code should be consulted to determine the required design and dimensions.

Ferrous metal backing rings which become a permanent part of the weld should be made from a material of weldable quality and should be compatible with the base material. The sulphur content should not exceed 0.05%. If two butting surfaces are to be welded to a third member used as a backing ring, and one or two of the three members are ferritic and the other one or two members are austenitic, the satisfactory use of such materials should be determined by a welding procedure specification. Backing rings of nonferrous materials may be used for backing provided they are included in a welding procedure specification.

Consumable Inserts

Consumable inserts may be used provided they are made from material compatible with the chemical and physical properties of the base material. The welding procedure for using consumable inserts must be procedure-specified.

Girth Butt Welds

Girth butt welds should be complete penetration welds and should be made with a single V, double V, or other suitable type of groove, with or without backing rings or consumable inserts. The depth of the weld measured between the inside surface of the weld preparation and the outside surface of the pipe should not be less than the minimum thickness required by the Code.

The rules for welding pressure piping systems are covered in detail in the ASME B31 Code for Pressure Piping. Any designer or fabricator planning to weld pressure piping should be familiar with the requirements of the Code, particularly with the Section which applies to the application involved.

PRESSURE REDUCER

A device designed to reduce and regulate the pressure of gases used in cutting and welding.

PRESSURE REGULATOR

A device designed to maintain a nearly constant welding gas pressure from a cylinder, generator or pipe line. Pressure regulators are sometimes called *reducer valves.* They may be used to lower the pressure of gas from the source of supply to the necessary working pressure. *See* PRESSURE GAUGE *and* REGULATOR.

PRESSURE TESTING

See HYDROSTATIC TEST *and* TUBE TESTING.

PRESSURE THERMITE WELDING

A pressure welding process in which the heat is obtained from the liquid product of a thermite reaction.

PRESSURE VESSEL CODE

See BOILER CONSTRUCTION CODE. *See also* UNFIRED PRESSURE VESSEL CODE.

PRESSURE VESSEL INSPECTOR

See Appendix 16, National Board of Boiler and Pressure Vessel Inspectors.

PRESSURE WELDING

A nonstandard term for SOLID-STATE WELDING, HOT PRESSURE WELDING, FORGE WELDING, DIFFUSION WELDING, PRESSURE GAS WELDING, and COLD WELDING.

In this group of welding processes, the parts are joined by applying mechanical pressure while the metal is in a highly plastic or molten state.

PRETINNING

A nonstandard term for PRECOATING.

PREWELD INTERVAL, Resistance Welding

The elapsed time between the initiation of the squeeze time and the beginning of the weld time or weld interval time. See STANDARD WELDING TERMS. *See also* Figure I-1.

PRICK PUNCHING

Producing a series of closely spaced indentations with a hard pointed instrument, such as a center punch, to lay out a line on a metal surface to mark the location of a planned weld or cut.

PRIMARY CIRCUIT

The coil or circuit to which alternating current power is applied and which transfers it to a secondary circuit by induction.

PRIMARY LEADS

The wires or cables connecting the primary winding of a transformer to the main power source used in all types of transformers, including arc and resistance welding transformers.

PRIMARY WINDINGS

The windings which are connected to and receive power from an electrical circuit.

PROCEDURE

The detailed elements of a process or method used to produce a specific result. See STANDARD WELDING TERMS.

PROCEDURE CONTROL (Welding Procedure Specification)

The fundamental principles for the control and supervision of every step in a welding operation. The procedure control is intended for the guidance of those in charge of planning and directing the work, rather than the operator or welder. It involves:

(1) Checking the welding machines
(2) Selection and inspection of materials
(3) Design and layout of the welded joint
(4) Preparing the components for welding

(5) Establishing the welding technique and organizing the procedures

(6) Inspecting welding operations and testing weldments

A systematic method of obtaining and retaining complete control over all factors involved in a welding job is an important requirement in production welding, and is equally valuable in repair work of a repetitive nature. It can also be useful for investigating welding operations to assure full efficiency.

PROCEDURE QUALIFICATION

The demonstration that welds made by a specific procedure can meet prescribed standards. See STANDARD WELDING TERMS.

PROCEDURE QUALIFICATION RECORD (PQR)

A document containing all of the actual values of the welding variables used to fabricate a welding procedure qualification test weldment and the actual values of the results of tests performed on the test weldment. See STANDARD WELDING TERMS. *See also* BRAZING PROCEDURE QUALIFICATION RECORD *and* WELDING PROCEDURE QUALIFICATION RECORD.

PROCESS

A grouping of basic operational elements used in welding, thermal cutting, or thermal spraying. See STANDARD WELDING TERMS. *See also* Appendix 3, Master Chart of Welding and Allied Processes.

PROCESS ANNEALING

See ANNEALING.

PROD

A contact used in magnetic inspection. *See* MAGNETIC INSPECTION OF WELDS.

PROGRESSIVE BLOCK SEQUENCE

A block sequence in which successive blocks are completed progressively along the weld, either from one end to the other or from an intermediate location of the weld toward either end. See STANDARD WELDING TERMS.

PROGRAM WELDING

A term sometimes applied to sequence resistance welding.

PROJECTION WELDING (PW)

A resistance welding process that produces a weld by the heat obtained from the resistance to the flow of the welding current. The resulting welds are localized at predetermined points by projections, embossments, or intersections. See STANDARD WELDING TERMS. *See also* RESISTANCE WELDING.

As with spot and seam welding, projection welding can be used to produce lap joints. The purpose of a projection is to localize the heat and pressure at a specific point on the joint. The number and shape of the projections depend upon the requirements for joint strength.

Circular or annular ring projections can be used to weld parts requiring either gas-tight or water-tight seals, or to obtain a larger area weld than button-type projections can provide.

Projection Designs

The projection design determines the current density. Various types of projection designs are shown in Figure P-21.

The method of producing projections depends on the material in which they are to be produced. Projections in sheet metal parts are generally made by embossing, as opposed to projections formed in solid metal pieces which are made by either machining or forging. In the case of stamped parts, projections are generally located on the edge of the stamping.

Applications

Projection welding is primarily used to join a stamped, forged, or machined part to another part. One or more projections are produced on the parts during the forming operations. Fasteners or mounting devices, such as bolts, nuts, pins, brackets, and handles, can be projection-welded to a sheet metal part. Projection welding is especially useful for producing several weld nuggets simultaneously between two parts. Marking of one part can be minimized by placing the projections on the other part.

The process is generally used for section thicknesses ranging from 0.5 to 3.2 mm (0.02 to 0.125 in.) thick. Thinner sections require special welding machines capable of following the rapid collapse of the projections. Various carbon and alloy steels and some nickel alloys can be projection welded.

Advantages and Limitations

In general, projection welding can be used instead of spot welding to join small parts to each other and to larger parts. Selection of one method over another depends on the economics, advantages, and limitations of the two processes. The chief advantages of projection welding include the following:

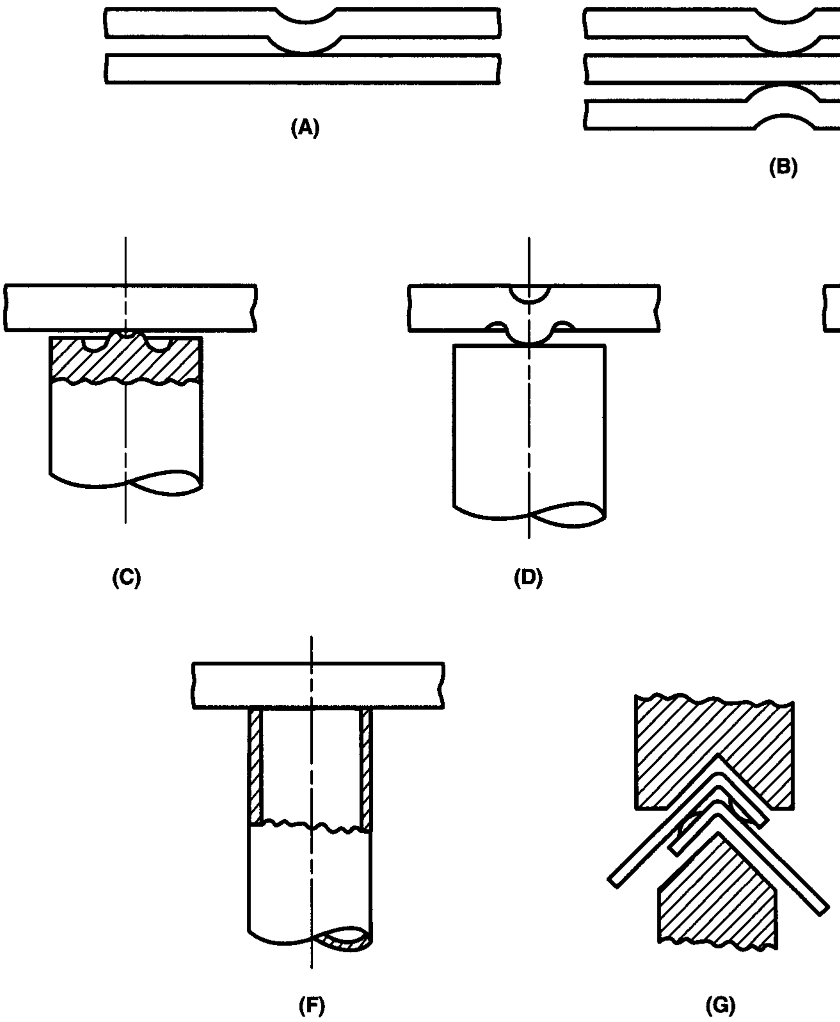


Figure P-21—Examples of Various Projection Designs

(1) A number of welds can be made simultaneously in one welding cycle of the machine. The limitation on the number of welds is the ability to apply uniform electrode force and welding current to each projection.

(2) Less overlap and closer weld spacings are possible, because the current is concentrated by the projection, and shunting through adjacent welds is not a problem.

(3) Thickness ratios of at least 6 to 1 are possible, because of the flexibility in projection size and location. The projections are normally placed on the thicker section.

(4) Projection welds can be located with greater accuracy and consistency than spot welds, and the welds are generally more consistent because of the uniformity of the projections. As a result, projection welds can be smaller in size than spot welds.

(5) Projection welding generally results in better appearance, on the side without the projection, than spot welding can produce. The most deformation and greatest temperature rise occur in the part with the projection, leaving the other part relatively cool and free of distortion, particularly on the exposed surface.

(6) Large, flat-faced electrodes are used; consequently, electrode wear is much less than that with

spot welding and this reduces maintenance costs. In some cases, the fixturing or part locators are combined with the welding dies or electrodes when joining small parts together.

(7) Oil, rust, scale, and coatings are less of a problem than with spot welding because the tip of the projection tends to break through the foreign material early in the welding cycle; however, weld quality will be better with clean surfaces.

The most important limitations of projection welding are the following:

(1) The forming of projections may require an additional operation unless the parts are press-formed to design shape.

(2) With multiple welds, accurate control of projection height and precise alignment of the welding dies are necessary to equalize the electrode force and welding current.

(3) With sheet metal, the process is limited to thicknesses in which projections with acceptable characteristics can be formed, and for which suitable welding equipment is available.

(4) Multiple welds must be made simultaneously, which requires higher capacity equipment than does spot welding. This also limits the practical size of the component that contains the projections.

PROJECTION WELD SIZE

The diameter of the weld metal in the plane of the faying surfaces. See STANDARD WELDING TERMS. *See also* Appendix 11.

PROPANE

(Chemical symbol: C_3H_8). A colorless, liquefied petroleum fuel gas which is shipped in tank cars, stored in large tanks under pressure, and is available in small tanks under pressure for shop use and as a cooking gas. Small self-contained propane torch sets are available for home workshop use and incidental heating operations.

Propane is used for many purposes, among them to fuel heat treating furnaces, core baking ovens, soft metal melting, unit heaters for industrial buildings, gas fired refrigerators, automatic steam boilers and brazing torches.

PROPANE CUTTING

Propane and other liquefied petroleum (LP) gases are used in flame cutting. The maximum temperature of an oxypropane flame is approximately 2030°C (5300°F), and is achieved by using five volumes of tank oxygen to one volume of propane. This requires about three times as much oxygen to produce the same amount of heat as with acetylene.

Advantages of OxyLP Gas Cutting

In flame cutting, the function of the preheating flames of the cutting tips is to raise the temperature of the steel to the kindling temperature: cherry red or approximately 900°C (1650°F). At that temperature the steel will burn in a stream of air or oxygen. The oxyLP mixture will produce a very satisfactory cut, despite the fact that its flame temperature is lower than that of the oxyacetylene flame. This means that the time required to start a cut will be a few seconds longer than with acetylene.

Once a cut is started, there are a number of advantages of oxyLP gas. Because of its lower temperature flame, the edges of the cut are not overheated, and a narrower kerf is burned away. The smaller volume of metal removed requires less oxygen to oxidize the metal. This minimizes the slag adherence to the underside of the kerf. If slag is present, it is easily removed. The lower preheat temperature does not melt down the top edges of the cut.

A special tip is required when LP gas is used with a standard flame cutting outfit. The torch, regulators, and hoses are the same as for oxyacetylene cutting. Backfiring, pre-ignition, and flashback are very rare with LP gas because of its slower burning characteristic.

PROPERTIES OF METALS

The properties of metals can be divided into five general groups: (1) mechanical, (2) physical, (3) corrosion, (4) optical, and (5) nuclear. The specific properties in each of these groups are divided into structure-insensitive properties and structure-sensitive properties. This distinction in properties is commonly made in most textbooks on metals to emphasize the considerations that should be given to reported property values. See Table P-8.

Structure-insensitive properties are well defined properties of a metal. They do not vary from one piece of metal to another of the same kind. This is true for most engineering purposes, and is verified by the data obtained from standard engineering tests. These properties can often be calculated or rationalized by consideration of the chemical composition and the crystallographic structure of the metal. They are commonly listed in handbooks as constants for the particular metals.

Table P-8
Properties of Metals

General Groups	Structure-Insensitive Properties	Structure-Sensitive Properties
Mechanical	Elastic Moduli	Ultimate strength Yield strength Fatigue strength Impact strength Hardness Ductility Elastic limit Damping capacity Creep strength Rupture strength
Physical	Thermal expansion Thermal conductivity Melting point Specific heat Emissivity Thermal evaporation rate Density Vapor pressure Electrical conductivity Thermoelectric properties Magnetic properties Thermionic emission	Ferromagnetic properties
Corrosion	Electrochemical potential Oxidation resistance	
Optical	Color Reflectivity	
Nuclear	Radiation absorbtivity Nuclear cross section Wavelength of characteristic x-rays	

Structure-sensitive properties are dependent not only on chemical composition and crystallographic structure, but also on microstructural details that may be affected in subtle ways by the manufacturing and processing history of the metal. Even the size of the sample can influence test results obtained for a structure-sensitive property, and they are likely to vary to some degree if there are differences in the treatment and preparation of the samples.

The most important mechanical properties in the design of weldments, with the exception of elastic moduli, are structure-sensitive. Consequently, single values of these properties must be accepted with reservation. It is not uncommon for plates or bars of a metal, which represent unusual sizes or conditions of treatment, to have significant deviations in mechanical properties from those published for the metal. Also, the mechanical properties, as determined by standard quality acceptance tests in an American Society of Testing and Materials (ASTM) specification, do not guarantee identical properties throughout the material represented by the test sample. For example, the direction in which wrought metal is tested (longitudinal, transverse, or through-thickness) may give significantly different values for strength and ductility. Although the physical and corrosion properties of metals are considered to be structure-insensitive for the most part, some of the values established for these properties apply only to common polycrystalline metals.

Metals are appraised for the following mechanical characteristics: modulus of elasticity, elastic limit, yield strength, tensile strength, fatigue strength, ductility, fracture toughness, low temperature properties and elevated temperature properties.

Physical properties that may require consideration in designing or fabricating a weldment are: thermal conductivity, melting temperature, thermal expansion and contraction, and electrical conductivity.

Corrosion resistance is often an important consideration; particularly since weld joints often display corrosion properties that differ from the remainder of the weldment.

PROTECTION FOR WELDERS

The welding operator and personnel in the welding area must be protected from the potential hazards of welding. These include radiation from the arc and hot spatter from a welding electrode. Arc radiation can very quickly cause damage to the eye if viewed directly without adequate eye protection. Even when viewed directly from a distance of 6 m (20 feet), the retina can be damaged in a few seconds. Damage to the skin does not occur as quickly, but if exposed for several minutes, arc radiation can cause painful burns similar to sunburn. The severity depends on the intensity of the arc and the distance from the arc.

Eye Protection. Eye protection consists of wearing a helmet with the correct filter lens when welding, or using a hand shield with the correct filter when watching an arc. The filter lenses are available in several shades of darkness, numbered from 2 to 14 in a light-to-dark sequence. Number 2 would be used for torch soldering; number 14 would be used for arc welding at currents of more than 250 to 500 amperes. Shade selection for a given application should start with a dark shade. If it is difficult to see, successively lighter shades should be tried until the operation is sufficiently visible for good control. In no cases should a shade lower than number 7 be used for arc welding, and then only for arc current of less than 60 amperes. These lenses are designed to filter out harmful ultraviolet and infrared radiation from the arc.

Special radiation-sensitive helmet lenses are available which are clear when no radiation is present, but darken within milliseconds when an arc is initiated. The lenses become clear again when the arc is extinguished.

In addition to the welder, other workers in the shop area should be protected with curtains or screens surrounding the weld areas. These curtains or screens may be opaque, or made of a translucent plastic which absorbs ultraviolet radiation. Portable curtains can be moved to a weld operation to completely shield it from other workers. Shielding should be provided to protect crane operators from arc flashes. Shop wall areas should be painted with coating which provides a low reflectively for ultraviolet radiation. Paints or coatings formulated with titanium dioxide or zinc oxide have low reflectivity for ultraviolet radiation. *See* Appendix 18, Recommended Eye Protection.

Protective Clothing

Sturdy shoes or boots and heavy clothing should be worn to protect the whole body from flying sparks, spatter, and radiation burns. Leather gloves should be worn to protect the hands and forearms. Woolen clothing is preferred to cotton because it is not as readily ignited. Leather aprons and leg shields are much better protection against hot droplets of metal than wool or cotton cloth. A leather jacket should be worn to cover the upper body. Cuffless pants and covered pockets are recommended to avoid spark entrapment; the pants should be worn outside the shoes. A cap should be worn under the helmet to protect the hair or head from sparks.

PROTECTIVE ATMOSPHERE

A gas or vacuum envelope surrounding the workpieces, used to prevent or reduce the formation of oxides and other detrimental surface substances, and to facilitate their removal. See STANDARD WELDING TERMS.

PUDDLE

A nonstandard term when used for WELD POOL.

PUDDLE STICK

A steel rod flattened at one end used to break up oxides and to remove slags and impurities in aluminum welding. A puddle stick is especially useful when welding cast iron or aluminum without a flux. *See* ALUMINUM, Oxyfuel Gas Welding.

PUDDLE WELD

A nonstandard term for an ARC SPOT WELD, or PLUG WELD.

PUDDLING

Stirring the molten metal in a weld pool. Welds in cast iron and steel are usually puddled with the welding rod. Welds in aluminum are puddled with a puddle stick made of flattened steel rod.

PULL GUN TECHNIQUE

A nonstandard term for BACKHAND WELDING.

PULSATING CURRENT

A current that always flows in the same direction, but rises and falls at regular time intervals.

PULSATION WELDING

A nonstandard term for MULTIPLE-IMPULSE WELDING.

PULSE, Resistance Welding

A current of controlled duration of either polarity through the welding circuit. See STANDARD WELDING TERMS. *See also* Figure H-3.

PULSED ARC WELDING

See PULSED SPRAY WELDING.

PULSED GAS METAL ARC WELDING (GMAW-P)

A gas metal arc welding process variation in which the current is pulsed. See STANDARD WELDING TERMS. *See also* PULSED POWER WELDING.

PULSED GAS TUNGSTEN ARC WELDING (GTAW-P)

A gas tungsten arc welding process variation in which the current is pulsed. See STANDARD WELDING TERMS. *See also* PULSED POWER WELDING.

PULSED LASER

A laser whose output is controlled to produce a pulse whose duration is 25 milliseconds or less. See STANDARD WELDING TERMS. *See also* LASER.

PULSED POWER WELDING

An arc welding process variation in which the power source is programmed to cycle between low and high power levels. See STANDARD WELDING TERMS. *See also* PULSED SPRAY WELDING.

PULSED SPRAY TRANSFER

A variation of spray transfer in which the welding power is cycled from a low level to a high level, at which point spray transfer is attained, resulting in a lower average voltage and current. See STANDARD WELDING TERMS.

PULSED SPRAY WELDING

An arc welding process variation in which the current is pulsed to utilize the advantages of the spray mode of metal transfer at average currents equal to or less than the globular to spray transition current. See STANDARD WELDING TERMS.

Also known as pulsed arc welding, pulsed spray welding is a direct-current welding system in which a pulsing current is superimposed on a constant voltage d-c background current. It can be used for either gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW), but is generally associated with GMAW.

Pulsed arc welding is a modified form of gas metal arc spray transfer welding, which produces a controlled and periodic melting off of droplets which are projected across the arc. This process allows spray transfer welding at average currents which are considerably lower than the steady-state current necessary for spray transfer welding. The pulsed current process allows welding of thin sheet which would be melted through by the standard GMAW process. In the pulsed arc process the filler wire is heated by the background current and the end may start to melt into a drop. When the high current pulse occurs, the drop melts completely and is propelled, by the arc pinch effect, directly from the wire to the weld pool. One or more drops may be propelled across the arc during each pulse. The pulsed arc mode of gas metal arc welding produces deeper penetration and better root fusion than the dip transfer, or short circuiting mode, of GMAW. For this reason, pulse arc welding is particularly suited to welding the thinner materials.

Initially, pulsed arc power supplies consisted of a standard three phase d-c power rectifier and a 60 cycle half-wave rectifier. The 60 cycle half-cycle pulse was superimposed on the direct current to provide the pulsating dc. With the introduction of solid state devices and computers, pulse current power supplies are designed so that the pulsing rate can be varied over a wide range, and the width of the pulse can be varied independently of the pulsing rate. The magnitude of the background and pulse current levels can be adjusted independently of one another.

Pulsed arc welding can also be useful for gas tungsten arc welding (GTAW) applications, particularly for autogenous welding of tubing in a fixed position, where satisfactory penetration and weld face contours can be maintained. The high current pulse produces full penetration quickly, but does not remain at this high level long enough to cause excessive melting. The lower background current maintains the arc between pulses.Compared with the steady arc, the pulsing arc increases the penetration, with less heat input into the joint; however, welding speeds are reduced by 20 to 40%.

Generally the pulsation rate can be adjusted from 1 to over 100 pulses per second, and with some equipment, to over 1000 pulses per second. When a programmed weld is made involving current upslope and downslope, pulsation starts at the beginning of upslope where both the peak and background current increase to the beginning of main weld current and continue to pulse at those values for the remainder of weld time. At this time, both peak and background current start to diminish to a final current at the end of the downslope time. This type of weld program is often used for girth welding pipe or tubing by the automatic GTAW process.

PULSE START DELAY TIME

The time interval from current initiation to the beginning of current pulsation. See STANDARD WELDING TERMS. *See also* Appendix 19.

PULSE TIME, Resistance Welding

The duration of a pulse. See STANDARD WELDING TERMS. *See also* Figure H-3.

PURGING

The removal of any unwanted gas or vapor from a container, chamber, hose, torch, or furnace. It includes the removal of remaining gases or vapors from a container that may have held flammable material, such as grease, oil or gasoline, by washing with detergents or with live steam, and subsequently filling with carbon dioxide, nitrogen or inert gas to minimize explosion hazard during hot work. Purging includes removing air from an acetylene generator that may have entered while the generator was being charged with water and carbide.

PURGING, PIPE

Purging of pipe is the process of replacing the atmosphere within a pipe or tube with an inert gas atmosphere to prevent the contamination of the root bead during welding.

Satisfactory welds can be made in carbon steel pipe using consumable root insert rings without inert gas backup. However, the weld root will usually be rough and irregular, and the fused metal does not readily wet the base metal. When inert gas is used for a backup shield, the weld root will have a uniform, smooth, contour free of oxides. The fused metal will readily wet the base metal.

Total System Purging

If the use of purging dams is prohibited by code, or cannot be used for some other reason, it may be necessary to purge the entire system. In systemic purging, the ends of a pipe string are sealed off with plugs of rubber or other suitable material, and the pipe string is purged of air with inert gas, usually argon because it is heavier than air. The inert gas is introduced at one end of the string and vented at the other end through a small opening. The inlet opening should always be as low as possible and the vent as high as possible to take advantage of the different densities of air and argon.

Volume of Purging Gas Required. Purging an entire system is usually the most expensive method of purging because of the time and the volume of inert gas required. Usually a minimum of six volume changes is required to reduce the oxygen content of the purged volume to approximately 1%. The number of volume changes of gas required to achieve a suitable degree of inertness (usually less than 1% oxygen) depends on several factors. In a gas-tight system, as few as two or three volume changes will provide an atmosphere suitable for welding stainless steel and high-nickel alloys, but only if the inert gas is introduced slowly through a diffusing device. Theoretically, if argon is introduced slowly into the bottom of a closed chamber which is vented at the top, only one volume change should be necessary to remove all the air. However, this is not possible because gas molecules are in constant motion, and some of the heavier argon will rise and mix with the lighter air.

Analysis of a number of typical purges indicates that a minimum of ten volume changes is required to reduce the percentage of air to 0.1%. High flow rates reduce the time needed to purge a system; however, slow flow rates reduce gas consumption. If a system can be closed off and evacuated, then backfilled with inert gas, the air can be reduced to less than 0.1% with only one volume of gas. Once a system has been purged to a suitable level, the purging gas flow rate can be reduced substantially to a value which will maintain a positive pressure and flow.

Determining Oxygen Content. One method of determining the quality of the chamber or pipe atmosphere is to exhaust a sample of the gas through an oxygen analyzer. This provides a quick and accurate indication of the oxygen content, which will indicate whether the atmosphere is satisfactory for welding. If a gas analyzer is not available, flow rate charts can be used which indicate flow rates and times required to purge a given size chamber to 1% or less oxygen.

Purging Dams

Purging dams are plugs made of a variety of materials which are placed inside tubing or piping at both sides of a joint to be welded. These dams isolate the weld joint so that only the root of the weld zone needs to be shielded with inert gas rather than the whole pipe string. Some of the more commonly used systems are described in the following sections.

Soluble Dams. Soluble dams are constructed of a material which can be dissolved in a liquid, and are available commercially in the form of discs cut to fit the ID's of standard pipe sizes. The discs have the texture of heavy paper and sufficient strength to resist the slight pressures used for purging. The discs are placed in the two pieces of pipe to be joined, as close to the joint as the estimated maximum temperature will permit, and cemented in place with water soluble cement. A typical distance from disc to joint is 15.2 to 30.4 cm (6 to 12 inches).

The inert gas is usually introduced to the weld purge zone through small diameter tubing inserted into the center of the joint preparation or through one of the discs. Large pipe may require more than one purge tube for adequate purging. After welding, the dam can be removed by flushing with water, which dissolves all dam material. *See* Figure P-22 (A).

Inflatable Bladder Dam. Inflatable bladders are made of rubberized fabric, or a flexible plastic which will not soften or melt at slightly elevated temperatures. They have been used for many years in the repair and modification of low-pressure natural gas piping. An advantage of bladders is that they can be collapsed to

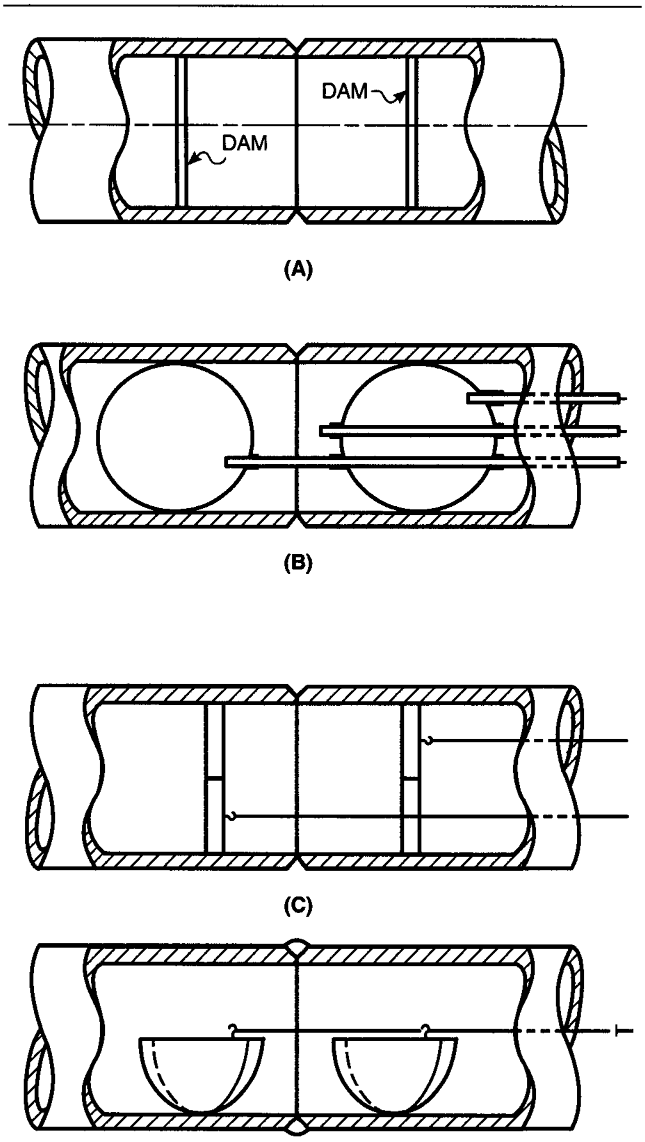


Figure P-22—Three Types of Purge Dams: (A) The Soluble Dam; (B) The Inflatable Bladder Dam; and (C) The Collapsible Disc Dam in Both Closed and Open Position

permit insertion into the pipe through a relatively small opening. The collapsed bladders are positioned in the pipe at the desired location and inflated, generally with the same gas used for purging. The gas used to inflate the bladders and for purging is introduced through a set of hoses passing through the open end of the pipe string. These are removed through the open end after welding. It is important to note that the bladder type dam can only be removed through an open end of the pipe string while soluble dams can be dissolved and thus removed through a small opening in the pipe string. *See* Figure P-22 (B).

Collapsible Disc Dam. Collapsible disc dams are the simplest and least expensive dam system. The discs may be fabricated from one-inch plywood or similar material, are hinged across the middle and are fitted with a thick band of foam rubber, or similar material, around the rim to provide a gas-tight seal with the pipe inside diameter. A chain attached to one side of the disc is positioned so that a tug will collapse the disc and rotate it so that it can be pulled out through the pipe's open end. The collapsible discs must be positioned in the pipe ends before they are brought together. *See* Figure P-22 (C).

PURIFIER

A device or apparatus for removing sulphurated hydrogen and other gases from acetylene.

PUSH ANGLE

The travel angle when the electrode is pointing in the direction of weld progression. This angle can also be used to partially define the position of guns, torches, rods, and beams. See STANDARD WELDING TERMS. *See also* DRAG ANGLE, FOREHAND WELDING, TRAVEL ANGLE, *and* WORK ANGLE.

PUSH-PULL GMAW

A welding system in which a motor and set of drive rolls in the wire feeder pushes, or drives, the welding wire toward the welding gun, where another motor and set of drive rolls pulls the wire. This arrangement permits welding to take place 15 to 18 m (50 to 60 feet) away from the wire feeder, or three times the usual operating range for GMAW equipment. The system is especially useful when welding with relatively soft wires like aluminum.

PUSH-PULL WELDING

A spot welding process using series-opposed split transformers. It consists of a dual point moving electrode welding unit and a dual point backup unit with flat electrodes. Advantages of this type of equipment are that spot welds are produced with flat surfaces, without indentations, on the side of the joint against the flat backup electrodes. This is particularly desirable for spot welding sheet metal cabinets, furniture and boxes.

Mounting flexibility is achieved when the backup unit is mounted in a fixed position with large flat electrodes, so that the moving unit may be moved to any position where the electrodes would make contact with the backup electrodes.

PUSH WELD

A spot or projection weld made by push welding.

PUSH WELDING

A resistance welding process variation in which spot or projection welds are made by manually applying force to one electrode and using the workpiece or a support as the other electrode. See STANDARD WELDING TERMS.

In push welding, sometimes called *poke welding,* pressure is applied manually to one electrode only. It differs from spot welding in that only one electrode is used in direct contact with the spot to be welded. The other electrode is clamped to any part of the metal in much the same manner that the workpiece is connected to the power supply in arc welding. This element makes it possible to weld in places that would be inaccessible for machine-made spot welds. In poke welding, the moveable electrode is operated by hand and placed at the point to be welded. When sufficient pressure is exerted on the workpiece, a pressure switch initiates the weld current at a preset value. Usually the welding machine controls the time of current flow to a set value.

PYROMETER

An instrument capable of indicating temperatures higher than a mercurial thermometer will indicate. There are several types of pyrometers, including the following:

Optical Pyrometer. There are several variations of optical pyrometers which use a lens system to focus the radiation from the heated object to be measured on the sensor of the instrument. One type focuses the radiation from the object to be measured on a thermopile, which produces a small voltage proportional to the body temperature. The voltage is converted to temperature and is indicated on a calibrated meter.

Another type of optical pyrometer measures the temperature of a heated object to be measured by comparing the color, or redness, of the heated object with a wire heated in the instrument by an electric current. This current converted to temperature is indicated on a calibrated meter.

Photoelectric Pyrometer. This type measures the voltage from a photronic or photoelectric cell, which receives radiation from the heated object. The voltage is converted to temperature and is indicated on a calibrated meter.

Electrical Resistance Pyrometer. This type uses a Wheatstone bridge to measure the resistance (which varies with temperature) of a fixed length of platinum wire which is exposed to the temperature to be measured. It is useful to 2400°C (4350°F).

Thermocouple Pyrometer. Thermocouple pyrometers make use of the small voltage produced when two different metals which are in contact are heated. Wires of the two different metals are welded to form a hot junction and a voltage is measured by a sensitive voltage measuring instrument at the other ends of the wires at room temperature. Several standard metal combinations are available, and temperature-voltage values have been determined and published for each. The more common thermocouple metal combinations are: chromel-alumel; platinum-platinum 10% rhodium; platinum-platinum 13% rhodium; iron-Constantan; and copper-Constantan.

Mechanical Pyrometer. A mechanical pyrometer utilizes the differential expansion of two different metals when heated to actuate a pointer by means of gears or levers. These are not accurate over 538°C (1000°F).

Q

QUALIFICATION

See STANDARD WELDING TERMS. *See also* WELDER PERFORMANCE QUALIFICATION, PROCEDURE QUALIFICATION *and* QUALIFICATION AND TESTING.

QUALIFICATION AND CERTIFICATION

The words *qualification* and *certification* are probably the two most misunderstood words in the vocabulary of a welder. These two terms are erroneously used interchangeably. Often the person who speaks these words has in mind a meaning that is entirely different from what the person who hears them perceives. Generally, "certified" refers to the welder who has a certificate signed by somebody and certificates can be issued by almost anyone. A welder can get a certificate of welding proficiency on graduating from a vocational training course, high school course, community college or industrial training school. However, none of these will qualify the welder for doing code welding. Where welding codes are concerned, specific qualification tests are spelled out by the various codes.

Often the statement, "I'm a certified pipe welder" leaves unanswered questions such as:

(1) Qualified to what pipe welding code? There are several, including those drawn up by the American Petroleum Institute, the American Society for Mechanical Engineers, American Welding Society, Nuclear Regulatory Commission, and the American Water Works Association.

(2) Qualified for what procedure? For what position; what type of electrode and base material; what thickness of base material?

Another question is that of duration of the qualification. Some qualifications, such as AWS, are considered to remain in effect indefinitely unless the welder is not engaged in a given process of welding for a period of three months or more, or unless there is some specific reason to question the ability of the welder.

Code Welding

Every welding operation is intended to be carried out to assure operator performance at a stipulated level of quality for a given design, with certain built-in safety factors. These performance features may be required by shop standards, customer specifications, or rules and regulations of a specific code.

A code is generally considered to be the most rigid of these requirements, since it carries the implication of law, and in some cases, actually is a law enacted by a government body. Standards are commonly included or referenced in the code in a municipal, state or federal government project to establish limits and controls over some features of the code. Some examples are a municipal building code, a state boiler and pressure vessel code, or a federal highway bridge code.

A properly worded code does not include explanatory matter. Since the features outlined in the code must be enforceable as a law, the code is written in mandatory language, using the imperatives "shall" and "must," or equivalent words. Explanatory matter is relegated to other documents or to appendices.

The most frequently cited codes involving the welding industry are the ASME *Boiler and Pressure Vessel Code* and the AWS D1.1 *Structural Welding Code—Steel.* Other codes and standards, such as API 1104 *Standard for Welding Pipelines and Related Facilities,* and ASME B31, *Code for Pressure Piping*, include specified qualification tests.

There may be other instances when a welder may be qualified to a code, even though the work being done is not involved with such a code. This frequently happens when shop welding personnel are qualified to the D1.1, D1.2, D1.3, and D1.4 series of the AWS Structural Welding Codes.

Requalification. Some codes require requalification for every job. For example, even though a person may have qualified as an EXX18 welder (most qualifications are by type of electrode) on a certain building, that qualification may not be accepted at another building site, although it can be accepted at the option of the local building commission and the owners or architects. In most areas, even though a welder may still be working for the same contractor, the owners or architects of a new project will usually call for requalification of all welders involved. The same is true in most types of pressure vessel and pressure piping work. A welder will also be required to requalify when certain changes in the welding procedure are made. These changes are listed in the codes as *Limitations of Welder Qualification.*

A welder is qualified after passing a particular qualification test. For example, a welder might be qualified under the requirements of Section IX of the ASME Boiler and Pressure Vessel Code. In general, an employer is responsible for assuring that welders are given the correct qualification tests before work begins, since the employer is responsible for the work of the welders.

The welder who wants to be certified (not just qualified), should learn and practice the procedures described in AWS B2.1 latest edition, *Standard for Welding Procedure and Performance Qualification Procedure*, issued by the American Welding Society, as well as any particular requirements of the specific codes governing the type of work the welder wants to do.

Qualification. There are two distinct steps toward qualification. The first is qualification of the welding procedure; the second is qualification of the welder.

The procedure qualification is a common requirement of all codes and specifications governing welding. Its purpose is to test the capability of the procedure to produce a satisfactory welded joint, although this does not guarantee that all welds made under the procedure will be satisfactory. It merely serves to prove that satisfactory welds can be made by following the various steps of the procedure. Quality in welding depends on a great many interrelated factors, in which the procedure is the dominating control.

The second qualification is a test of the welder's ability to perform the work; this is a mandatory requirement in many codes. Again, passing this test is not a guarantee; it merely proves that the welder has the ability to make satisfactory welds under given circumstances.

Procedure Qualification. Before taking the welding procedure qualification test, the welder will have to select a welding process, equipment, and materials, then design appropriate weld joints, and conduct trial welds. Each of these must be considered according to the metallurgical and mechanical properties of the materials involved, the degree of weld soundness or quality required, and cost. The step-by-step method which evolves is the welding procedure, and all codes require that it be in written form. The procedure may be expressed in broad, general terms, or it may be explicit in detail, depending on the class of work or type of product being welded, the ease or difficulty of reproducing satisfactory welds, and the knowledge, skill and integrity of the person doing the work. The welding procedure is a written specification covering the necessary steps to be taken to produce a satisfactory weld.

Test Administration. Most codes are not specific on the point of who is to do the testing, but usually leave it to the option of the fabricator (or owner). In order to become certified under an AWS code, the welder must take the qualification test at an AWS accredited test facility. While the architect or owner may demand control over testing, in most cases they do not, leaving it up to the contractor. The latter, however, is responsible for every weld made during construction, so the contractor must document the qualification of each procedure used and of every welder working on the job.

The qualification test record, or certification of procedure or welder, generally calls for the signature of the person conducting the test, as well as that of an individual who witnessed it. Whether they are employed by the weld fabricating company or by an independent testing laboratory, they are responsible for documenting the qualification.

Preparation of the test specimen is a key factor in the success of the mechanical tests; improper preparation of a specimen may cause it to fail.

There are five different types of codes which require weld qualification: (1) industrial (AWS, ASME, API, AWWA, and others); (2) military (NAVSHIPS, MILSPEC; (3) governmental (local, state and federal); (4) consumer or customer specifications, and (5) manufacturers specifications on products for which weld quality is mandatory, but for which there are no existing specifications.

In many product areas, the influence of the insurance companies affects the codes. The insurers, while not code-writing bodies in themselves, have been influential in having codes written since the beginning of welded fabrication. The insurance companies got involved in metal fabrication in the early days of this century with the introduction of pressure vessels of riveted construction. This culminated in 1915 in the publication, by the American Society for Mechanical Engineers, of the first Boiler and Pressure Vessel Code, which is updated as required and is considered the bible of the industry.

Nuclear Systems Code

ASME's responsiveness to the needs of nuclear systems development and for public safety led to the first Nuclear Systems Code. This was accomplished through a close relationship with the Atomic Energy

Commission, which requested that one organization accept responsibility for codifying the pressure boundary of the entire nuclear system. As a result, Section III of the Boiler and Pressure Vessel Code, initially published in May. 1971, includes rules for design, fabrication and inspection of various classes of nuclear components such as piping, vessels, pumps, valves and metal containment vessels. Previous issues had included provisions for nuclear vessels.

QUALIFICATION FOR CODE WORK

The primary purpose of all the codes is to secure safe boilers, pressure vessels, and piping through minimum construction standards. Welding codes also provide means that will disclose inherent defects in methods of welding and lack of competency on the part of welding operators, since defective welds are almost invariably due to lack of control of the welding procedure.

No two codes are exactly alike with respect to the provisions for qualifying welding operators. It is therefore necessary, when seeking detailed information as to the types of tests required, and the method of test supervision, to consult the specific code or specification governing the particular type of work to be done.

QUALIFICATION AND TESTING

Procedure and performance qualification and testing standards for welding procedures, thermal spraying, brazing, testing and inspection are published by the American Welding Society.

AWS C2.16, *Guide for Thermal Spray Operator and Equipment Qualification* provides for qualification of operators and equipment for applying thermal sprayed coatings. It recommends procedural guidelines for qualification testing. The criteria used to judge acceptability are determined by the certifying agent alone or together with the purchaser.

AWS D10.9, *Specification for Qualification of Welding Procedures and Welders for Piping and Tubing,* covers circumferential groove and fillet welds but excludes welded longitudinal seams involved in pipe and tube manufacture. An organization may make this specification the governing document for qualifying welding procedures and welders by referencing it in the contract and by specifying one of the two levels of acceptance requirements. One level applies to systems that require a high degree of weld quality. Examples are lines in nuclear, chemical, cryogenic, gas, or steam systems. The other level applies to systems requiring an average degree of weld quality, such as low-pressure heating, air conditioning, sanitary, water, and some gas or chemical systems.

MIL-STD-248, *Welding and Brazing Procedure and Performance Qualification,* and MIL-STD-1595, *Qualification of Aircraft, Missile, and Aerospace Fusion Welders* may be used when federal government or military requirements are involved.

AWS B2.1, *Standard for Welding Procedure and Performance Qualification,* provides requirements for qualification of welding procedures, welders and welding operators. It may be referenced in a product code, specification, or contract documents. Applicable base metals are carbon and alloy steels, cast irons, aluminum, copper, nickel, and titanium alloys.

AWS B2.2, *Standard for Brazing Procedure and Performance Qualification*, covers requirements for qualification of brazing procedures, brazers, and brazing operators for furnace, machine, and automatic brazing. It is to be used when required by other documents, such as codes, specifications, or contracts. Those documents must specify certain requirements applicable to the production brazement. Applicable base metals are carbon and alloy steels, cast iron, aluminum, copper, nickel, titanium, zirconium, magnesium, and cobalt alloys.

ANSI/AWS C3.2, *Standard Method for Evaluating the Strength of Brazed Joints in Shear,* describes a test method used to determine shear strengths of brazed joints. For comparison purposes, specimen preparation, brazing practices and testing, procedure must be consistent. Production brazed joint strength may not be the same as test joint strength if the brazing practices are different. With furnace brazing, for example, the actual part temperature or time at temperature, or both, during production may vary from those used to determine joint strength.

ANSI/AWS B4.0, *Standard Methods for Mechanical Testing of Welds*, describes the basic mechanical tests used for evaluation of welded joints, weldability, and hot cracking. The tests applicable to welded butt joints are tension, Charpy impact, drop-weight, dynamic-tear, and bend types. Tests of fillet welds are limited to break and shear tests.

For welding materials and procedure qualifications, the most commonly used tests are round-tension; reduced-section tension; face-, root-, and side-bend; and Charpy V-notch impact. Fillet weld tests are employed to determine proper welding techniques and conditions, and the shear strength of welded joints for design purposes.

AWS B1.10, *Guide for the Nondestructive Inspection of Welds,* describes the common nondestructive methods for examining welds. The methods included are visual, penetrant, magnetic particle, radiography, ultrasonic and eddy current inspection.

Qualification tests help determine the proficiency of welders to ensure that failures will not be caused by lack of skill. Also, the application of the welding processes in some fields is subject to regulation and inspection which, in some cases, is very rigid. Most welding codes require that individual operators pass a qualification test.

The nature and the comprehensiveness of qualification tests varies with the work to be done. In general, the qualifying welds made by an operator will be made under conditions which duplicate, as nearly as practicable, the working conditions of the prospective job. For example, there would be a great deal of difference between the test required of a welder working on an aerospace application and those required for a welder who works wholly with structural steel.

There is some difference of opinion as to the necessity of examining a welder on the theoretical knowledge of a process. Whether or not it is worthwhile to insist that an operator know something about the scientific background of the process would seem to depend on individual circumstances. There are many supervisors who think that if the foreman or head welder is well informed, satisfactory results can be obtained from welders who have demonstrated only their ability to manipulate the torch or the arc. It is certain, however, that knowledge of the process is no handicap.

Before requiring welders to take qualification tests for any kind of work, it is advisable to prepare forms on which a record can be made of all the operating conditions, the observations made by the inspector, and a complete record of test results. These individual records should be carefully preserved for reference.

A good deal of unnecessary expense can be circumvented if the qualification test is divided into two parts: first, observation of a preliminary break test, and second, a quantitative test.

Preliminary Break Test

A preliminary break test should be a made with a simple weld that can easily be broken through the weld itself. There are several methods of doing this: (1) using a plain butt weld and breaking it in a vise, (2) welding one plate to another in the form of a T on one side only and breaking by a sharp blow on the side of the plate opposite the weld and (3) making a lap fillet weld on one side only, then breaking through the weld by supporting the outside edges of the plates and hammering or pressing on the center of the weld; (4) making a butt weld and cutting nicks in both ends of the weld so that a sharp blow with a sledge hammer will result in a break directly through the weld metal.

Other methods of designing an observation test can, of course, be used. It is always desirable to use a design which approximates the working conditions. The important thing is to complete a fracture through the weld so that the entire cross section of the inside of the weld can be examined for fusion, penetration, porosity, slag inclusions and grain structure.

This test can be made with ordinary shop tools and involves a minimum of expense. It is obviously unnecessary to proceed to a more expensive laboratory test in the case of operators who do not show satisfactory proficiency at this point.

Quantitative Test

The quantitative test is for the purpose of determining how strong a weld the operator can make. If the welder is to be tested on butt welds only, the specimen plates are welded together and coupons are cut from these. The coupons are then tested for tensile strength and ductility in a laboratory. If the welder is to be tested on fillet welds, a double-strap lap joint is recommended. As a rule, it is difficult to make these test specimens with the welds in longitudinal shear.

Hartford Test

The Hartford Test refers to qualifying an employer's organization for an insurance company. The qualifying tests of the procedures and the welding which operators have completed are part of the requirements for qualifying the employer's organization. The welding operators can weld on code work only for the employer with whom the tests were performed.

An insurance company engaged in shop inspection does not issue certificates of qualification to welding operators, since the certificates would be of no value to another shop.

See TESTING for further reference to various qualification tests and testing methods. *See also* QUALIFICATION FOR CODE WORK, ASME BOILER CONSTRUCTION CODE; BOILER WELDING; BUILDING CONSTRUCTION CODES; HARTFORD TEST; *and* TRAINING.

QUARTZ

A crystalline form of silica (silicon dioxide SiO_2). Found abundantly in nature, quartz is the main constituent of granite, sandstone and other stones. In the welding industry it is used in powdered form in electrode coatings to prevent access of air to the hot weld metal. The quartz powder and other ingredients in the electrode coating form a protective slag on the weld bead.

QUATERNARY ALLOY

An alloy containing four principal elements. An example of a quaternary alloy is a "chrome-moly-steel," which contains the key elements of chromium, molybdenum, and carbon in iron.

QUENCHING

The sudden cooling of heated metal by immersion in oil, water, or some other liquid medium (e.g., glycol or liquid nitrogen), a molten salt, or by spraying with a jet of water or compressed air. The purpose of quenching is to produce desired weld strength properties in hardenable steel.

Ferrous alloys (e.g., especially, plain carbon, high-strength low-alloy, and tool steels) which can undergo transformation hardening, or non-ferrous alloys which can be precipitation hardened, are generally quenched to either produce or retain a particular microstructure.

In non-ferrous alloys (for example age-hardenable aluminum alloys with copper, magnesium-silicon, lithium, or other additions) quenching is usually applied after the alloy is rendered single-phase by heating, i.e., is solution-treated or solutionized, in order to retain that single phase in a supersaturated state relative to a key solute element. Heating under controlled temperature-time cycles allows a second-phase to precipitate and induce hardening in what is called *aging*.

The rate of cooling through the critical range determines the form in which the steel will be retained. In annealing, the heated steel may be furnace-cooled to about 595°C (1100°F), then it may be air cooled to room temperature. Slow cooling to 595°C (1100°F), which is below the critical range, provides sufficient time for complete transition from austenite to pearlite, which is the stabilized condition of steel at atmospheric temperature. In normalizing, the heated steel is removed from the furnace and allowed to cool slowly in the air. Such cooling is more rapid than in annealing and complete transition to pearlite is not obtained. In this instance, air cooling is a mild form of quenching.

To harden steels it is necessary to use a more rapid quenching medium. The three common mediums used are brine, water, and oil. Brine produces the fastest temperature change; water is next, while oil produces the least drastic change. Although oil does not cool the heated steel through the critical range as rapidly as water or brine, it cools the steel rapidly enough to develop sufficient hardness for practical purposes.

A drastic quench is required for relatively low-carbon steels in order to develop the required hardness. However, this type of quench is likely to cause the steel to warp and crack, and may set up internal stresses. When the structure changes from austenite to martensite, the volume of the steel is increased. If the change is too sudden cracking will occur. Cracking occurs particularly in the lower temperature ranges, when the steel is no longer plastic enough to adjust itself to expansion and contraction.

The shape and thickness of the workpiece influences warping and cracking. Thin flanges on heavy sections are especially susceptible to warping. When tubular parts are quenched they should be immersed with the long axis vertical to reduce warping. Because of the less drastic action of the oil quench, many of these difficulties are avoided, and for this reason oil is preferred over brine or water if sufficient hardness can be obtained.

The quenching medium is normally maintained at about 20°C (70°F), and provision should be incorporated to prevent temperature change of more than ±10°C (±20°F). This involves a large reservoir of liquid and a method of providing circulation and cooling. It is important to note that the rate of cooling throughout the critical range is governed by the temperature maintained in the quenching medium. Since a slight variation in the temperature of the quenching medium will have an appreciable effect on the rate of cooling, the quenching medium temperature must be held within narrow limits to obtain consistent results.

After steel is reheated and prepared for tempering, it is quenched in either air or oil. Chrome-nickel steels, because of their tendency toward temper brittleness, should always be quenched in oil.

QUENCHING, INTERRUPTED

Interrupted quenching is used to modify the rate of cooling of an alloy in heat treatment. An example of interrupted quenching is found in the treatment of an axle after repair by welding. A specific time in oil will cool the surface rapidly enough to suppress the transformation to a given depth below the surface. In interrupted quenching, if immersion time is sufficiently short, there will be enough heat in the interior of the axle to raise the temperature of the exterior layer, effecting a tempering treatment. Subsequent tempering is unnecessary, and the highly stressed condition caused by full quenching is avoided.

QUENCHING MEDIA

There are various quenching media such as water, oil, brine, molten salts, molten metal, still air or blasted air. Water and brine are the most drastic quenching mediums. To satisfactorily harden steel, water should be kept below 25°C (80°F) and continually agitated during the quenching operation. Agitation of the cooling medium insures a more uniform and faster cooling action. Brine is faster, is more uniform, and is less affected by increases in temperature. Oil is used as a quenching medium in hardening operations. Molten salts or molten metals are high-temperature quench baths and are frequently used with interrupted or timed quenching. Air provides the mildest type of quench.

QUENCH TIME, Resistance Welding

The time from the end of the weld, weld interval, or downslope time to the beginning of the temper time, during which no current flows through the workpieces and the weld is rapidly cooled by the electrodes. See STANDARD WELDING TERMS. *See* Figure I-1.

QUICKLIME

(Chemical symbol: CaO). Quicklime, or calcium oxide, is unslaked lime. When quicklime is added to coke and heated in an electric furnace, the resulting products are calcium carbide and carbon monoxide. Calcium carbide is used in the process of generating acetylene.

QUICKSILVER

Common name for mercury; used in instruments, vapor lamps and batteries.

In 1997, the Carnival Destiny set the record as the world's largest cruise ship. The 101,353-ton ship has a capacity of 3,400 passengers. Welding was used extensively in building this ship.

Photo courtesy of Carnival Cruise Lines

R

RADIAN

A term applied to the angle at the center of a circle where the arc of the circumference is equal to the radius of the circle. Expressed as an angle, the radian is 57.3°.

RADIATION

A combination of the processes of emitting, transmitting and absorbing waves or particles.

RADIOACTIVE

The property of some elements to emit charged or uncharged particles as alpha or beta rays, and sometimes gamma rays, caused by the disintegration of the nuclei of atoms. *See* RADIUM *and* RADIOGRAPHIC EXAMINATION.

RADIOGRAPH

A "shadow picture" or image produced by passing radiation, such as X-rays, gamma rays, or high-energy neutrons, through an object and recording the variations in the intensity of the emerging radiation on a sensitized film or screen.

A radiograph shows the gross structure of a metal or weld, such as the presence of blowholes, slag, high- or low-density inclusions, porous spots, cracks, or other defects or abnormalities which could not otherwise be found except by cutting through the material.

RADIOGRAPHIC EXAMINATION

The use of radiant energy in the form of X-rays, gamma rays, or high-energy neutrons for the nondestructive examination of visually opaque objects which yield a record of their soundness on a sensitized film or screen.

Radiography is a nondestructive test method based on the principle of preferential radiation transmission, or absorption. Areas of reduced thickness or lower density transmit more, and therefore absorb less radiation. The radiation which passes through a test object will form a contrasting image on a film receiving the radiation.

Areas of high radiation transmission, or low absorption, appear as dark areas on the developed film. Areas of low radiation transmission, or high absorption, appear as light areas on the developed film. Figure R-1 shows the effect of thickness on film darkness. The thinnest area of the test object produces the darkest area on the film because more radiation is transmitted to the film. The thickest area of the test object produces the lightest area on the film because more radiation is absorbed and thus, less is transmitted. Figure R-2 shows the effect of the material density on film darkness.

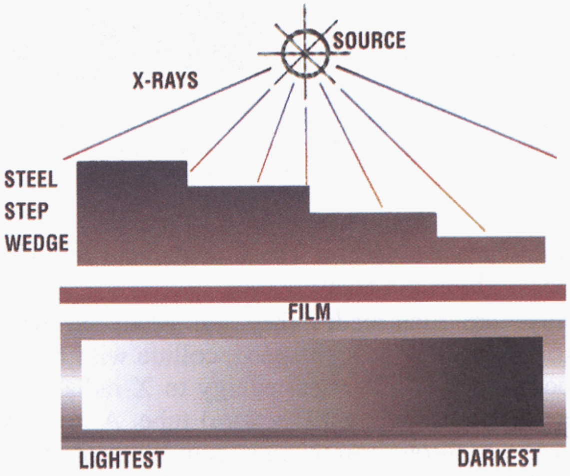


Figure R-1—Effect of Part Thickness on Radiation Transmission (Absorption)

Of the metals shown in Figure R-2, lead has the highest density: 11.34 g/cm^3 (0.409 lb/in.^{3}), followed in order by copper: 8.96 g/cm^3 (0.323 lb/ in^3); steel: 7.87 g/cm^3 (0.284 lb/in.^{3}), and aluminum: 2.70 g/cm^3 (0.097/lb in.^{3}). With the highest density (weight per unit volume), lead absorbs the most radiation, transmits the least radiation, and thus produces the lightest film.

Lower energy, non-particulate radiation is in the form of either gamma radiation or X-rays. Gamma rays are the result of the decay of radioactive materials; common radioactive sources include Iridium 192, Cesium 137, and Cobalt 60. These sources are constantly emitting radiation and must be kept in a shielded storage container, referred to as a "gamma

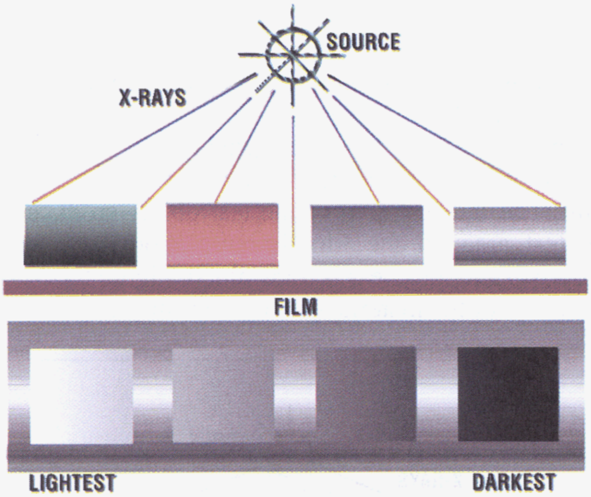


Figure R-2—Effect of Material Density on Radiation Transmission (Absorption)

camera" when not in use. These containers are often shielded with lead or steel.

X-rays are man-made; they are produced when electrons, traveling at high speed, collide with matter. The conversion of electrical energy to X-radiation is achieved in an evacuated (vacuum) tube. A low current is passed through an incandescent filament to produce electrons. Application of a high potential (voltage) between the filament and a metal target accelerates electrons across this voltage differential. The action of an electron stream striking the target produces X-rays. Radiation is produced only while voltage is applied to the X-ray tube. Whether using gamma or X-ray sources, the test object is not radioactive following the test.

The following are essential elements of radiographic testing:

(1) A source of penetrating radiation, such as an X-ray machine or a radioactive isotope

(2) The object to be radiographed, such as a weldment

(3) A recording or viewing device, usually photographic (X-ray) film enclosed in a light-proof holder

(4) A qualified radiographer, trained to produce a satisfactory exposure

(5) A means to process exposed film or operate other recording media

(6) A person skilled in the interpretation of radiographs

When a test object or welded joint is exposed to penetrating radiation, some of the radiation will be absorbed, some scattered, and some transmitted through the metal to a recording medium. The variations in amount of radiation transmitted through the weld depend on the following:

(1) The relative densities of the metal and any inclusions

(2) The relative thickness of materials in the radiation path

(3) The penetrating power of the radiation source. Nonmetallic inclusions, pores, aligned cracks, and other discontinuities result in more or less radiation reaching the recording or viewing medium. The variations in transmitted radiation produce optically contrasting areas on the recording medium.

The most important factor of any nondestructive weld test method is the ability of the inspector to correctly interpret the meanings of the discovered defects. Only through careful study of many radiographs exhibiting known defects can such ability be gained. The common welding faults revealed by radiographs are, in order of frequency, porosity, entrapped slag, cracks, and lack of fusion.

Porosity. Porosity usually (but not always) appears as small, black circular spots. A certain amount of porosity is allowable in a weld; how much is allowable is determined by comparing the radiograph with standard radiographs of acceptable welds.

Inclusions. Entrapped slag is readily distinguished from porosity because of its large and irregularly shaped shadows. Slag often extends parallel to a sidewall of the joint, and is easily and quickly identified. Only a very limited amount of entrapped slag is permissible in acceptable welded structures.

Slag inclusions show as dark areas in ferrous materials, but may appear as comparatively light streaks in lighter weight metals. The dark areas are created because the slag is less dense than the ferrous alloy, but may be of greater density than the lighter weight metal.

Tungsten inclusions in aluminum welds, produced by improper GTAW techniques, appear as very light areas on the film; the density of tungsten is 19.3 g/cm^3 (0.697 lb/in.^{3}).

Cracks. Cracks appear as dark lines in the weld. Shrinkage and stress cracks may be readily distinguished by their appearance. Shrinkage cracks are generally irregular, while stress cracks are regular and well defined.

Lack of Fusion. Lack of fusion is usually easy to recognize, since it has the appearance of a thin line of slag, or a crack, close to the joint wall.

Equipment

The equipment required to perform radiographic testing begins with a source of radiation; this source can be either an X-ray machine, which requires electrical input, or a radioactive isotope which produces gamma radiation. The isotopes usually offer increased portability. Either radiation type requires film and a light-tight film holder, and an alphabet of lead letters which are used to identify the test object. Because of the high density of lead and the local increased thickness, these letters form light areas on the developed film. Image Quality Indicators (IQI), or penetrameters ("pennys"), are used to verify the resolution sensitivity of the test. These IQIs are usually one of two types: *shim* or *wire*. They are both specified as to material type. The shim type will have a specified thickness and included hole sizes, and the wire type will have specified diameters. Sensitivity is verified by the ability to detect a given difference in density due to the penetrameter thickness and hole diameter, or wire diameter.

Shim penetrameters vary in thickness and hole diameters, depending on the metal thickness being radiographed. Figure R-3 shows the essential features of various penetrameter designs. When the penetrameter thickness is 0.025 in., it will have the designation of #25, for the shim thickness in mils (a #10 is 0.010 in. thick; a #50 is 0.050 in. thick). The hole diameters and positions are specified, and are noted in terms of multipliers of the individual shim thickness. The largest hole in a #25 penny is 0.100 in., and is called the "4T" hole, indicating that it is equal to four times the shim thickness. A "2T" hole (0.050 in.) is equal to two times the shim thickness. The smallest hole between the 4T and 2T hole is referred to as the "lT" hole and is exactly equal to the shim thickness, 0.025 in. These holes are used to verify resolution sensitivity, which is usually specified to be 2% of the weld thickness. However, a 1% sensitivity can also be specified, but is more difficult to attain.

Film processing equipment is required to develop the exposed film and a special film viewer with intense lighting is best for interpretation of the film. Because of the potential dangers of radiation exposure to humans, radiation monitoring equipment is always required.

The major advantage of this test method is that it can detect subsurface discontinuities in all common engineering materials. A further advantage is that the developed film serves as an excellent permanent record of the test if properly stored away from excessive heat and light.

Along with these advantages are several disadvantages. One of those is the hazard posed to humans by excessive radiation exposure. Many hours of training in radiation safety are required to assure the safety of both the radiographic test personnel and other personnel in the testing vicinity. For that reason, the testing may be performed only after the test area has been evacuated, which may present scheduling problems. Radiographic testing equipment can also be very expensive, and the training periods required to produce competent operators and interpreters are somewhat lengthy. Interpretation of film should always be done by those currently certified to a minimum Level II per the AWS NDE Certification or ASNT's SNT TC-1A. Another limitation of this test method is the need for access to both sides of the test object (one side for the source and the opposite for the film).

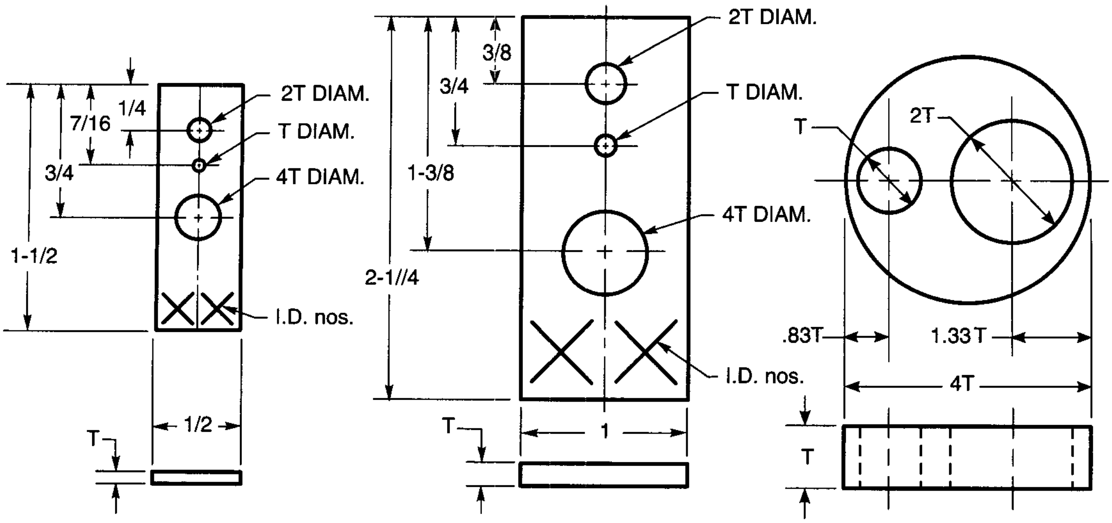
Another disadvantage of radiographic testing is that it may not detect those flaws which are considered to be more critical (e.g., cracks and incomplete fusion) unless the radiation source is preferentially oriented with respect to the flaw direction. Further, certain test object configurations (e.g., branch or fillet welds) can make both the performance of the testing and interpretation of results more difficult. However, experienced test personnel can obtain radiographs of these more difficult geometries and interpret them with a high degree of accuracy. *See also* X-RAY TESTING OF WELDS.

RADIO INTERFERENCE

The high-frequency radiation used to stabilize a-c gas tungsten arc welding may cause telephone, radio and television interference. This problem can be alleviated by using an earth ground to ground the workpiece and the welding power supply case. It is also helpful to keep cables as short as possible and to shield the primary wiring.

RADIUM (Ra)

A rare, brilliant white, radioactive metallic element used in luminous materials. Atomic number 88; atomic weight, 226.05. Melting point, 700°C (1292°F).



in.	mm
1/4	6.4
3/8	9.5
7/16	11
3/4	19
1-3/8	35
1-1/2	38
2-1/4	57

DESIGN FOR PENETRAMETER THICKNESS FROM 0.005 in. TO AND INCLUDING 0.050 in.

DESIGN FOR PENETRAMETER THICKNESS FROM 0.060 in. TO AND INCLUDING 0.160 in. MADE IN 0.010 in. INCREMENTS.

DESIGN FOR PENETRAMETER THICKNESS FROM 0.180 in. AND ABOVE. MADE IN 0.020 in. INCREMENTS.

DIMENSIONS ARE IN INCHES.

Figure R-3—Typical Penetrameter Designs

RADON

(Chemical symbol: Rn). A heavy, gaseous element which is given off as the initial product during radium disintegration. Radon is a gas which has a half-life period of 3.85 days. Either radium salts or radon may be used in industrial radiography, however, when radon is used, complicated corrections in exposure time estimates are necessary because of its short half-life. *See* RADIOGRAPHIC EXAMINATION.

RAIL-END HARDENING

In railroad tracks, the wearing down, or battering, of rail ends is caused mainly by the cold flow of metal. When trains pass over a rail, the concentrated load applied under the wheels produces at times a stress greater than the elastic limit of the steel in the rail. This stress is further increased by the hammer-like blows resulting from any unevenness in the height of the abutting rails, or poor joint or surface maintenance. In addition, the metal at the ends of the rail can flow in two directions, laterally and longitudinally. This causes a much more rapid lowering of the surface of the rail at the very ends.

In the past, rails were heat treated to raise the elastic limit of the steel in the tread portion of the rail sufficiently to overcome the cold flow effect. The oxyacetylene process was used. Heat treating was accomplished by heating the end portions of the tread surface of the rails until they were well above the transformation point, then quenching the rail ends. If necessary, a second heat treatment was applied to obtain the required degree of hardness, about 400 on the Brinell hardness scale.

The advent of rail joint welding almost completely did away with the need for rail-end hardening.

RAIL JOINT WELDING

Rails are joined in the field by either flash butt welding (a resistance welding process) or by thermite welding. In the shop, flash butt welding is used to weld the standard (11.9 m [39 ft]) lengths of rail into 300-ft sections. For additional information, refer to ANSI/AWS D15.2, *Recommended Practices for the Welding of Rails and Related Rail Components for Use by Rail Vehicles.*

Rail joints are welded for the following reasons: smoother riding qualities, reduced track maintenance, and to eliminate the need for shimming and building up worn rail ends. Welded joints increase the life of ties and reduce the effects of vibration on cars and locomotives. Most American railroad systems are operating on trackage that has continuous welded rail. *See* FLASH WELDING *and* THERMITE WELDING.

Expansion and Contraction Problems. Since railroads frequently operate in temperatures which range from –34 to 48°C (–30 to 120°F), an 82°C (150°F) range, continuous rails would expand as much as 152 cm (60 in.) in a length of 1.6 km (1 mile) if they were free to move. To prevent this movement, welded rail is spiked down to the ties using cleats. The spikes keep the rails from rising and the cleats restrain the rail from moving longitudinally.

It is important to install the welded rail at a temperature above the median operating temperature so that the rail will be in tension more than in compression. If the compression forces (from heating) exceed the restricting effect of the cleats, the track may bulge sideways and cause a derailment. If the tension forces (from cooling) exceed the tensile strength of the rail, it will break. This will automatically signal the train engineer and the right-of-way technicians that there is a problem so that traffic on the defective rail will be shut down.

Records are maintained on each rail showing when it was initially installed, the ambient temperature when it was installed, and other pertinent data. Monitoring systems keep technicians in constant touch with rail conditions.

Historical Background

The first significant stretches of welded rail joints were completed in 1938, but it was not until 1950 that welded joints became a standard of railroad construction.

Early production rail joint welding was done with gas pressure welding. In this process, the rail ends were squared up by power sawing. After cleaning, they were clamped together in a welding machine under a pressure of 17 to 18 MPa (2500 to 2700 psi). Multiflame torch tips were used to heat the ends of the rails to 1260°C (2300°F). After about five minutes of heating under this extreme pressure, the rails were welded. Excess weld metal was trimmed from the rail by air-powered shears, and the rails were ground to contour. Gas pressure welding was eventually phased out in favor of flash butt welding.

Continuous welded rail was introduced in 1930 by the Central Georgia Railroad for the track through two tunnels. Its first use in open track occurred in 1932. Today there are open track installations ranging from 1 to 68 km (1/2 to 42 miles) in length on railroads in all sections of the country.

In tunnels, continuous welded rails have eliminated the use of joint bars, bolts and other connections that often served as a focal point for corrosion. The continuous rail technique was quickly adapted to subway tracks. On bridges, continuous welded rail systems eliminated noise and vibration and reduced impact. At road crossings, welded rail reduced the usual excessive maintenance and helped greatly to prevent the frequent breakdown of the pavement. Similar advantages were realized in station platforms and tracks running through city streets, privately owned railroads on industrial sites, and rails for cranes and other equipment. *See* THERMITE WELDING, RESISTANCE WELDING, FLASH WELDING, *and* OXYACETYLENE PRESSURE WELDING.

RAILROAD CAR REPAIR

Information on the repair of railroad cars is contained in ANSI/AWS D15.1, latest edition, *Railroad Welding Specification—Cars and Locomotives.* This publication contains material on processes, consumables, base metals, operator and procedure qualification, and design of welded joints. Reference: American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126.

RAILWAY EQUIPMENT, Welding

The primary source of welding information relating to the construction of new railway equipment is the *Manual of Standards and Recommended Practices* prepared by the Mechanical Division, Association of American Railroads (AAR). This manual includes specifications, standards, and recommended practices adopted by the Mechanical Division. Several sections of the manual relate to welding, and the requirements are similar to those of ANSI/AWS D1.1, *Structural Welding Code—Steel.* This code is frequently referenced for weld procedure and performance qualification. In 1986, the American Welding Society published AWS D15.1, *Railroad Welding Specification,* which has been endorsed by AAR.

RANDOM INTERMITTENT WELDS

Intermittent welds on one or both sides of a joint in which the weld increments are made without regard to spacing. See STANDARD WELDING TERMS.

RANDOM SEQUENCE

A longitudinal sequence in which the weld bead increments are made at random. See STANDARD WELDING TERMS.

RANDOM WOUND

Spooled or coiled filler metal that has not been wound in distinct layers. See STANDARD WELDING TERMS. *See also* LEVEL WOUND.

RATE OF DEPOSITION

See STANDARD WELDING TERMS. *See also* DEPOSITION RATE.

RATE OF FLAME PROPAGATION

See STANDARD WELDING TERMS. *See also* FLAME PROPAGATION RATE.

REACTANCE

The property of a device to impede the flow of an alternating current while allowing direct current to flow without opposition.

REACTANCE COIL

A choke coil. It is used to oppose the flow of high-frequency currents in a circuit. *See* REACTOR.

REACTION FLUX, *Soldering*

A flux composition in which one or more of the ingredients reacts with a base metal upon heating to deposit one or more metals. See STANDARD WELDING TERMS.

REACTION SOLDERING

A soldering process variation in which a reaction flux is used. See STANDARD WELDING TERMS.

REACTION STRESS

A stress that cannot exist in a member if the member is isolated as a free body without connection to other parts of the structure. See STANDARD WELDING TERMS.

REACTOR

A device used in arc welding circuits to minimize irregularities in the flow of the welding current. See STANDARD WELDING TERMS.

Reactors are choke coils used in an electrical circuit for protection or for changing the power factor.

On an arc welding machine, a reactor is an inductive coil of copper wire or strap, surrounded by a laminated iron circuit provided with an air gap. The reactor slows the rate of change of the current, and stores electromagnetic energy. The first feature enables the operator to strike the metal electrode arc more easily, because the tendency of the electrode to freeze to the work is minimized. The second feature gives the arc additional stability, counteracting any influences, such as air drafts or gas formation caused by impurities in metal being welded, which tend to extinguish the shielded metal electrode arc.

REACTOR CONTROL

As used in a-c welding machines, reactor controls provide for remote adjustment of welding currents. The reactor control consists of a motor-driven gear device that may be applied to crank-adjusting units, or a rheostat at the work station for reactors that are adjusted electrically. Foot-operated remote control units are available which permit a gradual buildup or reduction of the welding current. This type of control device is useful in preventing weld craters.

RECALESCENCE

The liberation of heat when steel is cooled from a white heat to a dull red heat, at which point it suddenly brightens, then continues to cool to ambient temperature. *See* METALLURGY.

RECOVERY

The amount of alloying elements in a weld deposited from the filler metal. For example, the deposit from a bare rod containing 0.50% carbon generally will not contain over 0.05% carbon. In this case, the recovery is 10%. If the electrode is coated, the carbon recovery may rise to 50 or 100%, depending on the coating. Low recovery of an alloying element may be due to the low boiling point of the element, its tendency to join with the slag because of its affinity for oxygen, nitrogen or other gases, or may be due to incorrect welding procedure, such as overheating the base metal.

RECTIFIER

A device for changing alternating current into direct, or continuous, current.

RECTIFIER WELDING MACHINE

A rectifier welding machine is used for welding processes or electrodes that require direct current rather than alternating current. It is a machine in which a-c input power is changed to d-c welding power. Alternating current is supplied to the rectifier from the power line through a transformer. The welding current control may be incorporated in the transformer, or may be a separate reactor between the transformer and the rectifier.

Rectifier welding machines may have either single-phase or three-phase input. While some machines may supply either a-c or d-c output, the most efficient are those designed for d-c welding only. The three-phase welding machine will show the lowest ripple percentage; that is, it will exhibit very smooth arc characteristics. Rectifier welding machines may be divided broadly into two general types, according to volt-amperage curves and application.

Constant-Current Welding Machines. A constant-current welding machine has characteristically drooping volt amperage curves, producing relatively constant current within a limited change in load voltage. This type of welder is conventionally used with shielded metal arc welding, gas tungsten arc welding, plasma arc welding or air carbon arc cutting. Constant current welding units, when adjusted for full-rated output, should maintain the current within 5% of its rated value, with a variation of 1% above or below normal arc voltage.

A constant current welding machine is best suited for most manual operations where variations in the arc length are most apt to occur because of the individual technique of the operator. It may also be used, however, in automatic and semi-automatic operations with a variable electrode feed mechanism, and in operations in which an effort is made to maintain a constant arc length by automatic changes in the wire feed speed.

Constant Potential. Constant-potential power supplies are designed specifically to power the various automatic welding processes which use a continuous wire electrode that is fed at a constant speed. In this type of welding machine, the arc voltage curve approaches a horizontal line and maintains its voltage within 5% of the rated full-load setting, over the range from open circuit to full load.

The methods of current control on rectifier type welders vary between different equipment manufacturers. Among commercial designs, the means of current control are movable coil transformers, movable core reactors, saturable reactors, magnetic linkage controls, and various solid-state devices.

The advantages of mechanical current controls are stability and the capacity of duplicating current settings. The principal advantages of electrical controls are convenience of operation and adaptability to automatic welding process control.

RED SHORT

See HOT SHORT.

REDUCED SECTION TENSION TEST

A test in which a transverse section of the weld is located in the center of the reduced section of the specimen. See STANDARD WELDING TERMS.

REDUCING AGENT

A deoxidizer.

REDUCING ATMOSPHERE

A chemically active protective atmosphere that will reduce metal oxides to their metallic state at elevated temperature. See STANDARD WELDING TERMS.

REDUCING FLAME

An oxyfuel gas flame with an excess of fuel gas. See STANDARD WELDING TERMS.

A reducing flame may be used to prevent oxidation of an active metal, so that wetting is not hindered or unacceptable dross is not produced. The reducing flame may also preclude loss of a key oxidizable alloying element, such as carbon. Specific to plain and alloyed steels, a reducing flame imparts carbon into the surface of the weld metal. In such situations, a reducing flame is often referred to as a *carburizing flame. See also* CARBURIZING FLAME, NEUTRAL FLAME, OXIDIZING FLAME, *and* REDUCING ATMOSPHERE.

REDUCING VALVE

See REGULATOR.

REFINED ZONE

The portion or area of the base metal bordering on the fusion zone, in which grain refinement has taken place as a result of the heat of welding. *See* METALLURGY.

REFLOWING

A nonstandard term when used for FLOW BRIGHTENING.

REFLOW SOLDERING

A nonstandard term for soldering with preplaced filler metal.

REFRACTORY METALS

Refractory metals are those with high melting points. Popular usage has established 2000°C (3632°F) as the minimum melting point. *See* Table R-1.

Table R-1
Melting Points of Various Refractory Metals

Metal	Melting Point °C	Melting Point °F
Boron	2100	3812
Hofnium	2130	3866
Ruthenium	2400	4352
Niobium	2415	4379
Iridium	2454	4449
Molybdenum	2622	4752
Osmium	2700	4892
Tantalum	2996	5425
Rhenium	3167	5732
Tungsten	3400	6152

REFRIGERATED WELDING

See RESISTANCE WELDING, Refrigerated.

REGULATOR

Regulators are reducing valves which are attached to the cylinder valves of oxygen, acetylene, and other gas cylinders to reduce the pressure in the cylinder to a suitable working pressure at the torch. The components of a regulator are: a diaphragm, a seat, a nozzle, springs, and a suitable case, usually made of a brass forging. A cross sectional view of a typical single-stage regulator is shown in Figure R-4.

Regulator Types

There are two general types of regulators: the single-stage regulator and a more complex two-stage regulator. A two-stage regulator has two seats, two nozzles and two diaphragms, with one adjusting screw.

Regulator Action

When the adjusting screw is turned to the right, pressure is applied to the spring, causing the diaphragm and the seat carriage to force the seat away from the nozzle, permitting gas to enter the chamber. The high-pressure gas entering the chamber increases the pressure on the diaphragm until it overcomes the pressure of the large spring, permitting the seat to be closed by the small spring, or springs. The position of the seat over the nozzle is controlled by the difference in balance between the pressure of the spring and the pressure of the gas in the chamber; this maintains a constant flow of gas through the regulator at a given pressure. This pressure may be increased or decreased by changing the position of the adjusting screw.

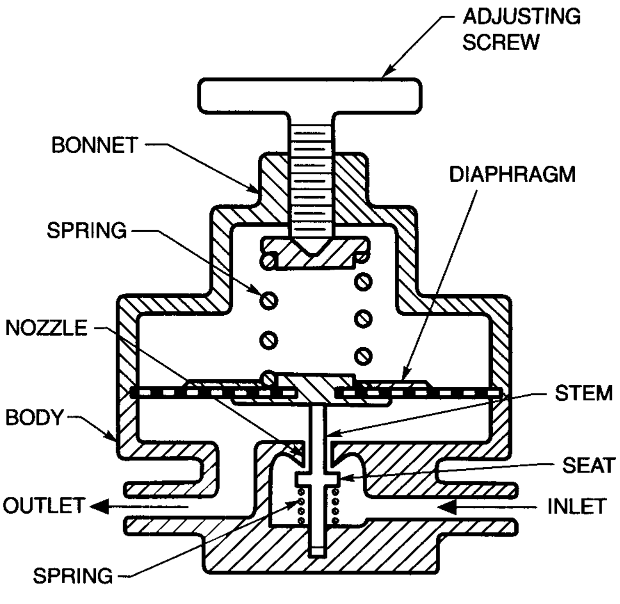


Figure R-4—Cross-Sectional View of a Typical Single Stage Stem-Type Regulator

A single-stage oxygen regulator is usually used to step the pressure down from a cylinder pressure of 13.8 MPa (2000 psi), when the cylinder is full, to torch pressures of from 7 to 240 kPa (1 to 35 psi), depending on the size of the tip in use and the type of torch. A 21 MPa (3000 psi) gauge is attached to the high-pressure side of the regulator and a gauge which will reduce pressure to 1 MPa (150 psi) or less is attached to the low-pressure side.

The initial reduction in a two-stage oxygen regulator is from a maximum of 13 MPa (2000 psi) to an intermediate pressure of 1.7 MPa (250 psi), the second reduction is to the required torch pressure, which is controlled by the adjusting screw.

Acetylene regulators reduce cylinder pressures from a maximum of about 1.7 MPa (250 psi) to torch pressures not ordinarily exceeding 75 or 82 kPa (11 or 12 psi). These are usually equipped with 2.7 MPa (400 psi) gauges on the high-pressure side and 340 kPa (50 psi) gauges on the low pressure side.

Connections

The standard inlet threading of the nuts and nipples of oxygen and acetylene regulators is different to prevent attaching the regulators to the wrong cylinders. The threading of the outlet nipples for the hose connections also differ so that hoses cannot be interchanged. *See* HOSE CONNECTION STANDARDS.

REGULATOR SCREW

The threaded connection to the adjusting knob of a pressure regulator. Turning the adjusting knob to the right causes the adjusting screw to push against a spring button which compresses the pressure-adjusting spring. The force of the compressed spring causes the diaphragm to flex and push against the stem, which opens the regulator to allow gas to flow from the inlet chamber to the delivery chamber of the regulator.

REGULATOR, Station

A station regulator is used to step down (reduce) pressure from a pipeline system which delivers gases to the work stations of one or more operators, usually at 1.4 MPa (200 psi). Station regulators should never be connected to a gas cylinder because they are not designed to handle cylinder pressures.

REHEATING

A term sometimes applied to postweld heating. *See* HEAT TREATMENT.

REINFORCEMENT OF WELD

See STANDARD WELDING TERMS. *See also* WELD REINFORCEMENT.

RELUCTANCE

The resistance to the flow of magnetism through a material.

RESIDUAL MAGNETISM

The magnetism retained in the iron core of an electromagnet after the flow of current is stopped.

RESIDUAL STRESS

Stress present in a joint member or material that is free of external forces or thermal gradients. See STANDARD WELDING TERMS.

Residual stresses left in a welded joint when welding has been completed are the result of thermal or mechanical action, or both. In steel, these stresses are sometimes partially prevented or relieved by preheating, hammering, or annealing. The importance of stress relief in steel welding increases as the carbon content of the steel increases.

RESIDUE

Unwanted material, usually considered a contaminant, that is left on a metal surface following welding, brazing or soldering. In brazing and soldering, residue is a result of the flux used. It is made up of excess (unaltered) flux, and reacted and spent, (decomposed and burned) flux, known collectively as *flux residue. See also* RESIDUUM.

RESIDUUM

The accumulation of water and slaked lime in the bottom of an acetylene generator.

RESISTANCE

The property of a substance which causes it to oppose the flow of electricity through the substance. Resistance is the measure of free electrons in a material. *See* OHM.

RESISTANCE BRAZING (RB)

A brazing process that uses heat from the resistance to electric current flow in a circuit of which the workpieces are a part. See STANDARD WELDING TERMS.

RESISTANCE BUTT WELDING

A nonstandard term for UPSET WELDING and FLASH WELDING.

RESISTANCE FURNACE

A furnace which is heated by electric current flowing through resistance coils. *See* FURNACE.

RESISTANCE SEAM WELDING (RSEW)

A resistance welding process that produces a weld at the faying surfaces of overlapped parts progressively along a length of a joint. The weld may be made with overlapping weld nuggets, a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by resistance to the flow of the welding current. See STANDARD WELDING TERMS. *See* Figures H-4 *and* R-5. *See also* HIGH-FREQUENCY SEAM WELDING *and* INDUCTION SEAM WELDING.

RESISTANCE SEAM WELD SIZE

See STANDARD WELDING TERMS. *See also* SEAM WELD SIZE.

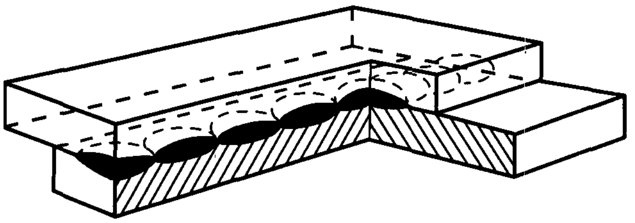


Figure R-5—Resistance Seam Weld. The Overlapping Spot Welds Provide a Leak-Tight Seam.

RESISTANCE SOLDERING (RS)

A soldering process that uses heat from the resistance to electric current flow in a circuit of which the workpieces are a part. See STANDARD WELDING TERMS.

RESISTANCE SPOT WELDING (RSW)

A resistance welding process that produces a weld at the faying surfaces of a joint by the heat obtained from resistance to the flow of welding current through the workpieces from electrodes that serve to concentrate the welding current and pressure at the weld area. See STANDARD WELDING TERMS. *See* Figure R-6. *See also* RESISTANCE WELDING.

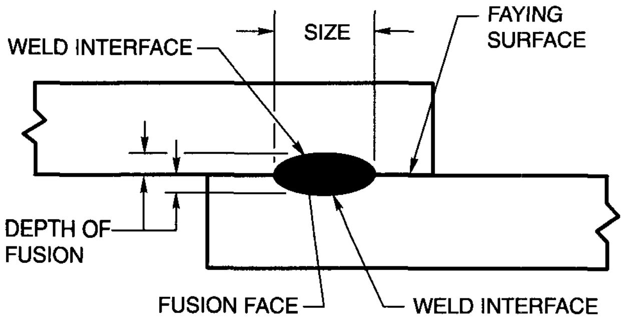


Figure R-6—Resistance Spot Weld

RESISTANCE SPOT WELD SIZE

See STANDARD WELDING TERMS. *See also* SPOT WELD SIZE.

RESISTANCE WELDER

A resistance welding machine.

RESISTANCE WELDING (RW)

A group of welding processes that produces coalescence of the faying surfaces with the heat obtained from resistance of the workpieces to the flow of the welding current in a circuit of which the workpieces are a part, and by the application of pressure. See STANDARD WELDING TERMS.

The theory of resistance welding is based on the principle that a low-voltage, high-amperage current flows through a heavy copper conductor, encountering little resistance until it reaches the material to be welded. Current flow through the greater resistance of the material being welded causes intense heat to be generated, then pressure is applied which forces together the two pieces being welded. The resulting weld between these two pieces is as strong as the weaker of the two pieces that have been joined.

Resistance welding is accomplished by clamping the work (two or more sheets of metal) between copper electrodes and passing an electric current through it. The heat generated at the point of contact between the pieces reduces the metal to a plastic state, and using clamping pressure, induces fusion.

Historical Background

The principle of resistance welding was discovered by the English physicist, James Joule, in 1856. In his experiments he buried a bundle of wire in charcoal and welded the wires by heating them with an electric current. This is believed to be the first application of heating by internal resistance for welding metal. It remained for Elihu Thompson to perfect the process and develop it for practical applications.

In 1877 Thompson invented a small low-pressure resistance welding machine. Welding was accomplished with this machine by causing the internal resistance in the workpiece to generate the heat required to reach its plastic stage. For several years, little was done with this development, since it seemed to have little commercial value. Nevertheless, resistance welding was introduced commercially in the early 1880s as *incandescent welding.*

Modern Resistance Welding Technology

Spot, seam, and projection welding are three resistance welding processes in which coalescence of metals is produced at the faying surfaces by the heat generated by the resistance of the work to the passage of electric current. Force is always applied before, during, and after the application of current to confine the weld contact area at the faying surfaces and, in some applications, to forge the weld metal during postheating. Figure R-7 illustrates the three processes.

In spot welding, a nugget of weld metal is produced at the electrode site, but two or more nuggets may be

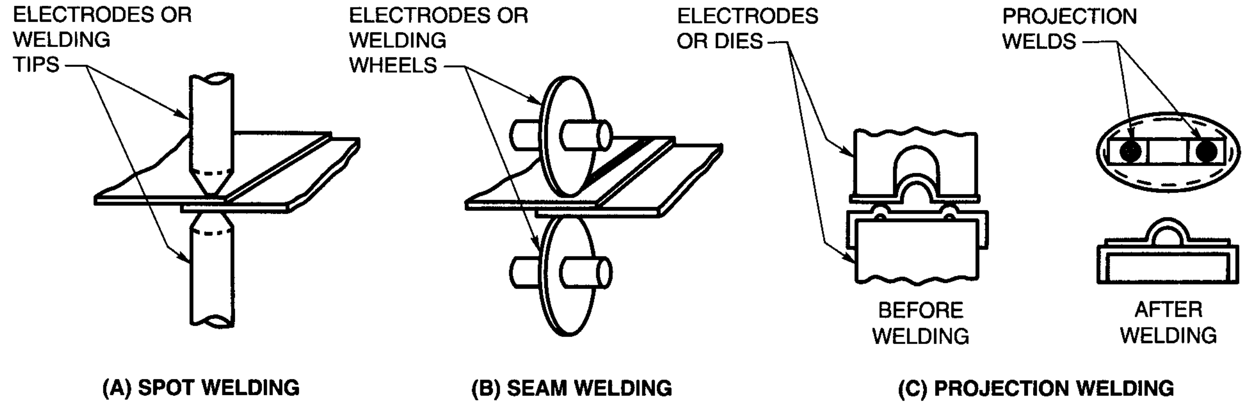


Figure R-7—Simplified Diagrams Showing the Basic Processes of Spot, Seam, and Projection Welding

made simultaneously using multiple sets of electrodes. Projection welding is similar except that nugget location is determined by a projection or embossment on one faying surface, or by the intersection of parts in the case of wires or rods (cross-wire welding). Two or more projection welds can be made simultaneously with one set of electrodes.

Seam welding is a variation of spot welding in which a series of overlapping nuggets is produced to obtain a continuous, leak tight seam. One or both electrodes are generally wheels that rotate as the work passes between them. A seam weld can be produced with spot welding equipment but the operation will be much slower.

A series of separate spot welds may be made with a seam welding machine and wheel electrodes by suitably adjusting the travel speed and the time between welds. Movement of the work may or may not be stopped during the spot weld cycle. This procedure is known as *roll spot welding*.

Principles of Operation

Spot, seam, and projection welding operations involve a coordinated application of electric current and mechanical pressure of the proper magnitudes and durations. The welding current must pass from the electrodes through the work. Its continuity is assured by forces applied to the electrodes, or by projections which are shaped to provide the necessary current density and pressure. The sequence of operation must first develop sufficient heat to raise a confined volume of metal to the molten state. This metal is then allowed to cool while under pressure until it has adequate strength to hold the parts together. The current density and pressure must be such that a nugget is formed, but not so high that molten metal is expelled from the weld zone. The duration of weld current must be sufficiently short to prevent excessive heating of the electrode faces. Such heating may bond the electrodes to the work and greatly reduce their life.

The heat required for these resistance welding processes is produced by the resistance of the workpieces to an electric current passing through the material. Because of the short electric current path in the work and limited weld time, relatively high welding currents are required to develop the necessary welding heat.

Heat Generation. In an electrical conductor, the amount of heat generated depends upon three factors: (1) the amperage, (2) the resistance of the conductor (including interface resistance), and (3) the duration of current. These three factors affect the heat generated as expressed in the formula

$$Q = I^2Rt$$

where:

Q = heat generated, joules

I = current, amperes

R = resistance of the work, ohms

t = duration of current, seconds

The heat generated is proportional to the square of the welding current and directly proportional to the resistance and the time. Part of the heat generated is used to make the weld and part is lost to the surrounding metal.

The secondary circuit of a resistance welding machine and the work being welded constitute a series of resistances. The total resistance of the current path affects the current magnitude. The current will be the same in all parts of the circuit regardless of the instantaneous resistance at any location in the circuit, but the heat generated at any location in the circuit will be directly proportional to the resistance at that point.

An important characteristic of resistance welding is the rapidity with which welding heat can be produced. The temperature distribution in the work and electrodes, in the case of spot, seam, and projection welding, is illustrated in Figure R-8. There are, in effect, at least seven resistances connected in series in a weld that account for the temperature distribution. For a two-thickness joint, these are the following:

(1) 1 and 7, the electrical resistance of the electrode material.

(2) 2 and 6, the contact resistance between the electrode and the base metal. The magnitude of this resistance depends on the surface condition of the base metal and the electrode, the size and contour of the electrode face, and the electrode force. (Resistance is roughly inversely proportional to the contacting force.) This is a point of high heat generation, but the surface of the base metal does not reach its fusion temperature during the current passage, due to the high thermal conductivity of the electrodes (1 and 7) and the fact that they are usually water cooled.

(3) 3 and 5, the total resistance of the base metal itself, which is directly proportional to its resistivity and thickness, and inversely proportional to the cross-sectional area of the current path.

(4) 4, the base metal interface resistance at the location where the weld is to be formed. This is the point of highest resistance and, therefore, the point of greatest heat generation. Since heat is also generated at points 2 and 6, the heat generated at interface 4 is not readily lost to the electrodes.

Heat will be generated in each of the seven locations in Figure R-8 in proportion to the resistance of each. Welding heat, however, is required only at the base metal interface, and the heat generated at all other locations should be minimized. Since the greatest resistance is located at 4, heat is most rapidly developed at that location. Points of next lower resistance are 2 and 6. The temperature rises rapidly at these points also, but not as fast as at 4. After about 20% of the weld time, the heat gradient may conform to the profile shown in Figure R-8. Heat generated at 2 and 6

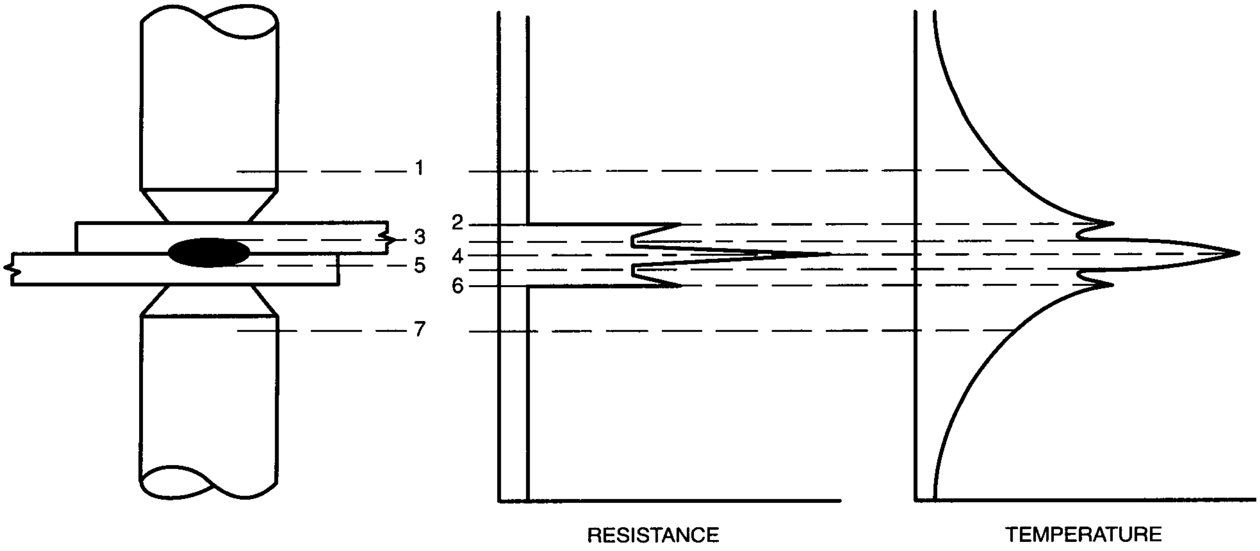


Figure R-8—Temperature Distribution During a Resistance Spot Weld

is rapidly dissipated into the adjacent water-cooled electrodes 1 and 7. The heat at 4 is dissipated much more slowly into the base metal. Therefore, while the welding current continues, the rate of temperature rise at plane 4 will be much more rapid than at 2 and 6. The welding temperature is indicated on the chart at the right of Figure R-8 by the number of dots within the drawing leading to the matching curve.

Factors that affect the amount of heat generated in the weld joint by a given current for a unit of weld time are (1) the electrical resistances within the metal being welded and the electrodes, (2) the contact resistances between the workpieces and between the electrodes and the workpieces, and (3) the heat lost to the workpieces and the electrodes.

A comprehensive and detailed description of resistance welding principles of operation, individual processes, power sources, machines, electrodes, key welding parameters, weld schedules, welding methods, and weldability of major metals and alloys can be found in the American Welding Society *Welding Handbook*, 8th Edition, Volumes 2, 1991; and *Welding Handbook* Volume 3, 1996, Miami, Florida.

Variations in the composition, shape and thickness of materials require different techniques to maintain productivity. For example, if one of the pieces to be resistance spot welded is considerably thicker than the other, the thin piece would heat much quicker and melt before the thick piece reached welding temperature. One solution to this problem is to fashion a projection (*see* Figure R-7) on the thicker sheet at the place to be welded. This projection concentrates the heat in a small area on the thicker sheet and brings it up to melting temperature at the same time as the thinner sheet.

Mash Welding. Mash welding is the term used to describe the spot welding of two wires or rods at an angle to one another. *See* Figure R-9, which shows how the electrodes are grooved to hold the stock. This method, also called *cross wire welding*, is used to weld such items as wire wastebaskets and lampshade frames.

RESISTANCE WELDING CONTROL

The device, usually electronic, that determines the welding sequence and timing with regard to the welding current pattern, electrode or platen force or movement, and other operational conditions of a resistance welding machine. See STANDARD WELDING TERMS.

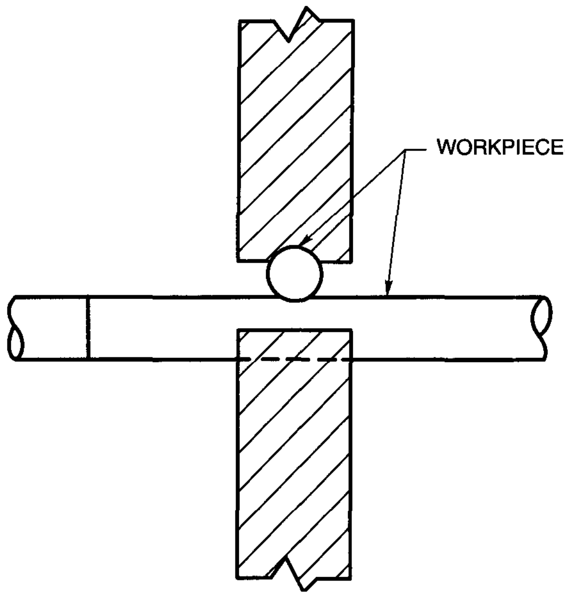


Figure R-9—View of Mash Welding Electrodes Grooved to Hold the Workpieces

RESISTANCE WELDING CURRENT

The current in the welding circuit during the making of a weld, but excluding preweld or postweld current. See STANDARD WELDING TERMS. *See* Figure R-10.

RESISTANCE WELDING DIE

A resistance welding electrode usually shaped to the workpiece contour to clamp the workpieces and to conduct the welding current. See STANDARD WELDING TERMS.

RESISTANCE WELDING DOWNSLOPE TIME

The time during which the welding current is continuously decreased. See STANDARD WELDING TERMS. *See* Figure R-10.

RESISTANCE WELDING ELECTRODE

The part of a resistance welding machine through which the welding current and, in most cases, force are applied directly to the workpiece. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck, or modification thereof. See STANDARD WELDING TERMS.

RESISTANCE WELDING GUN

A manipulatable device to transfer current and provide electrode force to the weld area (usually in refer-

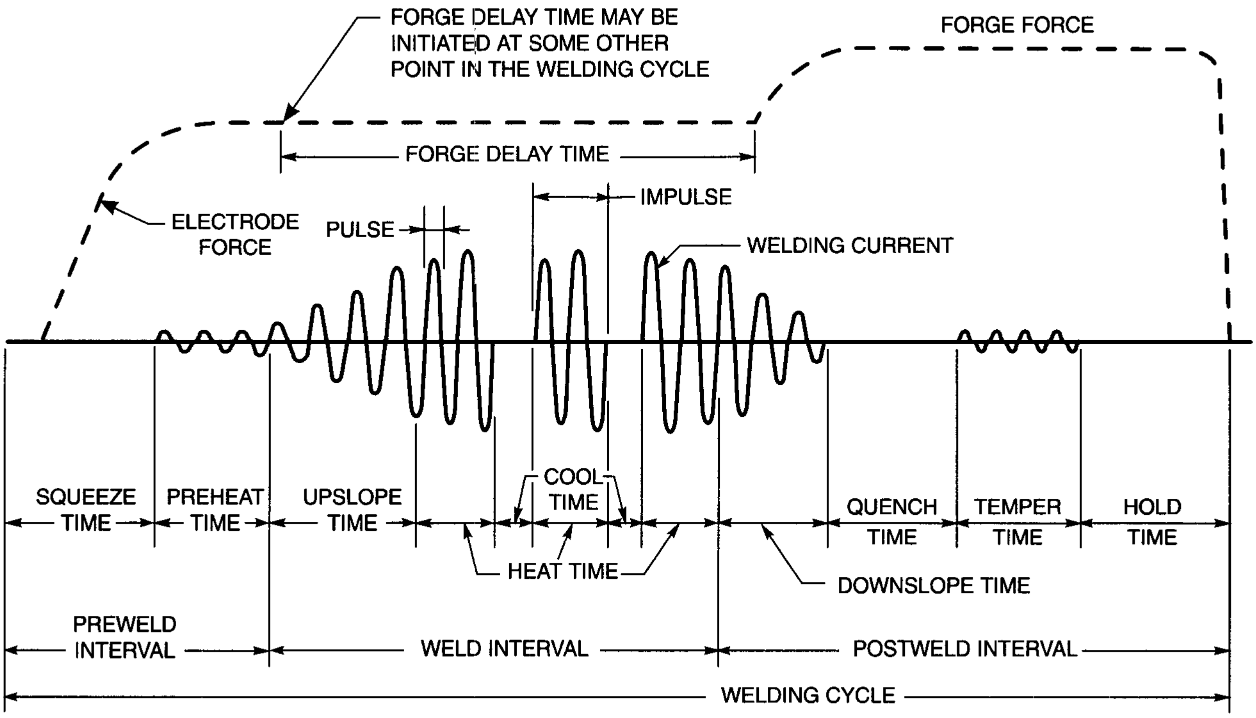


Figure R-10—Multiple-Impulse Resistance Spot Welding Schedule

ence to a portable gun). See STANDARD WELDING TERMS.

RESISTANCE WELDING, Refrigerated

A process developed to overcome pickup problems in the resistance welding of aluminum.

Aluminum is readily welded using the resistance spot welding process. However, because of the relatively low electrical resistance of aluminum, the current requirements for welding are two to three times the values required for welding a similar thickness of carbon steel. The high welding currents required for aluminum result in heating of the copper welding electrodes and "mushrooming" of the contact tips. There is also the problem of "pickup" of aluminum on the copper electrodes during the welding cycle. Both of these phenomena result in changes in current density, and therefore weld quality. Another problem is the oxide scale which forms on aluminum. In spite of careful cleaning methods prior to welding, the oxide layer forms on aluminum very quickly and can cause wide variations in the welding heat because of variations in the welding contact resistance.

One of the methods used to minimize these problems is to circulate a refrigerated coolant through the electrodes. A coolant temperature of –12°C (10°F) was found to reduce the softening and pickup problems to the point that the electrodes could be used to make as many as 2000 spot welds between electrode dressings (with a file or emery cloth). While this extended electrode service life by a factor of ten, the refrigerated coolant method has been partially replaced by the development of (1) copper alloy electrodes that do not deform plastically at the temperatures encountered, and (2) small replaceable electrode caps that resulted in discarding 14 g (1/2 oz) of copper rather than the previous 170 g (6 oz) when the tips were worn out.

RESISTANCE WELDING, Stored Energy

A form of resistance welding in which the electrical energy needed to cause Joule heating in the workpieces is obtained from a bank of capacitors or condensers. These machines draw power from the supply line over a relatively long time between welds, accumulating power to deliver to the electrodes during a short weld time. The process is also known as *Capacitor-Discharge Welding. See* ARC STUD WELDING.

RESISTANCE WELDING, Three-Phase

Resistance welding which employs three-phase alternating current primarily to overcome the demands of high-power loads on existing power lines and facilities.

Line currents in three-phase systems require only 1/6 to 1/4 of the current needed for single-phase equipment of the same welding capacity.

Additional advantages are:

(1) A machine power factor typically over 85%

(2) Identical (i.e., balanced) current demands on each leg (or line) of a three-phase power source

(3) The same secondary current regardless of the inductive load introduced into the throat of the welding machine

(4) Lower installation cost compared to single-phase

From the welding viewpoint, advantages include: (1) less tendency for metal expulsion; (2) longer electrode tip life; (3) less sensitivity to tip size; (4) self-regulating secondary current; (5) more uniform distribution of current during projection welding; (6) easier welding of aluminum, brass, magnesium and other non-ferrous metals, with less electrode pickup. Reference: American Welding Society, *Welding Handbook*, 8th Edition, Volume 2, *Three-Phase Power Sources*, Miami, Florida, 1991.

RESISTANCE WELDING TIMERS

See ELECTRONIC CONTROLS, Resistance Welding. *See* other references on Resistance Welding Controls, e.g., American Welding Society *Welding Handbook*, 8th Edition, Volume 2; Miami, Florida: 1991.

RESISTANCE WELDING UPSLOPE TIME

The time during which the welding current continuously increases from the beginning of the welding current. See STANDARD WELDING TERMS. *See* Figure R-10.

RESISTANCE WELDING WELD TIME

The duration of welding current flow through the workpieces in making a weld by single-impulse welding or flash welding. See STANDARD WELDING TERMS. *See* Figure R-10. *See also* WELD INTERVAL, RESISTANCE WELDING.

Practical solutions to the successful resistance spot welding of bare and coated steels and the non-ferrous group of metals and alloys, particularly in dissimilar combinations, are generally considered to be difficult or impossible. Control of the process is crucial. Control technology is continually advancing, so modern reference sources, including recently published papers, are recommended. The interested reader is referred to information on control of the resistance welding process in the American Welding Society's *Welding Handbook*, Volume 2, 8th Edition, Miami, Florida, 1991.

RESISTOR

A device that has measurable, controllable, or known electrical resistance, used in electronic circuits or in arc welding circuits to regulate the arc amperes.

RESPIRATOR

An apparatus used to assure adequate oxygen for life support; or, a device worn over the nose and mouth to protect the respiratory tract against airborne contaminants present in the welding atmosphere. Air-supplied respirators or face masks are generally preferred, and air-supplied welding helmets are available commercially.

Filter-type respirators, approved by the U.S. Bureau of Mines for metal fumes, give adequate protection against particulate contaminants that are less toxic than lead, provided they are used and maintained correctly. Filter-type respirators are not recommended for general use because of the difficulty in assuring proper use and maintenance. They will not protect against mercury vapor, carbon monoxide, or nitrogen dioxide. For these hazards an air-supplied respirator, hose mask, or gas mask is required.

RETAINING SHOE

A nonstandard term for BACKING SHOE.

REVERSE POLARITY

A nonstandard term for DIRECT CURRENT ELECTRODE POSITIVE.

RHEOSTAT

A variable electrical resistor for regulating currents; used in arc welding to regulate the arc amperes.

RIBBON FLAME

A narrow, ribbon-like flame produced by a welding torch tip with a narrow slot orifice.

RIDGE-WELDING

A modification of projection welding in which the current is concentrated by means of a ridge, which localizes the weld.

RIGID STRING WELDING

See STRINGER BEAD.

RIPPLE WELD

A term describing the appearance of a weld made in steel with a hand torch.

RIVET WASHING

Removing the heads of rivets with a cutting torch and a special tip which delivers oxygen to the rivet head at very low velocity.

The rivet head is preheated with flames surrounding a very large oxygen orifice. When the rivet head is red hot, the oxygen valve is opened and the central portion of the rivet head is burned up, leaving the external ring and a cup-shaped end to the shank. The remainder of the rivet can then be backed out without damaging the sheet.

ROBOTIC, *adj.*

Pertaining to process control by robotic equipment. See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL, AUTOMATIC, MANUAL, MECHANIZED, *and* SEMIAUTOMATIC.

A robot is a mechanical device capable of reproducing motions that may resemble human activity, capable of performing tasks in an automated way.

ROBOTIC BRAZING

See STANDARD WELDING TERMS. *See also* ROBOTIC WELDING.

ROBOTIC SOLDERING

See STANDARD WELDING TERMS. *See also* ROBOTIC WELDING.

ROBOTIC THERMAL CUTTING

See STANDARD WELDING TERMS. *See also* ROBOTIC WELDING.

ROBOTIC THERMAL SPRAYING

See STANDARD WELDING TERMS. *See also* ROBOTIC WELDING.

ROBOTIC WELDING

Welding that is performed and controlled by robotic equipment. Variations of this term are robotic brazing, robotic soldering, robotic thermal cutting, and robotic thermal spraying. See STANDARD WELDING TERMS. *See also* ADAPTIVE CONTROL WELDING, AUTOMATIC WELDING, MANUAL WELDING, MECHANIZED WELDING, *and* SEMIAUTOMATIC WELDING.

Robots are used where repetitive work functions are performed. They are usually computer driven. Robotic equipment is especially useful where the work is performed in environments that are uncomfortable or hazardous, for example, material handling in the proximity of a furnace. Production welding is a good application for robotic equipment because it involves repetitive welding on parts of a given size and shape.

Robotic equipment requires special features and capabilities to successfully perform arc welding operations. Arc welding robots are generally high-precision machines containing electric servomotor drives and special interfaces with the arc welding equipment. *See* Figure R-11.

Programming. An automatic arc welding system must be programmed to perform the welding operation. Programming is the establishment of a detailed sequence of steps that the machine must follow to successfully weld the assembly to specifications.

Developing a welding program involves the following steps:

(1) Calibrate the automatic welding system. Calibration insures that future use of the program will operate from a known set point.

(2) Establish the location of the assembly with respect to the welding machine. Often simple fixturing is sufficient.

(3) Establish the path to be followed by the welding gun or torch as welding progresses. Some robots can be "taught" the path while other automatic welding systems have to be programmed off-line.

(4) Develop the welding conditions to be used. They must then be coordinated with the work motion program.

(5) Refine the program by checking and verifying performance. Often, a program requires editing to obtain the desired weld joint.

There are four general geometric classifications of industrial robots:

(1) Rectilinear (cartesian coordinate) robots have linear axes, usually three in number, which move a wrist in space. Their working zone is box shaped.

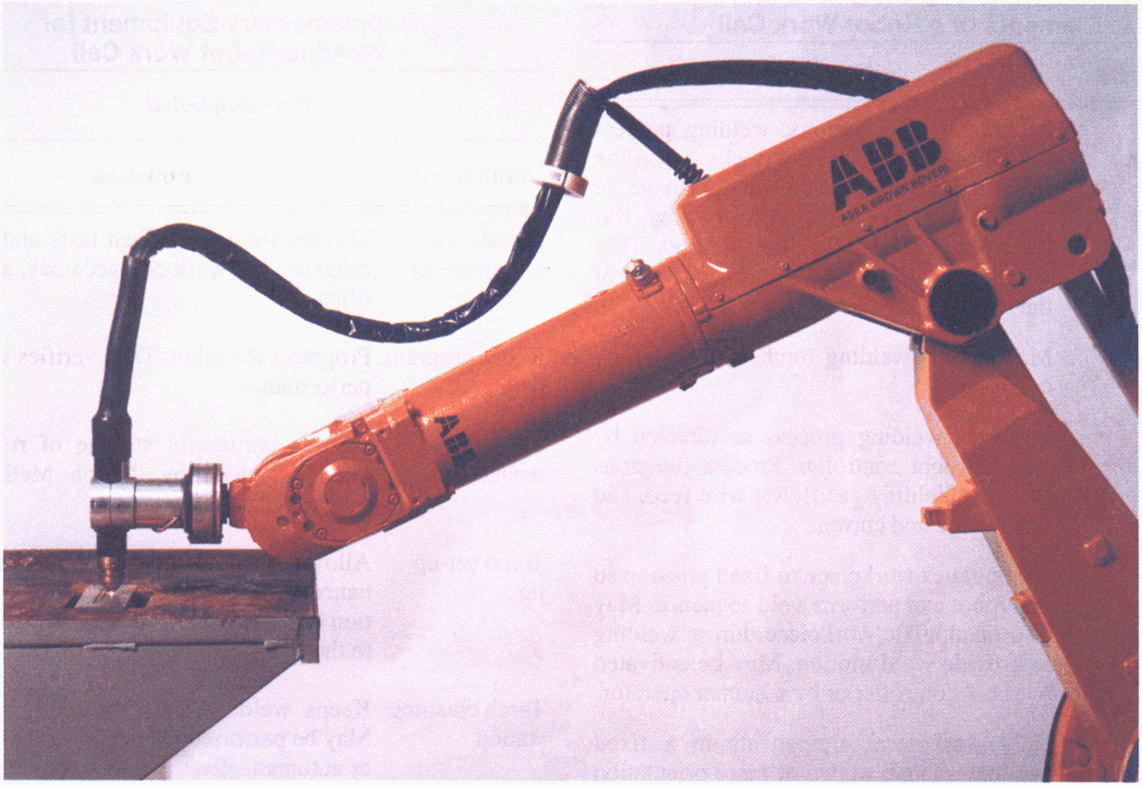


Figure R-11—Robot Making Test Welds

Photo courtesy of ABB Flexible Automation, Inc.

(2) Cylindrical coordinate robots have one circular axis and two linear axes. Their working zone is a cylinder.

(3) Spherical coordinate robots employ two circular axes and one linear axis to move the robot wrist. Their working zone is spherical.

(4) Articulating (jointed arm) robots utilize rotary joints and motions similar to a human arm to move the robot wrist. The working zone has a irregular shape.

All four robot geometries perform the same basic function: the movement of the robot wrist to a location in space. Each geometry has advantages and limitations under certain conditions. Articulating and rectilinear robots are favored designs for arc welding.

Robotic arc welding is applicable to high, medium, and low volume manufacturing operations under certain conditions. It can be applied to automation of medium and low volume production quantities where the total volume warrants the investment.

An arc welding robot requires a number of peripheral or supporting devices to achieve optimum productivity. The basic elements of a robotic work cell are shown in Table R-2. Many variations are possible, and each device could contain its own controller that would execute instructions from its program on command from the robot or host controller. All robot stations can be enhanced by one or more of the components listed in Table R-3. These components help to "teach" the robot quickly, minimize times for scheduled and unscheduled maintenance, and assure operator and equipment safety. Also included in Table R-3 are several features that are not necessary for efficient robot cell use but can enhance the productivity of the cell.

An articulating (jointed arm) robot is favored for arc welding small parts where there are long travel distances between welds. The arm of this type of robot is capable of quick motion. This robot design is also pre-

Table R-2
Elements of a Robot Work Call

Component	Function
Host controller	Manages robot motions, welding process functions, and safety interlocks according to stored program. May also manage or direct motions of positioners, tooling, fixtures and material handling devices. (For most systems, the host controller is part of the robot.)
Robot	Manipulates welding torch as directed by controller.
Process package	Performs welding process as directed by host or robot controller. Process functions include shielding gas flows, wire feed, and arc voltage and current.
Positioner	Manipulates workpiece to fixed position so that robot can perform weld sequence. May also manipulate workpiece during welding to provide weld motion. May be activated by robot controller or by a human operator.
Fixture and clamping tools mounted on positioner	Hold workpiece components in a fixed position relative to two or more orientation points on the fixture. Clamping tools may be activated by the robot controller or by a human operator.
Material handling	Moves components into work cell, and removes welded assemblies from work cell. May be manual, machine or automatic.

ferred for nonmovable assemblies that require the robot to reach around or inside a workpiece to position the robot wrist.

For safety reasons, rectilinear robots are favored for most other arc welding applications. They are particularly suited for applications where a welding operator is required to be in close proximity to the welding arc. Rectilinear robots move slower and in a more predictable path than articulating robots.

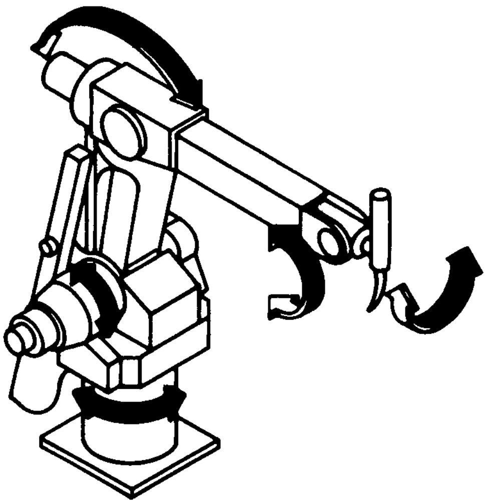
Axes. Arc welding robots usually have five or six axes (Figure R-12) and some may be equipped with seven or eight axes. A complete robotic work station may contain as many as eleven axes of coordinated motion.

Robot Transfer. Large assemblies and assemblies that require significant arc time can be welded by

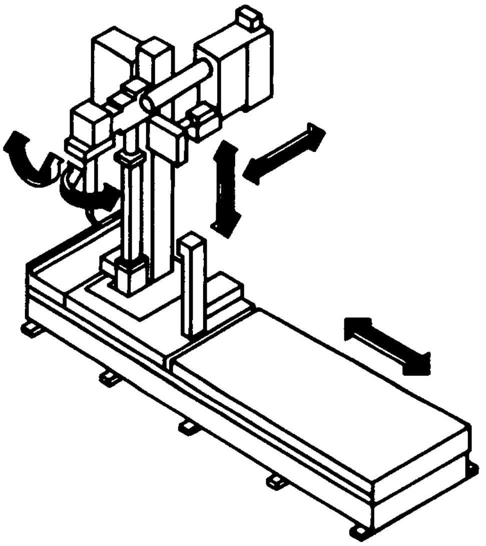
Table R-3
Supplementary Equipment for Welding Robot Work Cell

Recommended

Component	Function
Master part (component)	Teaches the robot. Then tests and verifies program and work cell accuracy, and identifies changes.
Robot program listing	Programs the robot. Then verifies work cell performance.
Program save device	Permits permanent storage of robot program produced by "Teach Method" for future use.
Torch set-up jig	Allows quick set-up after torch maintenance or replacement. Establishes the position of the point of welding arc with respect to the robot.
Torch cleaning station	Keeps welding torch operating properly. May be performed manually by an operator or automatically.
Safety screens and interlocks	Provide operator protection from arc flash, smoke and fume, burns and heat. Prevent physical harm from robot, tooling, or material handling equipment.
Desirable	
Inspection jig	Enables quick inspection of products, helps to identify set-up or program problems.
Cell set-up and troubleshooting guide	Permits quick detection of problems. Provides orientation and training for new operators, maintenance and supervisory personnel.
Work cell tool kit	Keeps at hand special critical tools used in work cell set-up, adjustment and repair.
Offline programming station	Enables reprogramming, program debugging, and program editing without lost cell time. Relatively new technology still under development.
Download link	Permits off-line programming station to send programs to work cell. May allow work cell to send programs for storage.



(A) ARTICULATED ROBOT



(B) RECTILINEAR ROBOT

Figure R-12—Robotic Motion Systems

moving or rotating a robotic arc welding machine into the welding area. This procedure is usually faster than moving the assembly, but it requires a relatively large working area.

A welding robot can be transferred between multiple work stations. This allows production flexibility, and reduces inventory and material handling costs. Work stations can be left in place when not in use while the robot is utilized at other locations.

Some robots can access multiple welding stations located in a semicircle. Rectilinear robots can move to welding stations that are organized in a straight line.

Positioner. A positioner can be used to move an assembly under an automatic arc welding head during the welding operation, or to reposition an assembly, as required, for robotic arc welding. The assembly can be moved so that the welding can be performed in a favorable position, usually the flat position.

There are two types of positioners for automatic arc welding. One type indexes an assembly to a programmed welding position. The other type is incorporated into the welding system to provide an additional motion axis. A positioner can provide continuous motion of the assembly while the machine is welding, to improve cycle time. Positioners can have fully coordinated motion for positioning a weld joint in the flat position in a robot cell.

Control Interfaces. An automatic arc welding system requires control interfaces for component equipment. Two types of interfaces are usually provided: contact closures and analog interfaces.

Welding Process Equipment. Welding power sources and welding wire feeders are controlled with both electrical contact closure and analog interfaces. Contact closures are used to turn equipment on and off. Analog interfaces are used to set output levels.

Fixtures and Positioners. Fixtures for automatic welding are often automated with hydraulic or pneumatic clamping devices. The welding machine often controls the operation of the clamps. Clamps can be opened to permit gun or torch access to the weld joint. Most clamping systems and positioner movements are activated by electrical contact closures.

Offline Programming and Interfacing with Computer Aided Design. The process of "teaching" the robot can be time consuming, utilizing productive robot time. If the need of only a few parts is forecast, robotic welding may not be economical. However, off-line programming using computer-aided design (CAD) systems can be used to program the sequence of motions of the robot and the positioner. Graphic animation programs help to visualize and debug the motion sequence. The CAD model cannot always duplicate the actual conditions at the actual welding station. It is often necessary to edit any motion program generated off line.

Each assembly to be welded requires an investment in programming. Programming costs vary widely depending on the welding system being used, the experience of the programmers, and the complexity of the welding process. Investment in programming must be taken into account when determining the economics of automatic welding. Once an investment is made for a specific weldment the program can be stored for future use.

Safety

The operator of a robotic system can easily avoid close proximity to jagged edges of parts, weld metal expulsion, and other welding hazards. However, the movement of the robot arm creates a dangerous environment. Workers in the area must be prevented from entering the working envelope of the robot. Protective fences, power interlocks and detection devices should be installed to assure worker safety.

ROCKWELL HARDNESS TEST

See HARDNESS TESTING.

ROD, Brazing

See BRAZING WIRE *and* COPPER ALLOY WELDING.

ROD, WELDING

See WELDING ROD.

ROLL

See OVERLAP.

ROLLOVER

A nonstandard term when used for OVERLAP.

ROLL SPOT WELDING

A resistance welding process variation that makes intermittent spot welds using one or more rotating circular electrodes. The rotation of the electrodes may or may not be stopped during the making of a weld. See STANDARD WELDING TERMS.

ROLL PLANISHING

A mechanical process of cold-working welds to improve mechanical properties, primarily fatigue resistance, by correcting surface and near-surface defects, introducing a compressive residual stress at the surface of the weld, and work-hardening the weld metal.

The roll planisher is a machine consisting of two rollers, diametrically opposed, which exert pressure at a small contact area on the weld. The top roller is a driver and the lower roller is an idler.

Extremely high or low loads may be exerted on contact. Magnitude of output load can be adjusted pneumatically, from 0 to 9000 kg (0 to 20 000 pounds).

ROLL WELDING (ROW)

A solid-state welding process that produces a weld by the application of heat and sufficient pressure with rolls to cause deformation at the faying surfaces. See STANDARD WELDING TERMS. *See also* FORGE WELDING.

ROOT

A nonstandard term when used for JOINT ROOT and WELD ROOT.

ROOT BEAD

A weld bead that extends into or includes part or all of the joint root. See STANDARD WELDING TERMS.

ROOT BEND TEST

A test in which the weld root is on the convex surface of a specified bend radius. See STANDARD WELDING TERMS.

ROOT CRACK

See STANDARD WELDING TERMS. *See* Appendix 9.

ROOT EDGE

A root face of zero width. See STANDARD WELDING TERMS. *See* Appendix 6.

ROOT FACE

That portion of the groove face within the joint root. See STANDARD WELDING TERMS. *See* Appendix 6.

ROOT GAP

A nonstandard term for ROOT OPENING.

ROOT OF JOINT

See STANDARD WELDING TERMS. *See* JOINT ROOT.

ROOT OF WELD

See STANDARD WELDING TERMS. *See also* WELD ROOT.

ROOT OPENING

A separation at the joint root between the workpieces. See STANDARD WELDING TERMS. *See* Appendixes 6 and 11.

ROOT PENETRATION

The distance the weld metal extends into the joint root. See STANDARD WELDING TERMS. *See* Appendix 12.

ROOT RADIUS

A nonstandard term for GROOVE RADIUS.

ROOT REINFORCEMENT

Weld reinforcement opposite the side from which welding was done. See STANDARD WELDING TERMS. *See* Figure R-13. *See also* FACE REINFORCEMENT.

ROOT SURFACE

The exposed surface of a weld opposite the side from which welding was done. See STANDARD WELDING TERMS. *See* Figure R-13.

ROOT SURFACE CRACK

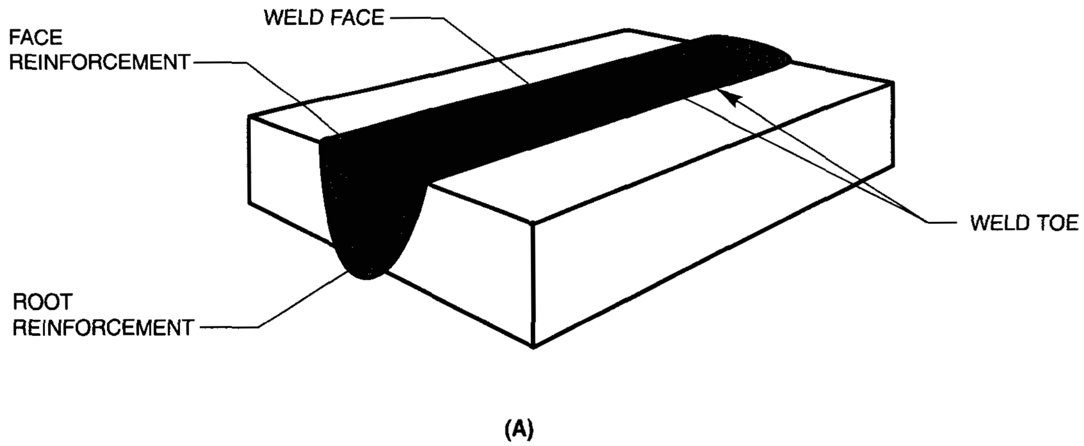
See STANDARD WELDING TERMS. *See* Appendix 9.

ROOT SURFACE UNDERFILL

See STANDARD WELDING TERMS. *See* Appendix 8. *See also* UNDERFILL.

ROTARY ROUGHENING, Thermal Spraying

A method of surface roughening in which a revolving tool is pressed against the surface being prepared, while either the work or the tool, or both, move. See STANDARD WELDING TERMS. *See* Figure R-14.



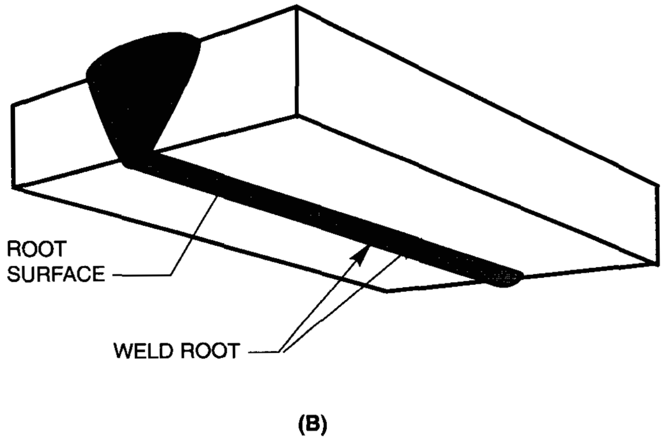


Figure R-13—Parts of a Weld

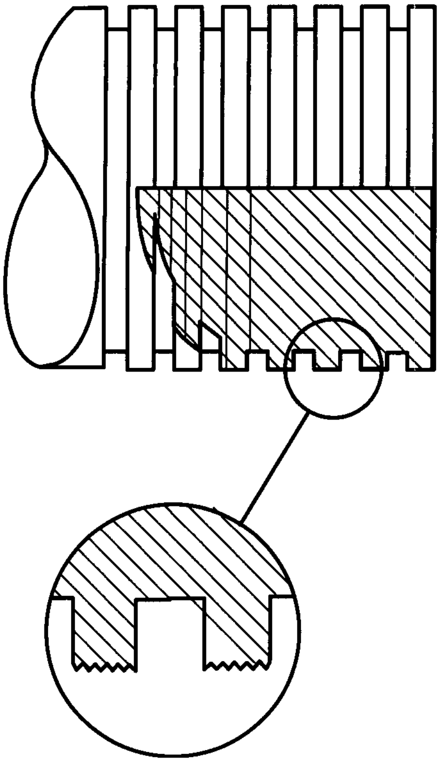


Figure R-14—Groove and Rotary Roughening

ROUGH THREADING, Thermal Spraying

A method of surface roughening that consists of cutting threads with the sides and tops of the threads jagged and torn. See STANDARD WELDING TERMS.

ROTATIONAL SPRAY TRANSFER, Arc Welding

A variation of spray transfer in which a longer electrode extension and specialized gas mixtures are used to produce a helical pattern of very fine droplets. See STANDARD WELDING TERMS.

ROTOR

The rotating member of an electric machine; the armature.

ROUND-EDGE SHAPE

A type of edge shape in which the surface is curved. See Appendix 6. *See* STANDARD WELDING TERMS.

RUNOFF WELD TAB

Additional material that extends beyond the end of the joint, on which the weld is terminated. See STANDARD WELDING TERMS.

RUST COATED ELECTRODES

Rust coated electrodes represented an early step in the development of coated electrodes. They were bare metal electrodes which were allowed to rust somewhat before drawing, and when used, had a smooth surface and a deep rust color. This rust coating did not affect the characteristics of the deposited metal, but served to produce more uniform arc characteristics than bare welding wire. *See* ELECTRODE MANUFACTURE.

RUTILE

Titanium dioxide (TiO_2) as found in nature. It is an important source of titanium and is used as a component in welding electrode coatings. Titanium dioxide is an effective agent which forms the nonmetallic nucleant in weld metal to gain better toughness.

S

SAFE PRACTICES

Safety is the first consideration for the welding operator and for all who are associated with welding, cutting and allied operations. *See* Appendix 13.

Various publications of the American Welding Society (AWS), 550 N.W. LeJeune Rd., Miami, FL 33126, deal specifically with safe practices while using welding processes and systems. These include but are not limited to the following:

ANSI/ASC Z49.1 (latest edition), *Safety in Welding, Cutting and Allied Processes*

EWH3-9, *Effects of Welding on Health.* Series

F1.1 (latest edition), *Methods for Sampling Airborne Particulates Generated by Welding and Allied Processes*

F1.2 (latest edition), *Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission for Welding and Allied Processes*

F1.3 (latest edition), *A Sampling Strategy Guide for Evaluating Contaminants in the Welding Environment*

F1.4 (latest edition), *Methods for Analysis of Airborne Particulates Generated by Welding and Allied Processes*

F1.5 (latest edition), *Methods for Sampling and Analyzing Gases from Welding and Allied Processes*

F2.1 (latest edition), *Recommended Safe Practices for Electron Beam Welding and Cutting*

F2.2 (latest edition), *Lens Shade Selector*

F3.1 (latest edition), *Guide for Welding Fume Control*

F4.1 (latest edition), *Recommend Safe Practices for Preparation of Welding and Cutting of Containers that have Held Hazardous Substances*

F6.1 (latest edition), *Method for Sound Level Measurement of Manual Arc Welding and Cutting Processes*

FGW, *Fumes and Gases in the Welding Environment*

For mandatory Federal Safety Regulations established by the U.S. Labor Department's Occupational Safety and Health Administration, refer to the latest edition of OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

Also refer to National Fire Protective Association (NFPA) Bulletin 53, available from NFPA, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA, 02269-9101.

In addition, refer to Material Safety Data Sheets, provided by manufacturers of consumables; and manufacturer's instructions for installation, operation and maintenance of equipment and apparatus.

Following are some general safety rules for operating arc and oxyfuel gas welding systems, and for handling compressed gases and combustible gases.

Arc Welding

(1) Protective clothing made of cotton or wool should be worn to shield all parts of the body from the rays of the arc and from metal spatter.

(2) A helmet should be worn to protect eyes and face. *See* EYE PROTECTION.

(3) The operator should be insulated from the workpiece when changing electrodes.

(4) Noncombustible or fire-resistant screens should be provided to protect workers or other persons in the vicinity of the welding or cutting operation from the rays of the arc and weld spatter. Workers in the vicinity of the operations are required to wear eye and face protection, and protective clothing.

(5) Hot metal should be marked to remind shop personnel not to touch it.

(6) The frame or case of a welding machine should be connected to an earth ground. The workpiece lead connecting the work to the power supply should be made as short as possible.

(7) Combustible material should not be used to support the workpieces.

(8) Clear glass goggles should be worn to protect the eyes when removing slag or spatter.

(9) Power lines to welding machines should be run overhead and out of reach of anyone standing on the ground.

(10) Pipe lines, tanks or containers should not be welded until they have been properly cleaned. Specific procedures are contained in ANSI/AWS F4.1, *Safe Practices for Preparation for Welding and Cutting of Containers and Piping.*

(11) A fire extinguisher should be available during any welding operation. *See* FIRE HAZARDS AND PROTECTION.

Oxyfuel Gas Welding and Cutting

Cylinder Safety. Compressed gas cylinders are safe for the purposes for which they are intended. Serious accidents connected with their handling, use and storage can often be traced to mishandling or abuse.

Only cylinders designed and maintained in accordance with specifications of the U.S. Department of Transportation (DOT) may be used in the United States. Cylinders must not be filled except by the owner, or with the consent of the owner, and then only in accordance with the regulations of the U.S. Department of Transportation. It is illegal to remove or change the numbers or marks stamped into cylinders.

Proper names for gases should always be used. Oxygen should not be referred to as "air," or acetylene as "gas." Several safety rules are specific to oxygen and acetylene.

Oxygen. Oxygen is not flammable, but it supports combustion. Oil and grease should not be allowed to come in contact with oxygen cylinders, valves, regulators, gauges, or fittings. Oxygen cylinders or apparatus should not be handled with oily hands or gloves because spontaneous combustion may occur.

Neither oxygen nor any gas should be used as a substitute for compressed air to power pneumatic tools or similar devices. It is dangerous to use oxygen to start a diesel engine, for imposing pressure in oil reservoirs, for paint spraying, or for blowing out pipelines. Pressure from an oxygen or gas supply should never be used to clear clogged oil lines.

Acetylene. The cylinder valve should be fully open when the cylinder is in use. Acetylene should never be used at a gauge pressure in excess of 103 Kpa (15 psi). Acetylene cylinders should be used and stored in an upright position to avoid the possibility of drawing out acetone. The pressure in an acetylene cylinder does not accurately indicate the amount of gas contained in the cylinder. The amount is determined by weight.

High-Pressure and Fuel Gas Cylinders

Gases used in oxyfuel gas welding, cutting, brazing, and heating operations are oxygen, acetylene, hydrogen, methylacetylene propadiene (MAPP), propylene, methane (natural gas), and propane.

The two main categories of cylinders used in these operations are high-pressure cylinders and fuel gas cylinders. The following rules apply to both these categories:

General Rules

(1) Regulators, pressure gauges, hoses or other apparatus provided for use with a particular gas must not be used on cylinders containing a different gas.

(2) Threads on regulators or other unions are designed to match those on cylinder valve outlets for specific gases. Connections that do not fit should not be forced.

(3) Attempting to mix gases in a cylinder, or attempting to transfer any gas from one cylinder to another, is prohibited.

(4) Never, under any circumstances, should the operator attempt to refill any cylinder.

(5) Tampering with safety devices on cylinders or cylinder valves is prohibited. Repairing or altering cylinders or valves should never be attempted.

(6) An open flame should never be used to detect combustible gas leaks. Soapy water should be used for this purpose.

(7) Connections to piping, regulators, and other appliances should always be kept tight to prevent leakage.

(8) Caps should be provided for valve protection; the caps should be kept on cylinders except when cylinders are in use.

Operating Safety

(1) Gases from cylinders should never be used without reducing the pressure through a suitable regulator attached directly to the cylinder.

(2) After the valve cap is removed, the valve should be opened for an instant to clear the opening of particles of dust or dirt.

(3) A pressure-reducing regulator should be attached to the cylinder valve before it is put in use.

(4) After attaching the regulator and before the cylinder valve is opened, the adjusting screw of the regulator must be released.

(5) The cylinder valve should be opened slowly, using only tools or wrenches provided or approved by the gas manufacturer. The gas should never be permitted to enter the regulator suddenly.

(6) Before a regulator is removed from a cylinder, the cylinder valve should be closed and all gas released from the regulator.

(7) The operator should not use the regulators attached to cylinders as brackets to hang torches.

(8) Sparks and flames from the welding or cutting torch should be kept away from cylinders.

(9) Hot slag should not be allowed to fall on combustible materials or on the cylinders.

(10) When cylinders are not in use, valves should be kept tightly closed.

Cylinder Storage

(1) Do not store cylinders near flammable material, especially oil, gasoline, grease, or any substance likely to cause or accelerate fire.

(2) Do not store reserve stocks of cylinders containing combustible gases with oxygen or other gases; they should be grouped separately.

(3) Store all cylinders in a well-ventilated place.

(4) All cylinders should be protected against excessive rise of temperature. Cylinders may be stored in the open, but in such cases, should be protected against extremes of weather. During winter, cylinders stored outdoors should be protected against accumulations of ice or snow. In summer, cylinders stored outdoors should be screened against continuous direct rays of the sun.

(5) Cylinders should not be exposed to continuous dampness.

(6) Full cylinders should not be stored near elevators or gangways, or in locations where heavy moving objects may strike or fall on them.

(7) Full and empty cylinders should be stored separately to avoid confusion.

Safe Handling

(1) Cylinders should never be dropped or permitted to strike each other violently.

(2) A lifting magnet, or a sling rope or chain should not be used when handling cylinders. A crane may be used when a safe cradle or platform is provided to hold the cylinders.

(3) Cylinders should never be used as rollers, supports, or for any purpose other than to carry gas.

(4) When empty cylinders are returned, cylinder valves should be closed before shipment. Protective caps and nuts for valve outlets should be in place before shipping empties.

SAFETY EQUIPMENT

Various items, including clothing, eye wear, head gear, hand wear, foot wear, instruments, tools, and devices used to protect workers from injury or death when working with potentially hazardous chemicals, materials, articles, equipment, processes or systems associated with welding. *See* EYE PROTECTION, ARC WELDING, OXYACETYLENE WELDING, WELDING FUMES, *and* SAFE PRACTICES. *See also* Appendix 13.

SAFETY VALVE

A pressure-release device installed in pressure vessels and pipe systems which is designed to blow out when the pressure rises above a predetermined point.

SALT BATH

Immersion of steel and other metals in a salt solution for tempering or heat treating.

Salt baths may be classified in three general types: neutral, reducing or oxidizing.

Neutral Baths

(1) Low-temperature baths which are operated at 150 to 595°C (300 to 1100°F) may be used for tempering or for low-temperature heat treatments such as the solution treatment or aging of aluminum alloys.

(2) Medium temperature baths, operated at 675 to 900°C (1250 to 1650°F) are used principally for heating steel before quenching.

High-temperature baths, higher than 925°C (1700°F), are used primarily for heat treatment of high-speed steel (tool steel alloys), but may also be used for copper brazing.

Among the precautions to be observed in using various types of salt bath: it is important to avoid contamination of neutral baths with cyanide salts. Another precaution is to avoid overheating the bath.

Reducing Baths

Reducing salt baths are used for carburizing or nitriding. A sufficient concentration of cyanide must be maintained in reducing salt baths for satisfactory results. A carbonaceous blanket on top of a bath of this type not only cuts down heat loss, but also helps to reduce the breakdown of cyanides in the bath.

Oxidizing Baths

Oxidizing baths are used for coloring steels or other metals and may also be used for annealing noble metals. Fused salt baths of this type may be used at 510°C (950°F) for blackening steel, and an aqueous solution of this type may be used at 150°C (300°F) for the same purpose.

The surface hardness of heat-treated tool steel alloys may be increased by nitriding them in a "high-speed case" salt bath at approximately 550°C (1025°F) for a relatively short period of time. The tendency of sharp edges of tools treated in this manner to chip can be reduced by a subsequent tempering operation at 540 to 565°C (1000 to 1050°F).

SALT-BATH DIP BRAZING

A dip brazing process variation. See STANDARD WELDING TERMS.

SANDBLAST

A method of discharging fine sand at high velocity to remove rust, dirt and scale from a surface before welding, painting, or finishing.

When welding, if more than one layer of metal is to be deposited, the oxide and scale should be removed from each layer before the next layer is applied. Sandblasting is probably the fastest and most efficient method of producing a thorough cleaning job.

A portable sandblaster consists of a sheet metal tank provided with a filling hole and a pipe T-outlet for an air-operated siphon. The siphon consists of a pipe from the vertical of the T to the bottom of the tank; the horizontal outlets of the T are fitted with a sand nozzle and an air control valve. The sand nozzle tip should be replaceable because it will wear quite rapidly. A sandblaster of this type will operate well with an air pressure of about 620 kPa (90 psi).

Care should be exercised when sandblasting to avoid entrapping sand in crevices or embedding sand in the surfaces of soft metals and alloys. Particles of sand can result in contamination of subsequent weld passes, and can lead to other problems in the weldment.

SAND HOLES

Craters or porous holes in castings.

SANDBERG (In Situ) RAIL HARDENING PROCESS

The Sandberg process is an application of the oxyacetylene flame to harden rails. In this process, rails already in service are heated with the torch, then quenched with water. In one experiment, rails treated by this process remained unaffected after 360 000 cars had passed over them, although adjoining lengths of untreated rails corrugated when subjected to the same test. *See also* FLAME HARDENING.

SAWS, MANUFACTURE AND REPAIR BY WELDING

Welding is used in the manufacture of saw blades for band saws, power hacksaws, and circular saws. A hard strip (or ring) containing the teeth is welded to a softer, tougher strip (or disc) to provide for safe operation of the saw blade. Processes include resistance seam and "mash" welding, high-frequency (resistance) welding, and laser-beam and electron-beam welding. Brazing is also used to manufacture saw blades.

Repairs. Cracks in band saw and circular saw blades can be repaired by welding. A section with broken teeth can be cut away, and replaced with a usable section cut from an old blade and welded in place. However, a special technique is necessary; special jigs and anvils are required, and specific welding rods must be used.

Band saw steel is made of nickel-, chrome-, or molybdenum-steel, or another alloyed steel. The carbon content often is about 0.70%. Welding rods, therefore, should approximate this alloy, and an excellent choice is a chrome-vanadium steel rod containing approximately 0.80 to 1.10% chromium, 0.15 to 0.18% vanadium and 0.40 to 0.50% carbon. There are many other good rods for welding saw blades.

Jigs for band saws are designed so that the broken or cracked parts of the saw blade can be clamped just above the anvil and, by a movement of a foot lever, brought down in contact with the anvil for hammering. A small torch must be used, and the flame adjusted exactly to neutral characteristics. It is very important that no oxide or slag particles be entrapped in the weld.

The crack is welded at its inner beginning, with weld progression toward the open end. Only about 9.5 to 13 mm (3/8 to 1/2 in.) should be welded, then the saw blade should be brought down on the anvil while the weld is peened with a light hammer. Peening should be applied only when the metal is at a forging heat. Another 9.5 mm (3/8 in.) is then welded and peened. This sequence is continued until the crack is completely welded.

If the break is all the way across a band saw blade, the first weld is made in the center of the saw blade and then on each side of the center, alternately, until the weld is completed.

Circular saw blades are usually welded in a similar manner, beginning at the inside end of the crack, welding about 8.5 mm (3/8 in.) on one side, then peening the weld. The blade is then turned over and the opposite side welded and peened. This is continued until the crack is completely welded. *See also* BAND SAW BLADE REPAIRS.

SCALE

A term sometimes applied to a surface coating of oxide on molten iron or steel.

SCALING POWDER

A flux used to dissolve the oxide that forms in cast iron welds.

SCARF

The chamfered surface of a joint.

SCARF GROOVE

A weld groove in a butt joint consisting of members having single-bevel edge shapes. The groove faces are parallel. See STANDARD WELDING TERMS. *See* Figure S-1.

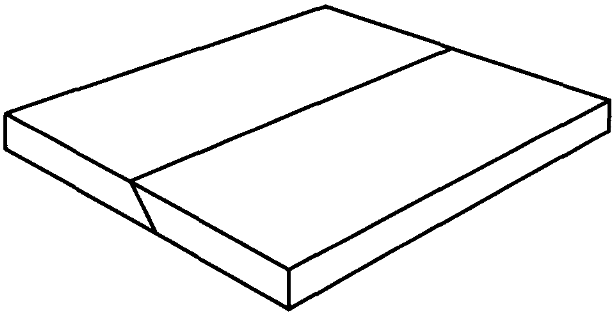


Figure S-1—A Scarf Groove

SCARFING

A process for removing defects and checks which develop in the rolling of steel billets. Scarfing is accomplished with a low-velocity oxygen deseaming torch, a specially designed torch with an unusually large oxygen orifice. The steel is preheated locally to a cherry red, and the oxygen, under low pressure and velocity, is projected against the red-hot surface. The steel around the defect is consumed and the defect is entirely burned away.

Alternatively, the term *scarfing* is used to refer to the process of preparing a scarf groove.

SCARF JOINT

A nonstandard term for SCARF GROOVE.

SCHAEFFLER DIAGRAM

A diagram proposed by A. E. Schaeffler in 1956 to predict the ferrite number (FN) of a stainless steel weld deposit. The user calculated the chromium and nickel equivalents of the deposit, based on weld chemistry, and was able to plot the ferrite number. The Schaeffler Diagram was followed by the DeLong diagram (proposed by W. T. DeLong in 1974), the Espy Diagram (proposed by R. H. Espey in 1982), and the WRC-1992 Diagram (developed by a Welding Research Council Sub-committee in 1992 and described in WRC Bulletin 342. *See* DELONG DIAGRAM, WRC-1988 DIAGRAM, *and* ANSI/AWS A5.4, *Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding.*

SCLEROSCOPE HARDNESS

See HARDNESS TESTING.

SCREEN

A device usually constructed of a fine wire mesh filter designed to prevent foreign matter from entering the regulator or torch. Also, the wire mesh used as a gas "lens" in gas tungsten arc welding torches to provide laminar flow of the shielding gas.

SCREENS, PROTECTIVE

A moveable, often portable, protective barrier or partition used around welders (especially in arc welding) to protect others in the vicinity from sparks, spatter, and arc flash. Screens may be constructed from translucent material that blocks ultraviolet radiation, or an opaque material. *See also* EYE PROTECTION *and* PROTECTION FOR WELDERS.

SCULPTURE

See WELDED SCULPTURE.

SEAL WELD

Any weld designed primarily to provide a specific degree of tightness against fluid leakage. See STANDARD WELDING TERMS.

SEAM

A nonstandard term when used for a welded, brazed, or soldered joint.

SEAM WELD

A continuous weld made between or upon overlapping members, in which coalescence may start and occur on the faying surfaces, or may have proceeded from the outer surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds. See STANDARD WELDING TERMS. *See* Figure S-2. *See also* ARC SEAM WELD *and* RESISTANCE SEAM WELDING.

Seam welds are made with resistance welding equipment in high-production manufacturing. Seam welds are typically used to produce continuous gas- or liquid-tight joints in sheet metal assemblies, such as automotive gasoline tanks. This process is also used to weld longitudinal seams in structural tubular sections that do not require leak-tight seams. A resistance seam weld is made on overlapping workpieces and is a con-

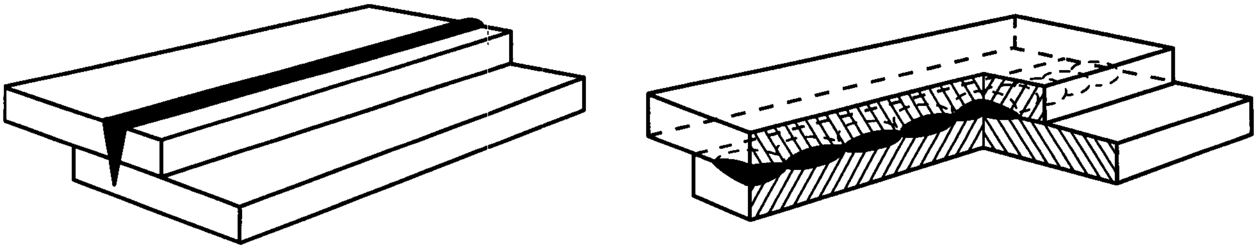

(A) ELECTRON BEAM SEAM WELD (B) RESISTANCE SEAM WELD

Figure S-2—Two Types of Seam Welds

tinuous weld formed by overlapping weld nuggets, by a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by its resistance to the welding current.

In most applications, two wheel electrodes, or one translating wheel and a stationary mandrel, are used to provide the current and pressure for resistance seam welding. Seam welds can also be produced using spot welding electrodes; this requires the purposeful overlapping of the spot welds in order to obtain a leak-tight seam weld. Two variations of this process are lap seam welding, using two wheel electrodes (or one wheel and a mandrel) and mash seam welding, which makes a lap joint primarily by high-temperature plastic forming and diffusion, as opposed to melting and solidification. In mash seam welding, overlap is maintained by clamping or tack welding the pieces.

The electrode wire seam welding process uses an intermediate wire electrode between each wheel electrode and the workpiece. This process is used almost exclusively for welding tin mill products to fabricate cans.

Butt joint seam welding is done with the edges of the sheets forming a butt joint. A thin, narrow strip of metal fed between the workpieces and the wheel electrode is welded to one or both sides of the joint. The metal strip bridges the gap between the workpieces, distributes the welding current to both sheet edges, adds electrical resistance, and contains the molten weld nugget as the nugget forms. The strip serves as a filler metal, and produces a flush or slightly reinforced weld joint.

Two seam welds can be made in series, using two weld heads. The two heads may be mounted side by side or in tandem. Two seams can be welded with the same welding current, and power demand will be only slightly greater than for a single weld.

A tandem wheel arrangement can reduce welding time by 50%, since both halves of a joint can be welded simultaneously. Thus, for a joint 182 cm (72 in.) long, two welding heads can be placed 91 cm (36 in.) apart, with the welding current path through the work from one wheel electrode to the other. A third continuous electrode is used on the other side of the joint. The full length of the joint can be welded with only 91 cm (36 in.) of travel. *See* RESISTANCE WELDING (RW) *and* TUBE MANUFACTURE.

SEAM WELD SIZE

The width of the weld metal in the plane of the faying surfaces. See Figure S-3 *and* Appendix 11.

SEARING

An iron-cleaning application accomplished by adjusting an oxyacetylene torch flame to slightly oxidizing (excess oxygen), and passing it over the surface of the iron to burn off the graphite film. Searing can also be used to preheat cast iron, which will braze more rapidly at a temperature of 90 to 150°C (200 to 300°F).

SEAT

In a regulator, the surface on which a valve disc rests when fully closed. *See* REGULATOR.

SECONDARY CIRCUIT

That portion of a welding machine that conducts the secondary current between the secondary terminals of the welding transformer and the electrodes, or electrode and workpiece. See STANDARD WELDING TERMS.

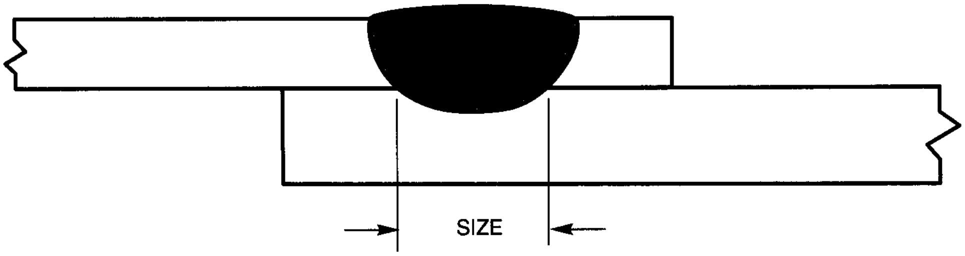


Figure S-3—Arc Seam Weld Size

SECONDARY CURRENT PATH, Resistance Welding

The electrical path through which the welding current passes. See STANDARD WELDING TERMS.

SEGREGATION

The tendency for alloy constituents to freeze at different temperatures during (real, non-equilibrium) solidification so that there is an uneven distribution of these elements in the alloy. Such segregation can occur on either a microscopic scale, as the natural result of solute redistribution (due to the distribution coefficient), or on a macroscopic scale as the result of improper (incomplete) mixing of dissimilar metals or alloys or due to gravity effects in alloys. *See* METALLURGY.

SELECTIVE BLOCK SEQUENCE

A block sequence in which successive blocks are completed in an order selected to control residual stresses and distortion. See STANDARD WELDING TERMS.

SELENIUM RECTIFIER

Selenium rectifiers were used in d-c welding power supplies until the development of silicon, or solid state, rectifiers. Selenium rectifiers provided a convenient means of changing alternating current to direct current. This ability was based on the characteristic of permitting the current to pass freely in one direction, while blocking, or greatly limiting, its passage in the opposite direction.

If the rectifier cell readily passes current in a forward direction, it indicates that the resistance to current flow in this direction is low. The resulting forward voltage drop across the cell thus must also be low. Conversely, if the current flow in the opposite direction is blocked, or held to a minimum value, the reverse resistance must be high. Consequently, the voltage drop across the cell in the reverse direction must also be high. The minimum value of the reverse voltage drop is limited by the breakdown potential of the barrier layer of the rectifier cell.

Selenium rectifiers had the advantage of being able to accept high-voltage surges without breaking down. Cooling was easily achieved, because selenium rectifiers were usually made up of a number of plates. This also made it easy to add more rectifying surface if required for a specific application. The disadvantage of the selenium rectifier was that it required more physical space in the power source. It was an important stepping stone in the development of solid state rectifiers.

SELF-EXCITED

A generator in which the current in the field coil is produced by the generator itself.

SELF-FLUXING ALLOY, Thermal Spraying

A surfacing material that wets the substrate and coalesces when heated to its melting point, with no flux other than the boron and silicon contained in the alloy. See STANDARD WELDING TERMS.

SELF-SHIELDED FLUX CORED ARC WELDING (FCAW-S)

A flux cored arc welding process variation in which shielding gas is obtained exclusively from the flux within the electrode. See STANDARD WELDING TERMS. *See also* FLUX CORED ARC WELDING.

SEMIAUTOMATIC, *adj.*

Pertaining to the manual control of a process with equipment that automatically controls one or more of the process conditions. See STANDARD WELDING

TERMS. *See also* ADAPTIVE CONTROL, AUTOMATIC, MANUAL, MECHANIZED, *and* ROBOTIC.

SEMIAUTOMATIC BRAZING

See STANDARD WELDING TERMS. *See also* SEMIAUTOMATIC WELDING.

SEMIAUTOMATIC SOLDERING

See STANDARD WELDING TERMS. *See also* SEMIAUTOMATIC WELDING.

SEMIAUTOMATIC THERMAL CUTTING

See STANDARD WELDING TERMS. *See also* SEMIAUTOMATIC WELDING.

SEMIAUTOMATIC THERMAL SPRAYING

See STANDARD WELDING TERMS. *See also* SEMIAUTOMATIC WELDING.

SEMIAUTOMATIC WELDING

Manual welding with equipment that automatically controls one or more of the welding conditions. See STANDARD WELDING TERMS.

Variations of this term are semiautomatic brazing, semiautomatic soldering, semiautomatic thermal cutting, and semiautomatic thermal spraying. See also ADAPTIVE CONTROL WELDING, AUTOMATIC WELDING, MANUAL WELDING, MECHANIZED WELDING, *and* ROBOTIC WELDING.

SEMIBLIND JOINT

A joint in which one extremity of the joint is not visible. See STANDARD WELDING TERMS.

SEMI-CONDUCTORS

Elements (like silicon, germanium, selenium, and others, especially in Group IV of the periodic table) or compounds (like gallium arsenic and indium tellurium), which exhibit electrical properties intermediate between conductive metals and non-conductive or insulating non-metals. Such materials are the basis for modern electronic devices referred to as *solid-state devices.*

These materials are particularly interesting for their characteristic of allowing current flow in one direction and not in the other, and, so, are used for rectifying (or converting) alternating current (ac) to direct current (dc). *See also* SELENIUM RECTIFIER, SILICON RECTIFIER, *and* RECTIFIER WELDER.

SEMI-RIGID JOINT

See RIGID JOINT.

SEMI-STEEL

A name sometimes used for a metal produced by melting and mixing scrap iron and pig iron.

SEQUENCE TIME

A nonstandard term when used for WELDING CYCLE.

SEQUENCE TIMER

In resistance welding, a device for controlling the sequence and duration of any or all of the elements of a complete welding cycle.

SERIES CONNECTED

Two or more electric machines or appliances connected so that the same electric current will flow through each one.

SERIES SUBMERGED ARC WELDING (SAW-S)

A submerged arc welding process variation in which the arc is established between two consumable electrodes that meet just above the surface of the workpieces, which are not part of the welding current circuit. See STANDARD WELDING TERMS.

SERIES WELDING

A resistance welding secondary circuit variation in which the secondary current is conducted through the workpieces and electrodes or wheels in a series electrical path to simultaneously form multiple resistance spot, seam, or projection welds. See STANDARD WELDING TERMS. *See* Figure S-4.

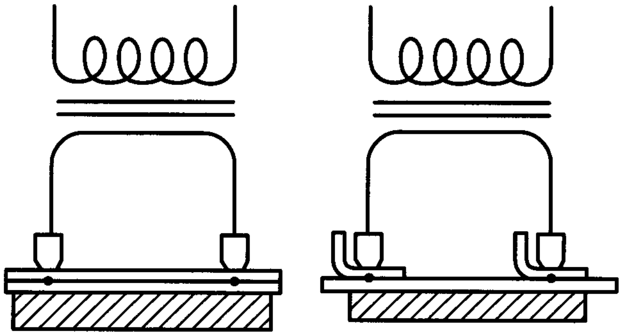


Figure S-4—Typical Arrangements for Series Resistance Spot Welding

SETBACK

See STANDARD WELDING TERMS. *See also* CONTACT TUBE SETBACK *and* ELECTRODE SETBACK.

SET DOWN

A nonstandard term when used for UPSET.

SHADOW MASK, Thermal Spraying

A device that partially shields an area of the workpiece, producing a feathered edge of the thermal spray deposit. See STANDARD WELDING TERMS.

SHAPE CUTTING

See THERMAL CUTTING *and* FLAME CUTTING.

SHAPE WELDING

Defining a shape by using a mold or dam when welding to build up lugs, gear teeth, or low spots.

SHEAR STRENGTH

The characteristic of a material to resist shear. *See* TORSION TEST.

SHEET METAL WELDING

Good sheet metal welding depends on the following principal factors:

(1) Preparation of the edges to be welded, including cleaning

(2) Correct procedure in the adjustment of the arc in arc welding, or adjusting the flame and using a suitable welding rod in oxyfuel welding

(3) The design of the article, the location of the welds, and the use of appropriate jigs and welding fixtures.

Resistance spot, seam or projection welding of sheet metal is commonplace, but still demands consideration of factors (1) and (3).

SHEET SEPARATION, Resistance Welding

The distance between the faying surfaces, adjacent to the weld, after a spot, seam, or projection weld has been made. See STANDARD WELDING TERMS.

SHERADIZE

A process for applying a zinc coating to steel. The object to be coated is heated to a temperature of 250 to 315°C (500 to 600°F) with zinc powder in a rotating furnace.

SHIELDED CARBON ARC WELDING (CAW-S)

A carbon arc welding process variation that uses shielding from the combustion of solid material fed into the arc, or from a blanket of flux on the workpieces, or both. See STANDARD WELDING TERMS. This is a rarely used, obsolete process.

SHIELDED METAL ARC CUTTING (SMAC)

An arc cutting process that uses a covered electrode. See STANDARD WELDING TERMS.

SHIELDED METAL ARC WELDING (SMAW)

An arc welding process with an arc between a covered electrode and the weld pool. The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode. See STANDARD WELDING TERMS. *See also* FIRECRACKER WELDING.

The core of the covered electrode consists of either a solid metal rod of drawn or cast material or one fabricated by encasing metal powders in a metallic sheath. The core rod conducts the electric current to the arc and provides filler metal for the joint. The primary functions of the electrode covering are to provide arc stability and to shield the molten metal from the atmosphere with gases created as the coating decomposes from the heat of the arc.

The shielding employed, along with other ingredients in the covering and the core wire, largely controls the mechanical properties, chemical composition, and metallurgical structure of the weld metal, as well as the arc characteristics of the electrode. The composition of the electrode covering varies according to the type and purpose of the electrode.

Principles of Operation

Shielded metal arc welding (SMAW) is by far the most widely used of the various arc welding processes. It employs the heat of the arc to melt the base metal and the tip of a consumable covered electrode. The electrode and the work are part of an electric circuit, illustrated in Figure S-5. This circuit begins with the electric power source and includes the welding cables, an electrode holder, a workpiece connection, the workpiece (weldment), and an arc welding electrode. One of the two cables from the power source is attached to the work. The other is attached to the electrode holder.

Welding commences when an electric arc is struck between the tip of the electrode and the work. The intense heat of the arc melts the tip of the electrode and the surface of the work close to the arc. Tiny globules of molten metal rapidly form on the tip of the electrode, then transfer through the arc stream into the molten weld pool. In this manner, filler metal is deposited as the electrode is progressively consumed. The arc is moved over the work at an appropriate arc length and travel speed, melting and fusing a portion of the base metal and continuously adding filler metal. The arc is one of the hottest of the commercial sources

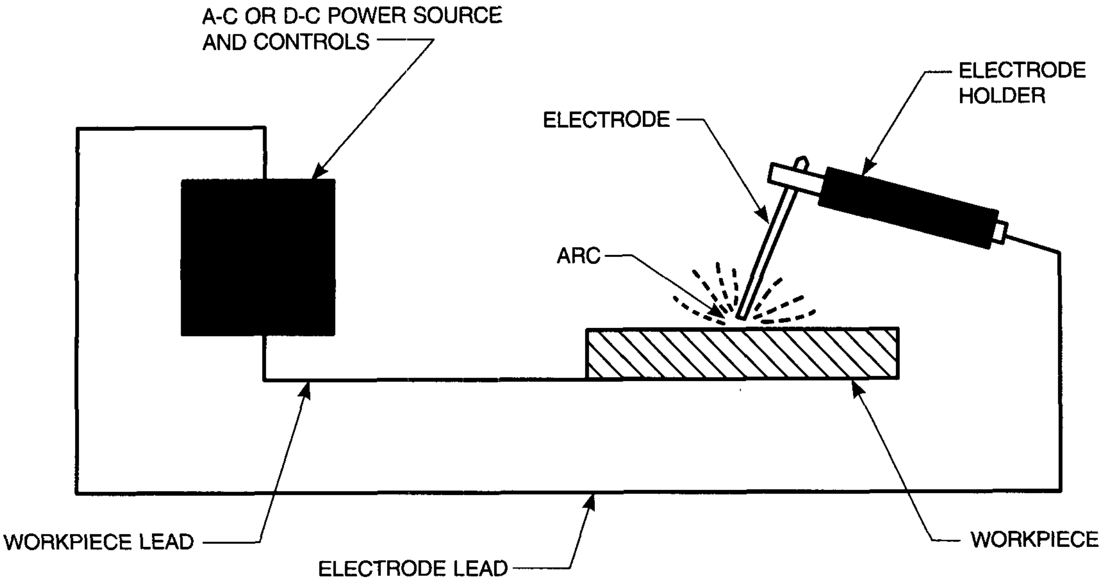


Figure S-5—Typical Welding Circuit for Shielded Metal Arc Welding

of heat; temperatures above 5000°C (9000°F) have been measured at its center. Melting of the base metal takes place almost instantaneously upon arc initiation. If welds are made in either the flat or the horizontal position, metal transfer is induced by the force of gravity, gas expansion, electric and electromagnetic forces, and surface tension. For welds in other positions, gravity works against the other forces.

The process requires sufficient electric current to melt both the electrode and a proper amount of base metal. It also requires an appropriate gap between the tip of the electrode and the base metal or the molten weld pool. These requirements are necessary to set the stage for coalescence. The sizes and types of electrodes for SMAW define the arc voltage requirements (within the overall range of 16 to 40 V) and the amperage requirements (within the overall range of 20 to 550 A). The current may be either alternating or direct, depending on the electrode being used, but the power source must be able to control the level of current within a reasonable range in order to respond to the complex variables of the welding process itself.

Covered Electrodes

In addition to establishing the arc and supplying filler metal for the weld deposit, the electrode introduces other materials into or around the arc, or both. Depending on the type of electrode being used, the covering performs one or more of the following functions:

(1) Provides a gas to shield the arc and prevent excessive atmospheric contamination of the molten filler metal

(2) Provides scavengers, deoxidizers, and fluxing agents to cleanse the weld and prevent excessive grain growth in the weld metal

(3) Establishes the electrical characteristics of the electrode

(4) Provides a slag blanket to protect the hot weld metal from the air and enhances the mechanical properties, bead shape, and surface cleanliness of the weld metal

(5) Provides a means of adding alloying elements to change the mechanical properties of the weld metal.

Functions (1) and (4) prevent the pickup of oxygen and nitrogen from the air by the molten filler metal in the arc stream and by the weld metal as it solidifies and cools.

The covering on shielded metal arc electrodes is applied by either the extrusion or the dipping process. Extrusion is much more widely used. The dipping process is used primarily for cast and some fabricated core rods. In either case, the covering contains most of the shielding, scavenging, and deoxidizing materials. Most SMAW electrodes have a solid metal core. Some are made with a fabricated or composite core consisting of metal powders encased in a metallic sheath. In this latter case, the purpose of some or even all of the metal powders is to produce an alloy weld deposit.

In addition to improving the mechanical properties of the weld metal, electrode coverings can be designed for welding with alternating current (ac). With ac, the welding arc goes out and is reestablished each time the current reverses its direction. For good arc stability, it is necessary to have a gas in the arc stream that will remain ionized during each reversal of the current. This ionized gas makes possible the re-ignition of the arc. Gases that readily ionize are available from a variety of compounds, including those that contain potassium. It is the incorporation of these compounds in the electrode covering that enables the electrode to operate on ac. To increase the deposition rate, the coverings of some carbon- and low-alloy steel electrodes contain iron powder. The iron powder is another source of metal available for deposition, in addition to that obtained from the core of the electrode. The presence of iron powder in the covering also makes more efficient use of the arc energy. Metal powders other than iron are frequently used to alter the mechanical properties of the weld metal.

The thick coverings on electrodes with relatively large amounts of iron powder increase the depth of the crucible at the tip of the electrode. This deep crucible helps to contain the heat of the arc and permits the use of the drag technique to maintain a constant arc length. When iron or other metal powders are added in relatively large amounts, the deposition rate and welding speed usually increase.

Iron powder electrodes with thick coverings reduce the level of skill needed to weld. The tip of the electrode can be dragged along the surface of the work while maintaining a welding arc. For this reason, heavy iron powder electrodes frequently are called *drag electrodes*. Deposition rates are high, but, because slag solidification is slow, these electrodes are not suitable for out-of-position welds.

Arc Shielding

The arc shielding action, illustrated in Figure S-6, is essentially the same for all electrodes, but the specific method of shielding and the volume of slag produced

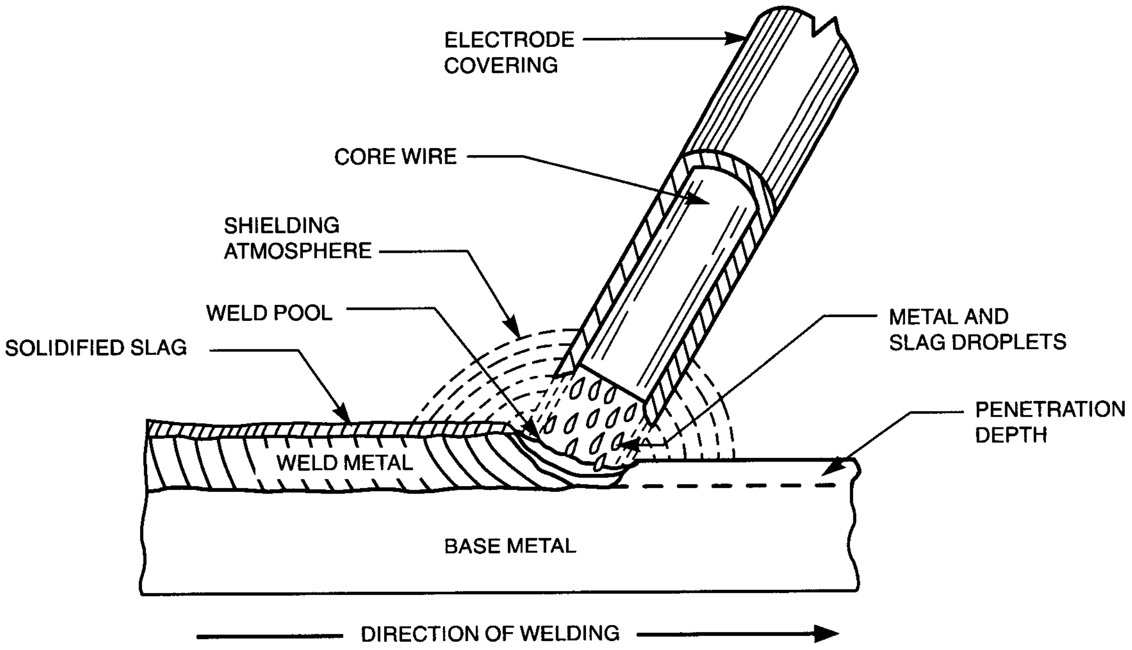


Figure S-6—Schematic View of Shielded Metal Arc Welding

vary from type to type. The bulk of the covering materials on some electrodes is converted to gas by the heat of the arc, and only a small amount of slag is produced. This type of electrode depends largely on a gaseous shield to prevent atmospheric contamination. Weld metal from such electrodes can be identified by the incomplete or light layer of slag which covers the bead.

For electrodes at the other extreme, the bulk of the covering is converted to slag by the heat of the arc, and only a small volume of shielding gas is produced. The tiny globules of metal being transferred across the arc are entirely coated with a thin film of molten slag. This molten slag floats to the surface of the weld puddle because it is lighter than the metal. The slag solidifies after the weld metal has solidified. Welds made with these electrodes are identified by the heavy slag deposits that completely cover the weld beads. Between these extremes is a wide variety of electrode types, each with a different combination of gas and slag shielding.

Variations in the amount of slag and gas shielding also influence the welding characteristics of covered electrodes. Electrodes which produce a heavy slag can carry high amperage and provide high deposition rates, making them ideal for heavy weldments in the flat position. Electrodes which produce a light slag layer are used with lower amperage and provide lower deposition rates. These electrodes produce a smaller weld pool and are suitable for making welds in all positions. Because of the differences in their welding characteristics, one type of covered electrode usually will be best suited for a given application.

SMAW Capabilities and Limitations

Shielded metal arc welding is the most widely used process, particularly for short welds in production, maintenance and repair work, and for field construction. The following are advantages of this process:

(1) The equipment is relatively simple, inexpensive, and portable.

(2) The filler metal, and the means of protecting it and the weld metal from harmful oxidation during welding, are provided by the covered electrode.

(3) Auxiliary gas shielding or granular flux is not required.

(4) The process is less sensitive to wind and draft than gas shielded arc welding processes.

(5) It can be used in areas of limited access.

(6) The process is suitable for most of the commonly used metals and alloys.

SMAW electrodes are available to weld carbon- and low-alloy steels, stainless steels, cast irons, copper, and nickel, and their alloys, and for some aluminum applications. Low-melting metals, such as lead, tin, and zinc, and their alloys, are not welded with SMAW because the intense heat of the arc is too high for them. SMAW is not suitable for reactive metals such as titanium, zirconium, tantalum, and niobium because the shielding provided is inadequate to prevent oxygen contamination of the weld.

Covered electrodes are produced in lengths of 230 to 460 mm (9 to 18 in.). As the arc is first struck, the current flows the entire length of the electrode. The amount of current that can be used, therefore, is limited by the electrical resistance of the core wire. Excessive amperage overheats the electrode and breaks down the covering. This, in turn, changes the arc characteristics and the shielding that is obtained. Because of this limitation, deposition rates are generally lower than for a welding process such as gas metal arc welding (GMAW).

Operator duty cycle and overall deposition rates for covered electrodes are usually less than provided with a continuous electrode process such as flux cored arc welding (FCAW). This is because electrodes can be consumed only to some certain minimum length. When that length has been reached, the welder must discard the unconsumed electrode stub and insert a new electrode into the holder. In addition, slag usually must be removed at starts and stops and before depositing a weld bead adjacent to or onto a previously deposited bead.

Equipment

Power Sources. Either alternating current (ac) or direct current (dc) may be employed for shielded metal arc welding, depending on the welding power supply and the electrode selected. The specific type of current employed influences the performance of the electrode. Each current type has its advantages and limitations, and these must be considered when selecting the type of current for a specific application. Factors which need to be considered are as follows:

(1) Voltage Drop. Voltage drop in the welding cables is lower with ac. This makes ac more suitable if the welding is to be done at long distances from the power supply. However, long cables which carry ac should not be coiled because the inductive losses encountered in such cases can be substantial.

(2) Low Current. With small diameter electrodes and low welding currents, dc provides better operating characteristics and a more stable arc.

(3) Arc Starting. Striking the arc is generally easier with dc, particularly if small diameter electrodes are used. With ac, the welding current passes through zero each half cycle, and this presents problems for arc starting and arc stability.

(4) Arc Length. Welding with a short arc length (low arc voltage) is easier with dc than with ac. This is an important consideration, except for the heavy iron powder electrodes. With those electrodes, the deep crucible formed by the heavy covering automatically maintains the proper arc length when the electrode tip is dragged on the surface of the joint.

(5) Arc Blow. Alternating current rarely presents a problem with arc blow because the magnetic field is constantly reversing (120 times per second). Arc blow can be a significant problem with d-c welding of ferritic steel because of unbalanced magnetic fields around the arc.

(6) Welding Position. Direct current is somewhat better than ac for vertical and overhead welds because lower amperage can be used. With suitable electrodes, however, satisfactory welds can be made in all positions with ac.

(7) Metal Thickness. Both sheet metal and heavy sections can be welded using dc. The welding of sheet metal with ac is less desirable than with dc. Arc conditions at low current levels required for thin materials are less stable on ac power than on dc power.

Constant-voltage power sources are not suitable for SMAW because with their flat volt-ampere curve, even a small change in arc length (voltage) produces a relatively large change in amperage. A constant-current power source is preferred for manual welding, because the steeper the slope of the volt-ampere curve (within the welding range), the smaller the change in current for a given change in arc voltage (arc length).

For applications that involve large diameter electrodes and high welding currents, a steep volt-ampere curve is desirable.

Where more precise control of the size of the molten pool is required (out-of-position welds and root passes of joints with varying fit-up, for example), a *flatter volt-ampere* curve is desirable. This enables the welder to change the welding current within a specific range simply by changing arc length. In this manner, the welder has some control over the amount of filler metal that is being deposited. Figure S-7 portrays these different volt-ampere curves for a typical welding power source. Even though the difference in the slope of the various curves is substantial, the power source is still considered a constant-current power source. The changes shown in the volt-ampere curve are accomplished by adjusting both the open circuit voltage (OCV) and the current settings on the power source.

Voltage. Open circuit voltage, which is the voltage set on the power source, does not refer to arc voltage. Arc voltage is the voltage between the electrode and the work during welding and is determined by arc length for any given electrode. Open circuit voltage, on the other hand, is the voltage generated by the welding machine when no welding is being done. Open circuit voltages generally run between 50 and 100 V, whereas arc voltages are between 17 and 40 V. The open circuit voltage drops to the arc voltage when the arc is struck and the welding load comes on the machine. The arc length and the type of electrode being used determine just what this arc voltage will be. If the arc is lengthened, the arc voltage will increase and the welding current will decrease. The change in amperage which a change in arc length produces is determined by the slope of the volt-ampere curve within the welding range.

Some power sources do not provide for control of the open circuit voltage because this control is not needed for all welding processes. It is a useful feature for SMAW, yet it is not necessary for all applications of the process.

Power Source Selection. Several factors need to be considered when a power source for SMAW is selected:

(1) The type of welding current required

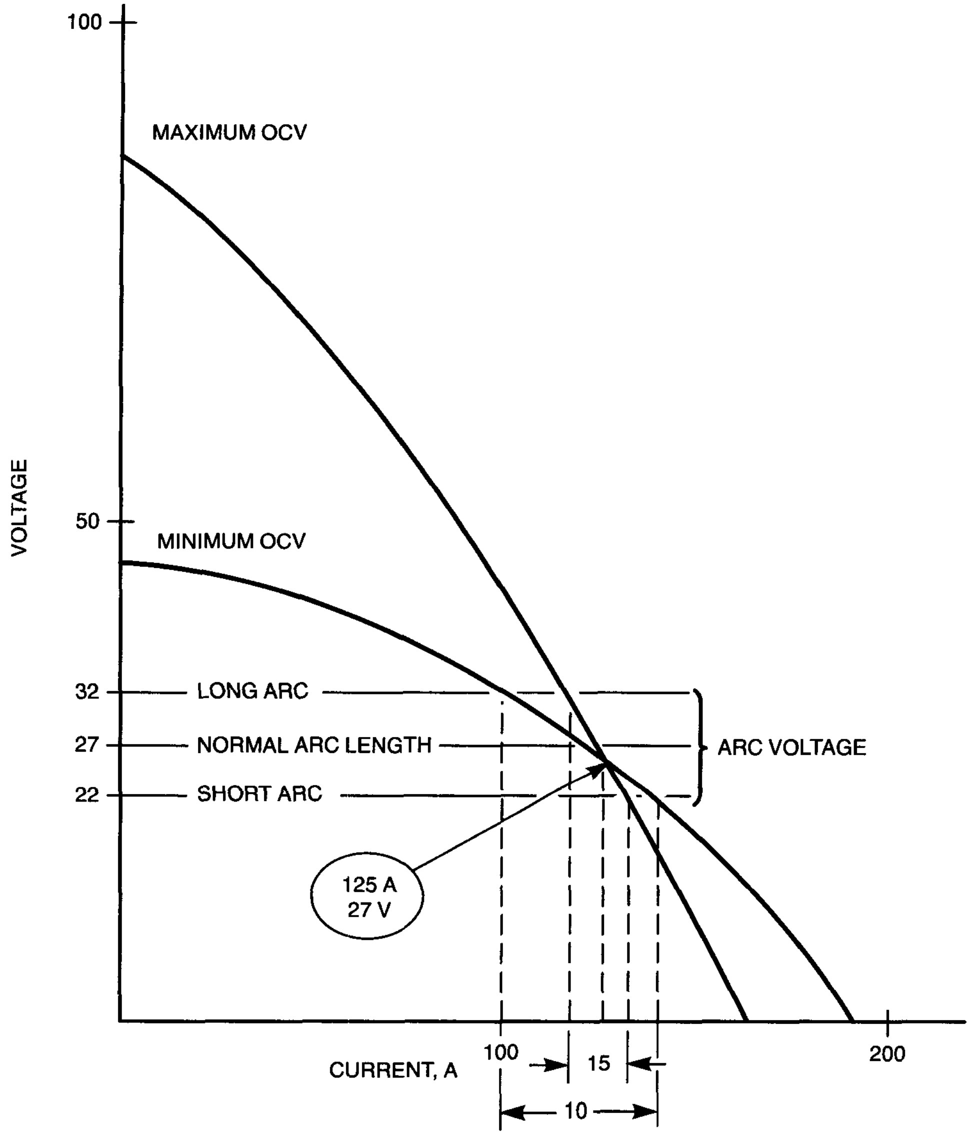
(2) The amperage range required

(3) The positions in which welding will be done

(4) The primary power available at the work station

Selection of the type of current, ac, dc, or both, will be based largely on the types of electrodes to be used and the kind of welds to be made. For ac, a transformer or an alternator type of power source may be used. For dc, transformer-rectifier or motor-generator power sources are available. When both ac and dc will be needed, a single-phase transformer-rectifier or an alternator-rectifier power source may be used. Otherwise, two welding machines will be required, one for ac and one for dc.

The amperage requirements will be determined by the sizes and types of electrodes to be used. When a variety will be encountered, the power supply must be



NOTE: LOWER SLOPE GIVES A GREATER CHANGE IN WELDING CURRENT FOR A GIVEN CHANGE IN ARC VOLTAGE.

Figure S-7—The Effect of Volt-Ampere Curve Slope on Current Output with a Change in Arc Voltage capable of providing the amperage range needed. The duty cycle must be adequate.

The positions in which welding will be done should also be considered. If vertical and overhead welding are planned, adjustment of the slope of the V-A curve probably will be desirable (*See* Figure S-7). If so, the power supply must provide this feature. This usually requires controls for both the output voltage and the current.

A supply of primary power is needed. If line power is available, it should be determined whether the power is single-phase or three-phase. The welding power source must be designed for either single- or three-phase power, and it must be used with the one it was designed for. If line power is not available, an engine-driven generator or alternator must be used.

Accessory Equipment

Electrode Holder. An electrode holder is a clamping device which allows the welder to hold and control the electrode, as shown in Figure S-8. It also serves as a device for conducting the welding current from the welding cable to the electrode. An insulated handle on the holder separates the welder's hand from the welding circuit. The current is transferred to the electrode through the jaws of the holder. To assure minimum contact resistance and to avoid overheating of the holder, the jaws must be kept in good condition. Overheating of the holder not only makes it uncomfortable for the welder, but also it can cause excessive voltage drop in the welding circuit. Both can impair the welder's performance and reduce the quality of the weld. The holder must grip the electrode securely and hold it in position with good electrical contact. Installation of the electrode must be quick and easy. The holder needs to be light in weight and easy to handle, yet it must be sturdy enough to withstand rough use. Most holders have insulating material around the jaws to prevent grounding of the jaws to the work. Electrode holders are produced in sizes to accommodate a range of standard electrode diameters. Each size of holder is designed to carry the current required for the largest diameter electrode that it will hold. The smallest size holder that can be used without overheating is the best one for the job. It will be the lightest, and it will provide the best operator comfort.

Workpiece Connection. A workpiece connection is a device for connecting the workpiece lead to the workpiece. It should produce a tight connection, yet be able to be attached quickly and easily to the work. For light duty, a spring-loaded clamp may be suitable. For high currents, however, a screw clamp may be needed to provide a good connection without overheating the clamp.

Figure S-8—Using the Shielded Metal Arc Process to Weld a Structure

Welding Cables. Welding cables are used to connect the electrode holder and the ground clamp to the power source. They are part of the welding circuit (*See* Figure S-5).The cable is constructed for maximum flexibility to permit easy manipulation, particularly of the electrode holder. It also must be wear and abrasion resistant. A welding cable consists of many fine copper or aluminum wires stranded together and enclosed in a flexible, insulating jacket. The jacket is made of synthetic rubber or of a plastic that has good toughness, high electrical resistance, and good heat resistance. A protective wrapping is placed between the stranded conductor wires and the insulating jacket to permit some movement between them and provide maximum flexibility. Welding cable is produced in a range of sizes from about AWG 6 to 4/0. The size of the cable required for a particular application depends on the maximum amperage to be used for welding, the length of the welding circuit (welding and work cables combined), and the duty cycle of the welding machine. Table C-1 shows the recommended size of copper welding cable for various welding currents and circuit lengths. When aluminum cable is used, it should be two AWG (American Wire Gauge) sizes larger than copper cable for the application. Cable sizes are increased as the length of the welding circuit increases to keep the voltage drop and the attendant power loss in the cable at acceptable levels.

If long cables are necessary, short sections can be joined by suitable cable connectors. The connectors must provide good electrical contact with low resistance, and their insulation must be equivalent to that of the cable. Lugs, at the end of each cable, are used to connect the cables to the power source. The connection between the cable and a connector or lug must be tight with low electrical resistance. Soldered joints and mechanical connections are used. Aluminum cable requires a good mechanical connection to avoid overheating. Oxidation of the aluminum significantly increases the electrical resistance of the connection. This of course, can lead to overheating, excessive power loss, and cable failure. Care must be taken to avoid damage to the jacket of the cable, particularly for the electrode cable. Contact with hot metal or sharp edges may penetrate the jacket and ground the cable.

Helmet. The purpose of the helmet is to protect the welder's eyes, face, forehead, neck, and ears from the direct rays of the arc and from flying sparks and spatter. Some helmets have an optional "flip lid" which permits the dark filter plate over the opening in the shield to be flipped up so the welder can see while the slag is being chipped from the weld. This protects the welder's face and eyes from flying slag. Slag can cause serious injury if it strikes a person, particularly while it is hot. It can be harmful to the eyes whether it is hot or cold.

Helmets are generally constructed of pressed fiber or fiberglass insulating material. A helmet should be light in weight and should be designed to give the welder the greatest possible comfort.

Miscellaneous Equipment. Cleanliness is important in welding. The surfaces of the workpieces and the previously deposited weld metal must be cleaned of dirt, slag, and any other foreign matter that would interfere with welding. To accomplish this, the welder should have a steel wire brush, a hammer, a chisel, and a chipping hammer. These tools are used to remove dirt and rust from the base metal, cut tack welds, and chip slag from the weld bead.

The joint to be welded may require backing to support the molten weld pool during deposition of the first layer of weld metal. Backing strips or nonmetallic backing materials are sometimes used, particularly for joints which are accessible from only one side.

Materials

Base Metals. The SMAW process is used in joining and surfacing applications on a variety of base metals. The suitability of the process for any specific base metal depends on the availability of a covered electrode whose weld metal has the required composition and properties. Electrodes are available for the following base metals:

(1) Carbon steels
(2) Low-alloy steels
(3) Corrosion-resisting steels
(4) Cast irons (ductile and gray)
(5) Aluminum and aluminum alloys
(6) Copper and copper alloys
(7) Nickel and nickel alloys

Electrodes are available for application of wear, impact, or corrosion resistant surfaces to these same base metals.

Covered Electrodes

Covered electrodes are classified according to the requirements of specifications issued by the American Welding Society (AWS). Certain agencies of the Department of Defense also issue specifications for covered electrodes. The AWS specification numbers and their electrode classifications are shown in Table S-1. The electrodes are classified on the basis of their chemical composition or mechanical properties, or both, of their undiluted weld metal. Carbon steel, low-alloy steel, and stainless steel electrodes are also classified according to the type of welding current they are suited for and sometimes according to the positions of welding that they can be used. *See* ELECTRODE CLASSIFICATION. *See also* Appendix 17.

Electrode Conditioning

SMAW electrode coverings are hygroscopic (they readily absorb and retain moisture). Some coverings are more hygroscopic than others. The moisture they pick up on exposure to a humid atmosphere dissociates to form hydrogen and oxygen during welding.

Table S-1
AWS Specifications for Covered Electrodes

AWS Specification	Type of Electrode
A5.1	Carbon steel
A5.5	Low alloy steel
A5.4	Corrosion resistant steel
A5.15	Cast iron
A5.3	Aluminum and aluminum alloys
A5.6	Copper and copper alloys
A5.11	Nickel and nickel alloys
A5.13 and A5.21	Surfacing

The atoms of hydrogen dissolve in the weld and the heat-affected zone and may cause cold cracking. This type of crack is more prevalent in hardenable steel base metals and high-strength steel weld metals. Excessive moisture in electrode coverings can cause porosity in the deposited weld metal.

To minimize moisture problems, particularly for low-hydrogen electrodes, they must be properly packaged, stored, and handled. Such control is critical for electrodes which are to be used to weld hardenable base metals. Control of moisture becomes increasingly important as the strength of the weld metal or the base metal increases. Holding ovens are used for low-hydrogen electrodes once those electrodes have been removed from their sealed container and have not been used within a certain period of time. This period varies from as little as half an hour to as much as eight hours, depending on the strength of the electrode, the humidity during exposure, and even the specific covering on the electrode. The time which an electrode can be kept out of an oven or rod warmer is reduced as the humidity increases.

The temperature of the holding oven should be within the range of 65 to 150°C (150 to 300°F). Electrodes that have been exposed too long require baking at a substantially higher temperature to drive off the absorbed moisture. The specific recommendations of the manufacturer of the electrode need to be followed because the time and temperature limitations can vary from manufacturer to manufacturer, even for electrodes within a given classification. Excessive heating can damage the covering on an electrode.

Applications

Shielded metal arc welding is the most widely used of the arc welding processes.

Materials. The SMAW process can be used to join most of the common metals and alloys. The list includes carbon steels, low-alloy steels, stainless steels, and cast iron, as well as copper, nickel, and aluminum and their alloys. Shielded metal arc welding is also used to join a wide range of chemically dissimilar materials.

The process is not used for materials for which shielding of the arc by the gaseous products of an electrode covering is unsatisfactory. The reactive (Ti, Zr) and refractory (Cb, Ta, Mo) metals fall into this group.

Thicknesses. The shielded metal arc process is adaptable to any material thickness within certain practical and economic limitations. For material thicknesses less than about 1.6 mm (1/16 in.), the base metal will melt through and the molten metal will fall away before a common weld pool can be established, unless special fixturing and welding procedures are employed. There is no upper limit on thickness, but other processes such as submerged arc welding (SAW) or flux cored arc welding (FCAW) are capable of providing higher deposition rates and economies for most applications involving thicknesses exceeding 38 mm (1-1/2 in.). Most of the SMAW applications are on thicknesses between 3 and 38 mm (1/8 and 1-1/2 in.), except where irregular configurations are encountered. Such configurations put an automated welding process at an economic disadvantage. In such instances, the shielded metal arc process is commonly used to weld materials as thick as 250 mm (10 in.).

Welding Position

One of the major advantages of SMAW is that welding can be done in any position on most of the materials for which the process is suitable. This makes the process useful on joints that cannot be placed in the flat position. Despite this advantage, welding should be done in the flat position whenever practical because less skill is required, and larger electrodes with correspondingly higher deposition rates can be used. Welds in the vertical and overhead positions require more skill on the welder's part and are performed using smaller diameter electrodes. Joint designs for vertical and overhead welding may be different from those suitable for flat position welding.

Location of Welding

The simplicity of the equipment makes SMAW an extremely versatile process with respect to the location and environment of the operation. Welding can be done indoors or outdoors, on a production line, a ship, a bridge, a building framework, an oil refinery, a cross-country pipeline, or any such type of work. No gas or water hoses are needed and the welding cables can be extended quite some distance from the power source. In remote areas, gasoline or diesel powered units can be used. Despite this versatility, the process should always be used in an environment which shelters it from the wind, rain, and snow.

Weld Backing

When full penetration welds are required and welding is done from one side of the joint, weld backing may be required. Its purpose is to provide something on which to deposit the first layer of metal and thereby prevent the molten metal in that layer from escaping through the root of the joint.

Four types of backing are commonly used:

(1) Backing strip
(2) Backing weld
(3) Copper backing bar
(4) Nonmetallic backing

Backing Strip. A backing strip is a strip of metal placed on the back of the joint, as shown in Figure S-9 (A). The first weld pass ties both members of the joint together and to the backing strip. The strip may be left in place if it will not interfere with the serviceability of the joint. Otherwise, it should be removed, in which case the back side of the joint must be accessible. If the back side is not accessible, some other means of obtaining a proper root pass must be used.

The backing strip must always be made of a material that is metallurgically compatible with the base metal and the welding electrode to be used. Where design permits, another member of the structure may serve as backing for the weld. Figure S-9 (B) provides an example of this. In all cases, it is important that the backing strip as well as the surfaces of the joint be clean to avoid porosity and slag inclusions in the weld. It is also important that the backing strip fit properly. Otherwise, the molten weld metal can run out through any gap between the strip and the base metal at the root of the joint.

Copper Backing Bar. A copper bar is sometimes used as a means of supporting the molten weld pool at the root of the joint. Copper is used because of its high thermal conductivity. This high conductivity helps prevent the weld metal from fusing to the backing bar. Despite this, the copper bar must have sufficient mass to avoid melting during deposition of the first weld pass. In high production use, water can be passed through holes in the bar to remove the heat that accumulates during continuous welding. Regardless of the method of cooling, the arc should not be allowed to impinge on the copper bar, for if any copper melts, the weld metal can become contaminated with copper. The copper bar may be grooved to provide the desired root surface contour and reinforcement.

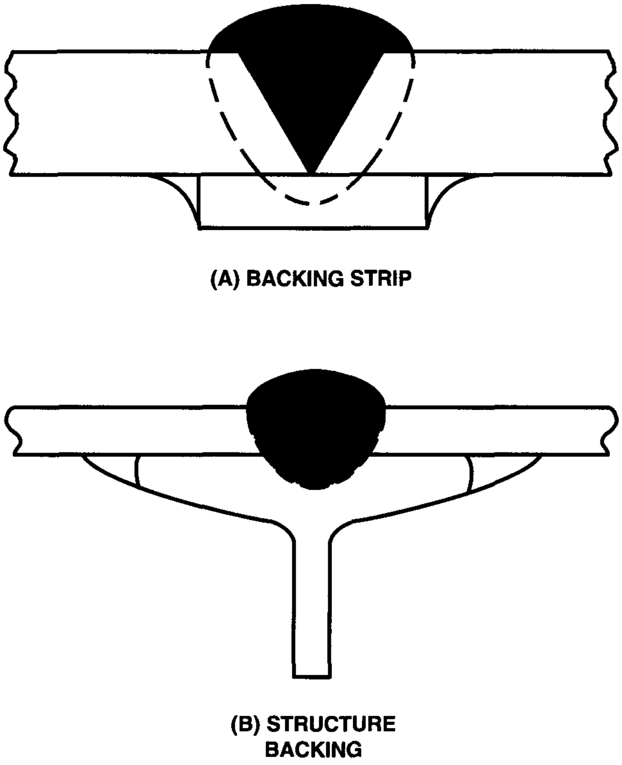


Figure S-9—Fusible Metal Backing for a Weld

Nonmetallic Backing. Nonmetallic backing of either granular flux or refractory material is also a method that is used to produce a sound first pass. The flux is used primarily to support the weld metal and to shape the root surface. A granular flux layer is supported against the back side of the weld by some method such as a pressurized fire hose. A system of this type is generally used for production line work, and it is not widely used for SMAW.

Refractory type backing consists of a flexible, shaped form that is held on the back side of the joint by clamps or by pressure-sensitive tape. This type of backing is sometimes used with the SMAW process, although special welding techniques are required to consistently produce good results. The recommendations of the manufacturer of the backing should be followed.

Backing Weld. A backing weld is one or more backing passes in a single groove weld joint. This weld is deposited on the back side of the joint before the first pass is deposited on the face side. The concept is illustrated in Figure S-10. After the backing weld, all subsequent passes are made in the groove from the face side. The root of the joint may be ground or gouged after the backing weld is made to produce sound, clean metal on which to deposit the first pass on the face side of the joint.

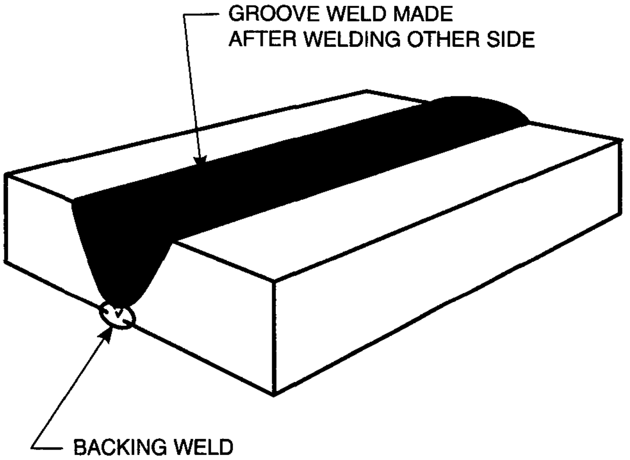


Figure S-10—A Typical Backing Weld

Safety Recommendations

The operator must protect eyes and skin from radiation from the arc. A welding helmet with a suitable filter lens should be used, as well as dark clothing, preferably wool, to protect the skin. Leather gloves and clothing should be worn to protect against burns from arc spatter.

Welding helmets are provided with filter plate windows, the standard size being 51 by 130 mm (2 by 4-1/8 in.). Larger openings are available. The filter plate should be capable of absorbing infrared rays, ultraviolet rays, and most of the visible rays emanating from the arc. Filter plates that are now available absorb 99% or more of the infrared and ultraviolet rays from the arc.

The shade of the filter plate suggested for use with electrodes up to 4 mm (5/32 in.) diameter is No. 10. For 4.8 to 6.4 mm (3/16 to 1/4 in.) electrodes, Shade No. 12 should be used. Shade No. 14 should be used for electrodes over 6.4 mm (1/4 in.).

The filter plate needs to be protected from molten spatter and from breakage. This is done by placing a plate of clear glass, or other suitable material, on each side of the filter plate. Those who are not welders but work near the arc also need to be protected. This protection usually is provided by either permanent or portable screens. Failure to use adequate protection can result in eye burn for the welder or for those working around the arc. Eye burn, which is similar to sunburn, is extremely painful for a period of 24 to 48 hours. Unprotected skin, exposed to the arc, may also be burned. A physician should be consulted in the case of severe arc burn, regardless of whether it is of the skin or the eyes.

If welding is being performed in confined spaces with poor ventilation, auxiliary air should be supplied to the welder. This should be done through an attachment to the helmet.

The method used must not restrict the welder's manipulation of the helmet, interfere with the field of vision, or make welding difficult. Additional information on eye protection and ventilation is given in ANSI Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society.

From time to time during welding, sparks or globules of molten metal are thrown out from the arc.This is always a point of concern, but it becomes more serious when welding is performed out of position or when extremely high welding currents are used. To ensure protection from burns under these conditions, the welder should wear flame-resistant gloves, a protective apron, and a jacket (*See* Figure S-8). It may also be desirable to protect the welder's ankles and feet from slag and spatter. Cuffless pants and high work shoes or boots are recommended.

To avoid electric shock, the operator should not weld while standing on a wet surface. Equipment should be examined periodically to make sure there are no cracks or worn spots on electrode holder or cable insulation.

SHIELDING GAS

Protective gas used to prevent or reduce atmospheric contamination of a weld, especially by oxygen and nitrogen. See STANDARD WELDING TERMS. *See also* PROTECTIVE ATMOSPHERE.

The arc is said to be shielded when the metal from the electrode, as it passes through the arc, is protected from contact with the oxygen and nitrogen of the air. With a shielded metal arc electrode, the shielding is usually accomplished by using a heavily coated electrode. The coating, in some instances, produces carbon monoxide and hydrogen as it burns, and also forms a crucible, or hollow shell, extending beyond the end of the electrode. A slag is also formed over the molten metal, protecting it from the air and slowing down the rate of cooling. By this means, varying in detail with different electrodes, the air surrounding the arc is deoxidized and the metal is protected, or shielded, from the oxygen and nitrogen which would otherwise be present. The result is greater tensile strength and ductility of the weld metal.

The primary function of a shielding gas is to exclude the atmosphere from contact with the molten weld metal. This is necessary because most metals, when heated to their melting point in air, exhibit a strong tendency to form oxides, and to a lesser extent, nitrides. Oxygen will also react with carbon in molten steel to form carbon monoxide and carbon dioxide. The various products of these reactions may result in weld deficiencies, such as trapped slag, porosity, and weld metal embrittlement. Reaction products are easily formed by exposure to the atmosphere unless precautions are taken to exclude nitrogen and oxygen.

In addition to providing a protective environment, the shield gas and flow rate also have a pronounced effect on the following:

(1) Arc characteristics
(2) Mode of metal transfer
(3) Penetration and weld bead profile
(4) Speed of welding
(5) Undercutting tendency
(6) Cleaning action
(7) Weld metal mechanical properties

Shielded Metal Arc Welding (SMAW). In SMAW, gas shielding is achieved by using covered electrodes with certain organic products in the electrode coating material. This material decomposes at arc temperature to produce an atmosphere consisting mainly of carbon dioxide (CO_2) and carbon monoxide (CO), with or without small amounts of hydrogen. These gases, while primarily shielding, also contribute to the stabilization of the arc and the general improvement of the arc characteristics.

Generally, the shielding gases developed by electrode coatings are most effective when welding ferrous materials, but they are also useful for some of the hard-to-weld materials, such as aluminum- and copper-base alloys. Specific fluxes are used with these electrodes to form fusible metal oxide slags which do not interfere with the welding operation.

Oxyfuel Gas Welding. Shielding gases in one form or another have always been utilized as a means of preventing contact of the surrounding air with the molten weld metal during a welding operation. In oxyhydrogen or oxyacetylene welding, the shielding gas is inherent and usually consists of a mixture of several gaseous products of combustion, such as hydrogen, water vapor, carbon monoxide, and carbon dioxide. Though these gases are chemically active at welding temperatures, the overall effect of the shielding gas mixture can be oxidizing, neutralizing, or reducing, as needed, by adjusting the oxyfuel-gas ratio. This makes it is possible to weld a variety of materials with the oxyfuel gas flame.

Historical Background

The fact that argon and helium would make ideal shielding gases for all types of welding operations had been known for many years. However, the problem of introducing these gases into the welding area, as well as the problem of high cost, precluded their use. In the early development of gas tungsten arc welding (GTAW), argon or helium, or a mixture of the two, were used. Not only did these inert gases provide protective atmospheres for all materials, but they also provided protection for the nonconsumable tungsten electrode.

With the development of the gas metal arc welding (GMAW) process, it became evident that the composition of the inert shielding gases could be tailored to specific applications by adding small amounts of an active gas, such as oxygen or carbon dioxide, to argon or helium. Later refinements, particularly in the area of welding steel, made it possible to use carbon dioxide or carbon dioxide-argon mixtures for effective shielding. Formerly called Mig welding, the term *gas metal arc welding* evolved because it is a more accurate description of the gases used in the process. *See* ARGON, HELIUM, *and* CARBON DIOXIDE.

SHIP WELDING

Several welding processes are required for the varied and specialized requirements of ship construction. Present day ships are larger and are designed for welding, with consideration given to vessel weight, welding processes, practices and procedures, and shipyard facilities. Hull designs of tankers have changed to provide increased protection against accidental oil spills after collisions with reefs, rocks or other ships.

The Oil Pollution Act of 1990 mandated double hulls by the year 2010 on all tankers entering United

States waters. As a result, the shipbuilding industry is investigating procedures to manufacture ships with double hulls. One approach employs curved hull plating and the electrogas welding (EGW) process.

Welding Processes. Ingenious modifications of the shielded metal arc welding process have been adopted in shipyards to improve productivity and to reduce the schedule times. The use of a sliding tripod to feed the electrode along the joint, after arc initiation, permits one welder to operate as many as six large-diameter welding electrodes simultaneously. This version, commonly called *gravity welding,* is used in many yards in the world. A less frequently used variation is a method called *firecracker welding*, which requires the electrode to be placed on the workpiece along the joint. Once the arc is established, the weld proceeds down the length of the electrode until the filler material is consumed. Both of these processes are effectively limited to the horizontal fillet weld position.

To aid in achieving higher deposition rates, the submerged arc welding (SAW) process was developed for the shipbuilding industry. Many of the deck plates and hull plates are flat and have long butt joint connections. Because of the size of the plates, much work is performed outdoors. The submerged arc process is ideal for the combination of these conditions. Portable self-propelled tractors that can carry the welding flux, a spool of welding electrode and the process control unit have been designed to implement the process in both the shop and field.

Multiple electrode SAW systems can provide very high deposition rates for the joining of thick plate assemblies. A unique arrangement of the electrical connections for "series arc" SAW produces a weld deposit that is effectively used for one-side butt welding of the plates. The need to turn the very large plate assemblies is eliminated, because there is no second-side welding required. This provides shipbuilders with a very effective method of fabrication for the most fundamental form of ship design, the construction of the deck and shell plate blankets.

Electrogas (EGW) and electroslag (ESW) welding have been used to join many ships having long vertical butt joints in the hull design. These processes make the vertical connections automatically, and the deposition rates for these processes are high. With the incorporation of higher strength steels in ship designs, these methods are not as popular because the high heat input inherent in the weld zone can have an adverse effect on the heat-affected zone properties. Also, with higher strength steels, the plates do not have to be as thick, again limiting the application for electrogas and electroslag welding. Figure S-11 shows the completion of a 3 m (10 ft) high vertical electrogas weld in a 16 mm (5/8 in.) thick steel barge hull.

Figure S-11—Electrogas Welding of a Vertical Hull Joint

Flux cored arc welding (FCAW) has become the most popular welding method for shipbuilding applications. Even though shipbuilders attempt to utilize the flat position or horizontal fillet weld position as much as possible, a high percentage of the welding required in ship construction must be done in the vertical, horizontal and overhead positions. The development of small-diameter flux cored welding electrodes with excellent mechanical properties has accelerated the use of this process in shipyards around the world.

Gas metal arc welding (GMAW) is also used for ship construction. Although not as common in the United States as elsewhere in the world, gas metal arc welding is used for hull and superstructure construction. The flexibility of the process permits high deposition rates using spray transfer in the flat and horizontal fillet positions while also having a pulsing transfer available for out-of-position work. Figure S-12 shows the GMAW process being used to weld a section of aluminum superstructure.

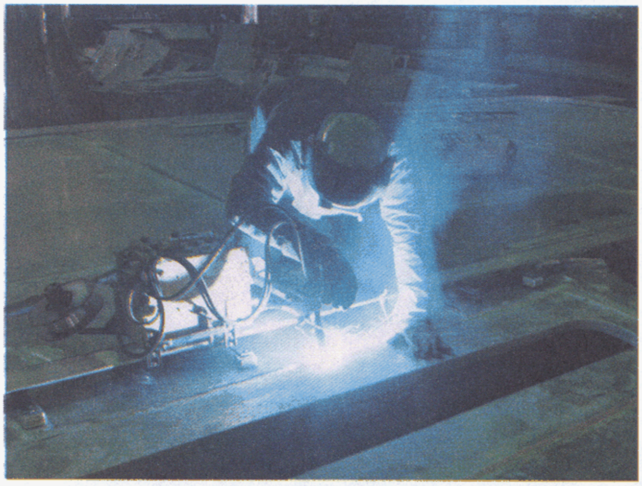


Figure S-12—Mechanized Gas Metal Arc Welding Aluminum Superstructure in a Shipyard

Photo courtesy of Ingalls Shipbuilding

In addition to the hull structure, ships require extensive use of piping and ventilation ducting to operate properly at sea. A common process for these applications is gas tungsten arc welding (GTAW). The precise control of the welding arc is ideally suited for many of the pipe and duct joints. To enhance the productivity of the outfitting shops, automated systems are commonly used for welding these components.

An innovation in shipbuilding technology is the use of welding robots. Robotic arc welding has been used in limited applications, however, with further developments in the software systems and hardware configurations, the number of robots being used in shipbuilding increases annually. The most common application for an arc welding robot is the joining of two structures using fillet welds. While some robots are portable enough to be placed on the assembly for access to the weld path, robots can be installed in the inverted position on movable gantries which span the assembly, permitting access using the arm reach of the robot and the positioning capability of the gantry.

Materials. The principle material used for shipbuilding is low-carbon steel. Many other materials are used for hull and structural components, including high-strength steel and high-strength, low-alloy steel, quenched and tempered steel, and aluminum. Other materials such as carbon steel, austenitic stainless steel, copper alloys, nickel alloys and titanium are used for the service distribution systems. The assortment of materials that may be used in a ship design results in many challenges for the correct selection of filler materials and welding processes.

Operating Systems. A ship is much like a moving city. Each ship requires installation of equipment for propulsion, water and electrical distribution, waste disposal, food preparation and the many other aspects of services required for the operation of the ship and the life of the crew. The equipment is manufactured from many welded components. Because of this variety of systems, shipbuilding requires the implementation of welding for structural, piping, pressure vessels and sheet metal applications.Considering also the diversity of materials that are incorporated in the designs of ships for strength, corrosion resistance, weight and fatigue life purposes makes ships an extraordinary welded product. Figure S-13 shows an Arleigh Burke class Aegis destroyer being fitted out.

Historical Background

Welding has been an important fabrication process for shipbuilding since World War I. It was during this era that the value of welding for the repair and construction of ships was recognized. It was essential for the war effort to transport troops and supplies by sea, and the demand for ships became critical. The use of welding made it possible to provide the ships required by the United States to effectively support the battle fronts in Europe. The government established a committee to investigate the accelerated use of electric arc welding in shipbuilding to support the national defense. It was from the formation of this body that the American Welding Society was created in 1919.

As welding came into use in shipbuilding, its first application was to barges. The hull of the barge is a simple box structure in which the stresses are easily calculable. This is not the case with ships in ocean service, such as cargo vessels and tankers. They are subject to high stresses due to wind and wave action, as well as to possible stresses caused by cargo weight dis-

Figure S-13—Fitting Out an Arleigh Burke Class Aegis Destroyer in a Shipyard

Photo courtesy of Ingalls Shipbuilding

tribution. The challenges encountered in the design of floating structures are very different from those facing the designers of bridges, buildings or other land structures. Weld joint designs also must meet the requirements of this rigorous service life.

Submarines were welded in 1918 and 1919, and in the 1920s, welding was used to build the tanker, the *Poughkeepsie Socony.* It was 77 m × 12 m × 4.3 m (252 ft × 40 ft × 14 ft), with a gross weight of 882 metric tons (1235 tons).

Although there have been many claims about the "first" all-welded ship, it is known that welding was used in constructing many ships during the first thirty years of the twentieth century. These early ships were both welded and riveted, as the industry was in transition between these methods of joining the steel hulls and decks. It was not until the late 1930s that a large ship was designed to be completely welded, using butt welded joints to connect the hull plating. Prior to that time, ship designs relied on lap welded plates that may or may not have required rivets.

Developments in the coating systems for shielded metal arc welding electrodes expanded the use of welding for ship applications. As the welding characteristics of electrodes were improved, arc welding was introduced to additional shipbuilders. Due to the size of the structures, it was necessary that the electrodes be used in all positions. In addition to having acceptable operating characteristics in the various welding positions, the introduction of iron powder to the coatings increased the deposition rate for the welding process. Since welding represents one of the largest proportions of skilled trade man-hours in ship construction, increases in the deposition rates of a process can have a significant effect on the selection of the welding methods.

Tankers. In the 1940s, Sun Shipbuilding Company built the *W. I. Van Dyck,* then the world's largest ocean-going tanker. It was 159 m (521 ft) long and 12 m (40 ft) high, with a beam of 21 m (70 ft), and a gross weight of 10 590 metric tons (11 650 tons). The building of this tanker constituted a landmark in shipbuilding, not only because of the size of a ship to which welding was applied, but also because this craft represented the first large-scale use of automatic welding in shipyard work.

In 1973, two supertankers rated at 476 025 DWT were built. These super tankers, the *Globtik Tokyo* and the *Globtik London,* are two-and-a-half times the length of the *Van Dyck,* three times as wide, and six times as high; the dimensions are 379.2 m (1244 ft) in length, 75.0 m (246 ft) high, with a beam of 62.2 m (204 ft). The cargo tanks hold 153 million gallons of crude oil, or more than three million barrels. These ships, like all of the super-tankers and most modern ocean-going vessels, are of all-welded construction.

SHORE SCLEROSCOPE HARDNESS

See HARDNESS TESTING.

SHOT BLASTING

A cleaning operation similar to sandblasting, except steel shot or grit is used instead of sand.

SHORT ARC

A nonstandard term when used for SHORT CIRCUIT GAS METAL ARC WELDING (GMAW-S) or SHORT CIRCUITING TRANSFER.

SHORT CIRCUIT GAS METAL ARC WELDING (GMAW-S)

A gas metal arc welding process variation in which the consumable electrode is deposited during repeated short circuits. See STANDARD WELDING TERMS.

A short circuiting arc is a method of metal transfer in gas metal arc welding (GMAW). This process is sometimes referred to as *short arc* or *dip transfer.* It can be used with most metals, providing the welding wire, which is a consumable electrode, has a good burn off characteristic, and the correct shielding gas and welding machine are used.

Short circuiting GMAW has gained wide acceptance in industry for welding thin materials in all positions, and some heavier gauges in the vertical and overhead positions. It has proven useful for applications that require welding large gaps.

Short circuiting metal transfer is most widely used in welding carbon steels and low-alloy steels. Stainless steels and light gauge aluminum are also being welded with this process, but to a lesser degree. Short circuiting metal transfer is done at low currents, generally from 50 to 225 amperes, and low voltage, 12 to 22 volts, using small diameter wires, usually with 0.8, 0.9 and 1.1 mm (0.030, 0.035, and 0.045 in.) diameters.

The outstanding characteristic of the short circuiting arc is the frequent shorting of the wire to the workpiece. All metal transfer takes place when the arc is extinguished. This happens at a steady rate from 20 to over 200 times a second. This results in a very stable arc of low energy and heat input. The low heat input minimizes distortion and metallurgical effects.

The arc voltage and arc current patterns during a typical short circuiting welding cycle are traced by means of an oscillograph; an example is shown in Figure S-14. Each short circuit should produce a definite controlled current surge sufficient to recreate the arc without an undesirable high surge or blast. The complete fusion cycle associated with short circuit metal transfer, followed by the reestablishment of the arc is pictured in the bottom portion of Figure S-14. The shorting action is shown in steps A through D. In E the pinch effect has been completed, and the arc is reignited to start the cycle over, as shown in E through H. At I, the short circuit is again extinguishing the arc, then the steps are repeated. The cycle is a complete round of events from one short circuit until the wire is again shorted by touching the weld puddle.

Special machines of the constant potential type are used for this welding method. They have appropriate induction or voltage-ampere slope control, or both, for producing the specific current surges needed to implement short circuit metal transfer for its full range of most metals.

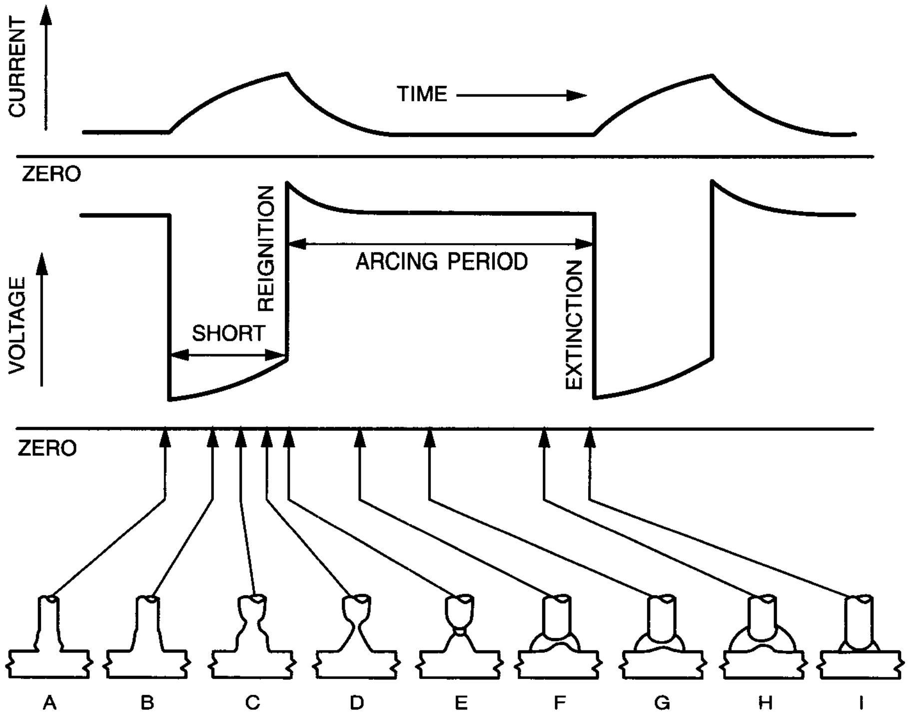


Figure S-14—Schematic Representation of Short Circuiting Metal Transfer

Equipment. Short circuit metal transfer can be accomplished on basic GMAW equipment. The wire feed system should be of a constant speed design, using either a mechanical or an electronic governor. A wire feed range of 12 to 340 mm/s (50 to 800 in/min) will make it adequate for nearly all applications.

The welding machine should be a direct-current type designed for short circuiting metal transfer, usually with a 200- or 300-ampere capacity.

The GMAW torch may be either air cooled or water cooled, with a straight or curved nozzle. The curved nozzle is the most popular design for welding in the short circuiting metal transfer mode.

Shielding Gases. Many of the shielding gases react favorably with short circuiting metal transfer.Pure argon and helium, or mixtures of both, are used on thin aluminum. For carbon and low-alloy steels, the gases generally used are carbon dioxide, or mixtures of argon and carbon dioxide, or argon and oxygen.

Shielding gas flow rates range from 7 to 12 L/min (15 to 25 cfh). This is less than required for spray arc welding, because a much smaller weld puddle is involved. *See also* FINE WIRE WELDING *and* DIP TRANSFER.

SHORT CIRCUITING ARC WELDING

A nonstandard term for SHORT CIRCUIT GAS METAL ARC WELDING.

SHORT CIRCUITING TRANSFER, Arc Welding

Metal transfer in which molten metal from a consumable electrode is deposited during repeated short circuits. See STANDARD WELDING TERMS. *See* Figure S-14. *See also* GLOBULAR TRANSFER *and* SPRAY TRANSFER.

SHOULDER

A nonstandard term when used for ROOT FACE.

SHRINKAGE

Shrinkage refers to a reduction in any of the dimensions of a material caused by contraction during cooling as the result of the material's coefficient of thermal expansion (or contraction), or a reduction in specific volume as the result of a change to a more dense phase on cooling (e.g., solid formed from liquid). *See* DISTORTION.

SHRINKAGE STRESS

A nonstandard term when used for RESIDUAL STRESS.

SHRINKAGE VOID

A cavity-type discontinuity normally formed by shrinkage during solidification. See STANDARD WELDING TERMS.

SHUNT

A parallel electrical circuit; a by-pass circuit.

SIDE BEND TEST

A test in which the side of a transverse section of the weld is on the convex surface of a specified bend radius. See STANDARD WELDING TERMS. *See also* BEND TEST.

SIDEWALL

A nonstandard term when used for GROOVE FACE.

SIEVE ANALYSIS

A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size. See STANDARD WELDING TERMS.

In welding, sieve analysis is conducted on powdered or particulate materials; for example when these materials are added to electrode coatings or cores, or for particulate size specification for submerged arc welding flux.

SIGMA WELDING

An acronym for shielded inert gas metal arc welding, formerly used for metal inert gas (MIG) welding, now standardized as gas metal arc welding (GMAW).

SILENT ARC

A term used in atomic hydrogen welding to describe a short arc with a voltage in the range of 20 to 40 volts, which fails to produce the characteristic hissing sound of an arc. *See* ATOMIC HYDROGEN WELDING.

SILENT MELTING

A term applied to aluminum, magnesium or other materials which give no indication of melting until the metal suddenly becomes liquid. Silent-melting materials melt before attaining a red heat.

SILICON

(Chemical symbol: Si). A non-metallic element resembling graphite in appearance, used extensively in alloys. Silicon is not found free in nature but in combination with other elements and is probably more widely distributed in the solid matter of the earth than any other element except oxygen. Silicon is usually found in the oxide (silicate) form. Atomic weight, 28.06; melting point, 1410°C (2570°F); specific gravity, 2.42.

In a molten steel bath, silicon acts to promote fluidity by effecting a control over the oxygen content of the steel. High percentages of silicon are added to steel to reduce certain magnetic characteristics of steel when it is used in electrical and magnetic applications. Adding silicon tends to improve oxidation resistance and increase the hardenability of steels carrying non-graphitizing elements. Silicon also contributes to the strength of low-alloy steels. It increases hardenability and performs a valuable function as a deoxidizer, eliminating occluded gas.

SILICON BRONZE

A bronze or brass containing silicon, which gives it toughness and strength. *See* COPPER ALLOY WELDING.

SILICON CARBIDE

See GRINDING MATERIALS.

SILICON RECTIFIER

A silicon diode that changes alternating current to direct current. It is a two-element rectifier that has become the most widely used rectifier for welding power sources. A silicon rectifier performs the same basic function as selenium rectifiers; both materials are used as semiconductors.

The most commonly used silicon rectifiers, or diodes, are the 150-ampere diode with a 9.5 or 13 mm (3/8 or 1/2 in.) diameter stud, and the 275-ampere diode with a 19 mm (3/4 in.) diameter stud.

Silicon diodes are stacked into single-phase and three-phase bridge rectifiers in much the same manner as the selenium cells are used. Fewer silicon diodes, however, are required for a given rectifier amperage rating.

Silicon diodes must be carefully installed to insure that no strain is placed on the copper pigtail lead. A stress could be introduced into the structure of the diode assembly that could possibly fracture the silicon wafer.

Silicon diodes must be carefully matched for voltage and ampere characteristics when they are installed in a main power source. Diodes may be used in parallel to achieve ampere ratings of 1000 amperes or more. *See* SELENIUM RECTIFIER.

SILICON STEEL

An alloy steel with low hysteresis and eddy current loss, used in transformer cores. Also, a high grade of structural steel.

SILICOSIS

A respiratory condition or disease caused by inhalation of fine particles of silicon or silicon dioxide that may be contained in dust and in welding fumes. *See* WELDING FUMES.

SILVER

A pure white metallic element used as an alloy to enhance corrosion resistance. Native silver often has variable admixtures of other metals, such as gold, copper and sometimes platinum. Silver is used extensively in alloys used to make containers for the food and chemical industries, where other metals fail to withstand corrosion. Atomic weight, 107.88; specific gravity at 20°C (68°F), 10.5; melting point, 960°C (1760°F); Brinell hardness 37.

SILVER ALLOY BRAZING

A nonstandard term for brazing with a silver-base filler metal.

SILVER-BASE FILLER METAL BRAZING

Silver-base filler metals (AWS Classification BAg) are used extensively in brazing both ferrous and nonferrous metals and alloys, except aluminum and magnesium. This classification includes a range of silver based filler metal composition which may have various additions such as copper, zinc, cadmium, tin, manganese, nickel and lithium. Table S-2 lists chemical composition requirements for silver brazing filler metals.

Silver brazing alloys are generally used in those cases where strength and resistance to shock are required. Examples of silver brazing applications are joining band saws, shrouds, and lacing wire for turbine blades, and in the fabrication of equipment where appearance as well as strength is important. Silver brazing alloys usually contain varying percentages of silver, copper and zinc, and are often called *silver solders*. These compositions have melting points from 700 to 870°C (1300 to 1600°F), depending on the proportions of the different metals, or a range below that of base metal brazing alloys or copper welding rods, which require from 870 to 1090°C (1600 to 2000°F). Table S-3 lists the brazing temperature ranges for the various silver brazing filler metals.

Table S-2
Chemical Composition Requirements for Silver Filler Metals

AWS Classification	UNS Number[a]	Composition, Weight Percent Ag	Cu	Zn	Cd	Ni	Sn	Li	Mn	Other Elements, Total[b]
BAg-1	P07450	44.0–46.0	14.0–16.0	14.0–18.0	23.0–25.0	—	—	—	—	0.15
BAg-1a	P07500	49.0–51.0	14.5–16.5	14.5–18.5	17.0–19.0	—	—	—	—	0.15
BAg-2	P07350	34.0–36.0	25.0–27.0	19.0–23.0	17.0–19.0	—	—	—	—	0.15
BAg-2a	P07300	29.0–31.0	26.0–28.0	21.0–25.0	19.0–21.0	—	—	—	—	0.15
BAg-3	P07501	49.0–51.0	14.5–16.5	13.5–17.5	15.0–17.0	2.5–3.5	—	—	—	0.15
BAg-4	P07400	39.0–41.0	29.0–31.0	26.0–30.0	—	1.5–2.5	—	—	—	0.15
BAg-5	P07453	44.0–46.0	29.0–31.0	23.0–27.0	—	—	—	—	—	0.15
BAg-6	P07503	49.0–51.0	33.0–35.0	14.0–18.0	—	—	—	—	—	0.15
BAg-7	P07563	55.0–57.0	21.0–23.0	15.0–19.0	—	—	4.5–5.5	—	—	0.15
BAg-8	P07720	71.0–73.0	Remainder	—	—	—	—	—	—	0.15
BAg-8a	P07723	71.0–73.0	Remainder	—	—	—	—	0.25–0.50	—	0.15
BAg-9	P07650	64.0–66.0	19.0–21.0	13.0–17.0	—	—	—	—	—	0.15
BAg-10	P07700	69.0–71.0	19.0–21.0	8.0–12.0	—	—	—	—	0.15	
BAg-13	P07540	53.0–55.0	Remainder	4.0–6.0	—	0.5–1.5	—	—	—	0.15
BAg-13a	P07560	55.0–57.0	Remainder	—	—	1.5–2.5	—	—	—	0.15
BAg-18	P07600	59.0–61.0	Remainder	—	—	—	9.5–10.5	—	—	0.15
BAg-19	P07925	92.0–93.0	Remainder	—	—	—	—	0.15–0.30	—	0.15
BAg-20	P07301	29.0–31.0	37.0–39.0	30.0–34.0	—	—	—	—	—	0.15
BAg-21	P07630	62.0–64.0	27.5–29.5	—	—	2.0–3.0	5.0–7.0	—	—	0.15
BAg-22	P07490	48.0–50.0	15.0–17.0	21.0–25.0	—	4.0–5.0	—	—	7.0–8.0	0.15
BAg-23	P07850	84.0–86.0	—	—	—	—	—	—	Remainder	0.15
BAg-24	P07505	49.0–51.0	19.0–21.0	26.0–30.0	—	1.5–2.5	—	—	—	0.15
BAg-26	P07250	24.0–26.0	37.0–39.0	31.0–35.0	—	1.5–2.5	—	—	1.5–2.5	0.15
BAg-27	P07251	24.0–26.0	34.0–36.0	24.5–28.5	12.5–14.5	—	—	—	—	0.15
BAg-28	P07401	39.0–41.0	29.0–31.0	26.0–30.0	—	—	1.5–2.5	—	—	0.15
BAg-33	P07252	24.0–26.0	29.0–31.0	26.5–28.5	16.5–18.5	—	—	—	—	0.15
BAg-34	P07380	37.0–39.0	31.0–33.0	26.0–30.0	—	—	1.5–2.5	—	—	0.15

a. SAE/ASTM Unified Numbering System for Metals and Alloys.

b. The brazing filler metal shall be analyzed for those specific elements for which values are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total does not exceed the limit specified.

Selecting Silver Filler Metals

Silver, alloyed with copper in a proportion of 72% silver, 28% copper, forms a eutectic with a melting point of 780°C (435°F). This filler metal (BAg-8) can be used to furnace braze nonferrous base metals in a protective atmosphere. This alloy, however, does not easily wet ferrous metals. The addition of zinc lowers the melting temperature of the silver copper binary alloys and helps wet iron, cobalt, and nickel. Cadmium is also effective in lowering the brazing temperature of these alloys and assists in wetting a variety of base metals. Cadmium oxide present in brazing fume is poisonous, and cadmium-free filler metals should be utilized wherever possible. Tin can effectively reduce the brazing temperature, and is used to replace zinc or cadmium in filler metals. Nickel is added to assist in wetting tungsten carbides and provides greater corrosion resistance. Brazing alloys containing nickel are especially recommended for joining stainless steels because they reduce susceptibility to interfacial corrosion. Manganese is sometimes added to improve wetting on stainless steel, other nickel-chromium alloys,

Table S-3
Solidus, Liquidus, and Brazing Temperature Ranges for Silver Filler Metals*

AWS Classification	Solidus		Liquidus		Brazing Temperature Range	
	°C	°F	°C	°F	°C	°F
BAg-1	607	1125	618	1145	618–760	1145–1400
BAg-1a	627	1160	635	1175	635–760	1175–1400
BAg-2	607	1125	702	1295	702–843	1295–1550
BAg-2a	607	1125	710	1310	710–843	1310–1550
BAg-3	632	1170	688	1270	688–816	1270–1500
BAg-4	671	1240	779	1435	779–899	1435–1650
BAg-5	663	1225	743	1370	743–843	1370–1550
BAg-6	688	1270	774	1425	774–871	1425–1600
BAg-7	618	1145	652	1205	652–760	1205–1400
BAg-8	779	1435	779	1435	779–899	1435–1650
BAg-8a	766	1410	766	1410	766–871	1410–1600
BAg-9	671	1240	718	1325	718–843	1325–1550
BAg-10	691	1275	738	1360	738–843	1360–1550
BAg-13	718	1325	857	1575	857–968	1575–1775
BAg-13a	771	1420	893	1640	893–982	1600–1800
BAg-18	602	1115	718	1325	718–843	1325–1550
BAg-19	760	1400	891	1635	877–982	1610–1800
BAg-20	677	1250	766	1410	766–871	1410–1600
BAg-21	691	1275	802	1475	802–899	1475–1650
BAg-22	680	1260	699	1290	699–830	1290–1525
BAg-23	960	1760	970	1780	970–1038	1780–1900
BAg-24	660	1220	750	1305	750–843	1305–1550
BAg-26	705	1305	800	1475	800–870	1475–1600
BAg-27	605	1125	745	1375	745–860	1375–1575
BAg-28	649	1200	710	1310	710–843	1310–1550
BAg-33	607	1125	682	1260	682–760	1260–1400
BAg-34	649	1200	721	1330	721–843	1330–1550

*Solidus and liquidus shown are for the nominal composition in each classification

and cemented carbides. Lithium is effective in reducing oxides of refractory metals to promote filler metal wetting, and improve flow on stainless steels furnace brazed in protective atmospheres.

Flux is required when torch brazing with these filler metals in an oxidizing environment. Mineral fluxes conforming to AWS FB3A, or other classifications, in powder, paste, or slurry form are generally used. Vapor flux introduced through a torch flame also is suitable although filler metal capillary action may be limited with this type application. Vapor (gas) flux is normally used as a supplement to mineral flux types, to improve protection, wetting and flow.

Silver brazing filler metals are available in numerous forms including: wire, rod, pre-formed shapes, paste, powder, and strip. Several filler metals are available as a clad or "sandwich" strip with filler metal bonded to both sides of a copper core. This clad strip is popular in brazing carbide tool tips. The copper core absorbs stresses set up by differences in thermal expansion between the carbide and base metal, thus helping to prevent cracking.

BAg-1 brazing filler metal has the lowest brazing temperature range of the BAg filler metals. Because of this, it flows freely into tight capillary joints. Its narrow melting range is suitable for rapid or slow methods of heating. This filler metal also contains cadmium, and toxic fumes may be formed when it is heated. Precautions must be taken to assure proper ventilation of the brazing area to protect brazing personnel. BAg-1a brazing filler metal has properties similar to BAg-1. Either composition may be used where low-temperature, free-flowing filler metals are desired. This filler metal also contains cadmium, and fume hazards must be eliminated.

BAg-2 brazing filler metal, like BAg-1, is free-flowing and suited for general purpose work. Its broader melting range is helpful where clearances are wide or not uniform. Unless heating is rapid, care must be taken that the lower melting constituents do not separate by liquation. This filler metal contains cadmium and fumes are toxic. Refer to Appendix 13 for safety information on use of the product.

BAg-2a brazing filler metal is similar to BAg-2, but is more economical than BAg-2 since it contains 5% less silver. This filler metal contains cadmium, and fumes formed on heating are toxic. Refer to Appendix 13 for more information.

BAg-3 brazing filler metal is a modification of BAg-1a; i.e., nickel is added. It has good corrosion resistance in marine environments and caustic media and when used on stainless steel will inhibit crevice (interface) corrosion. Because its nickel content improves wettability on tungsten carbide tool tips, the largest use is to braze carbide tool assemblies. Melting range and low fluidity make BAg-3 suitable for forming larger fillets or filling wide clearances. This filler metal contains cadmium, and toxic fumes are formed when it is heated. Consult Appendix 13 for safety information.

BAg-4 brazing filler metal, like BAg-3, is used extensively for carbide tip brazing, but flows less freely than BAg-3. This filler metal does not contain cadmium.

BAg-5 and -6 brazing filler metals are frequently used for brazing in the electrical industry. They are also used, along with BAg-7 and -24, in the dairy and food industries where the use of cadmium-containing filler metals is prohibited. BAg-5 is an excellent filler metal for brazing brass parts (such as in ships piping, band instruments, or lamps. Since BAg-6 has a broad melting range and is not as free flowing as BAg-1 and -2, it is a better filler metal for filling wide joint clearances or forming large fillets.

BAg-7 brazing filler metal, a cadmium-free substitute for BAg-1, is low-melting with good flow and wetting properties. Typical applications include:

(1) Food equipment where cadmium must be avoided

(2) Minimizing stress corrosion cracking in nickel or nickel-base alloys at low brazing temperatures

(3) Improving color match where the site color will blend with the base metal

BAg-8 brazing filler metal is suitable for furnace brazing in a protective atmosphere without the use of a flux, as well as for brazing procedures requiring a flux. It is usually used on copper or copper alloys. When molten, BAg-8 is very fluid and may flow out over the workpiece surfaces during some furnace brazing applications. It can also be used on stainless steel, nickel-base alloys and carbon steel, although its wetting action on these metals is slow. Higher brazing temperatures will improve flow and wetting.

BAg-8a brazing filler metal is used for zinc in a protective atmosphere and is advantageous when brazing precipitation hardening and other stainless steels in the 760 to 870°C (1400 to 1600°F) range. The lithium content serves to promote wetting and to increase the flow of the filler metal on difficult-to-braze metals and alloys. Lithium is particularly helpful on base metals containing minor amounts of titanium and aluminum.

BAg-9 and -10 filler metals are used particularly for joining sterling silver. These filler metals have different brazing temperatures, and so can be used for step-brazing of successive joints. The color, after brazing, approximates the color of sterling silver.

BAg-13 brazing filler metal is used for service temperatures up to 370°C (700°F). Its low zinc content makes it suitable for furnace brazing.

BAg-13a brazing filler metal is similar to BAg-13, except that it contains no zinc, which is advantageous where volatilization is objectionable in furnace brazing.

BAg-18 brazing filler metal is similar to BAg-8 in its applications. Its tin content helps promote wetting on stainless steel, nickel-base alloys, and carbon steel. BAg-18 has a lower liquidus than BAg-8 and is used in step-brazing applications and where fluxless brazing is important.

BAg-19 brazing filler metal is used for the same applications as BAg-8a. BAg-19 is often used in higher brazing temperature applications where the precipitation hardening heat treatment and brazing are combined.

BAg-20 brazing filler metal possesses good wetting and flow characteristics and has a brazing temperature range higher than the popular Ag-Cu-Zn-Cd compositions. Due to its good brazing properties, freedom from cadmium, and a more economical silver content, new uses for this filler metal are being developed.

BAg-21 brazing filler metal is used in brazing AISI/300 and 400 series stainless steels, as well as the precipitation hardening nickel and steel alloys. BAg-21 is particularly suited to protective atmosphere furnace brazing because of the absence of zinc and cadmium. It does not require a flux for proper brazing unless the temperatures are low. It requires a rather high brazing temperature, and it flows in a sluggish manner. The nickel content makes it immune to crevice corrosion, particularly on the 400 series stainless steels, by imparting a nickel-rich layer along the fillet edge. It has been used for brazing stainless steel vanes of gas turbine aircraft engines.

BAg-22 is a low-temperature, cadmium-free filler metal with improved strength characteristics over BAg-3, particularly in brazing tungsten carbide tools.

BAg-23 is a high-temperature, free-flowing filler metal usable both for torch and protective atmosphere furnace brazing. This filler metal is mainly used in brazing stainless steel, nickel-base and cobalt-base alloys for high temperature applications. If this filler metal is used in a high-vacuum atmosphere, a loss of manganese will occur due to its high vapor pressure. Thus a partial pressure vacuum is desirable.

BAg-24 brazing filler metal is low-melting, free-flowing, cadmium-free, and suitable for use in joining low carbon 300 series stainless steels (particularly food handling equipment and hospital utensils), and small tungsten carbide inserts for cutting tools.

BAg-26 brazing filler metal is a low-silver cadmium-free material suitable for carbide and stainless steel brazing. The low brazing temperature and good flow characteristics make it well suited for moderate strength applications.

BAg-27 brazing filler metal is similar to BAg-2, but has lower silver and is somewhat more subject to liquation due to a wider melting range. This filler metal contains cadmium. Toxic fumes are formed on heating. Refer to Appendix 13 for safety information.

BAg-28 brazing filler metal has a lower brazing temperature with a relatively narrower melting range than other cadmium-free classifications with similar silver content. BAg-28 also has free-flowing characteristics.

BAg-33 brazing filler metal was developed to minimize brazing temperature for a filler metal containing 25% silver. It has a lower liquidus and, therefore, a narrower melting range than BAg-27. Its higher total zinc plus cadmium content may require more care during brazing. Refer to Appendix 13 for information about safety requirements when brazing with cadmium-bearing alloys.

BAg-34 brazing filler metal is a cadmium-free material with free-flowing characteristics. The brazing temperature range is similar to that of BAg-2 and BAg-2a, making it an ideal substitute for these filler metals.

The silver copper eutectic (BAg-8), which contains 72% silver and 28% copper, melts at 780°C (1435°F) and is used when zinc in the alloy would give trouble. Alloys containing silver, copper, manganese, and those with a further addition of nickel and silicon are used for similar purposes. Zinc or zinc and cadmium combined with relatively high percentages of silver provide a series of alloys that melt at temperatures between 700 and 760°C (1300 and 1400°F), have a white color, and are used in applications where copper would be objectionable. An alloy containing silver, copper, zinc and cadmium (BAg-1a), which flows freely at 635°C (1175°F) is used extensively for joining both ferrous and non-ferrous metals and alloys, because it makes strong joints.

Conductivity. Silver brazing alloys have a higher electrical conductivity than base metal brazing alloys, and therefore their use is particularly desirable for brazing parts of electrical apparatus where the highest conductivity is required. Zinc tends to lower the conductivity, and the silver copper eutectic previously mentioned has about 70% of the conductivity of copper.

Corrosion. Any of the standard silver brazing alloys are resistant to most of the common types of corrosion. When unusual conditions have to be met, it is desirable to make up specimens and subject them to the actual conditions of use in order to determine the best alloy. Galvanic corrosion is a problem, but since it is generally in proportion to the areas exposed to attack, a cathodic joining alloy would give the best result. Silver alloys with high percentages of silver are cathodic to many metals and alloys used to resist corrosive conditions, therefore they are satisfactory for use under such conditions. For example, these high-grade silver alloys are cathodic to nickel-copper alloys and stainless steel under many corrosive conditions for which these metals are used. They should not be used, however, for joining stainless steel when the joints are likely to be attacked by nitric acid.

The question of color match with different metals and alloys is often raised. Those silver brazing alloys with low percentages of silver are yellow and the color becomes whiter as the silver is increased. Alloys with high silver and without any copper are the whitest, but in a properly fitted joint, the band of brazing alloy which is visible is so narrow that any slight difference in color is generally a negligible factor.

Fitting, Cleaning, and Assembling

Silver brazing alloys flow freely into narrow openings, and clearances in the range of 0.05 to 0.10 mm (0.002 to 0.004 in.) should be maintained to produce the strongest joints. Figure S-15 illustrates the effect of joint clearance on strength. The surfaces of the joint should be clean, and free from all grease, dirt and oxide scale. Any film that prevents the wetting of the joint surfaces will keep a strong bond from being made. After all contaminants have been removed, the surface can be cleaned with emery cloth, washed with an appropriate cleaning solution, or pickled with a suitable solution to remove any scale or highly polished surface that has resulted from rolling or drawing. A slight roughening of highly polished surfaces by either mechanical or chemical means will assist in good bonding.

When joining flat members, either with lap or butt joints, it is desirable to grind or machine the surfaces of the joint so that they may be held parallel and equidistant to each other. If thin sheet inserts are used, the parts should be clamped together with enough pressure to hold them firmly together after the alloy has melted.

After the members have been properly cleaned and fitted, the joint surfaces should be protected with a film of flux. This flux must be fluid and chemically active at the melting point of the brazing alloy and should be spread over the entire surface. It is also advisable to protect the brazing alloy with flux when it is fed into the joint.

Borax, or combinations of borax and boric acid are used, but specially prepared fluxes that are fluid and active at lower temperatures are available, and are preferred for the lower melting point alloys. These proprietary fluxes are composed of chemicals that dissolve refractory oxides readily, and should be used when brazing stainless steels.

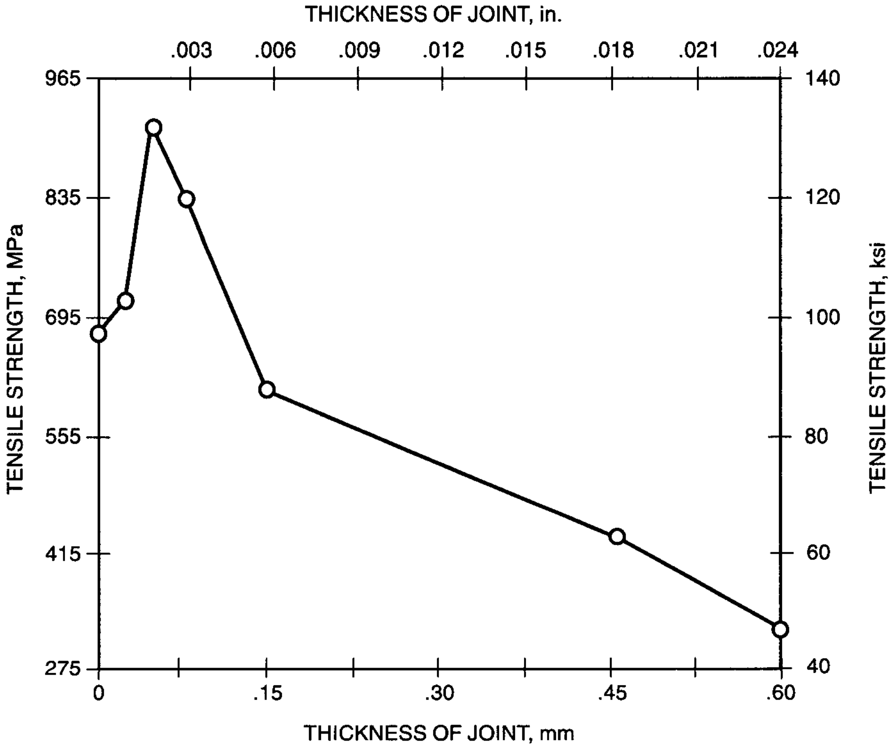


Figure S-15—Relationship of Tensile Strength to Joint Clearance for a Stainless Steel Joint Brazed with BAg-1a Filler Metal

Furnace Brazing. Furnace brazing is extensively used with silver-base filler metals. Either continuous or batch furnaces are used, and the heating may be supplied by gas or electricity. The atmosphere in the furnace is controlled to prevent oxidation by the use of various types of reducing or non-oxidizing gases.

A considerable amount of brazing is done with induction and resistance heating.

Dip Brazing. Dip brazing is another successful method of brazing. The metal bath form of dip brazing is principally used for dipping small parts like terminal wires. Salt bath brazing has been applied to different types of assemblies where the silver brazing alloy can be pre-placed, and the component parts jigged in a satisfactory manner.

Gas Brazing. Gas brazing includes all combinations of torch brazing, such as oxyacetylene, oxyhydrogen, oxygen and natural gas, and butane or propane; also air with these fuel gases. The air-gas and air-acetylene torches will produce satisfactory results with small parts, and the large torches or those with multiple flames may be used on fairly large workpieces.

In order to obtain the full benefit from these low-temperature silver brazing filler metals, the brazer should be trained to observe the rate at which different metals become heated to the brazing temperature, and to give particular attention to the relative mass of each of the members being brazed. Metals of high heat conductivity, such as copper, should be preheated some distance from the joint. If there is much difference in the size of the parts, then the one with largest cross section should be given the most heat.

Even though silver-base brazing filler metals are more expensive than soft solder, they are used for two reasons: (1) the demand of industry for better and quicker methods of joining and fabricating articles and equipment from sheet metal and tubing, and (2) the comparatively low melting points of these alloys, their free-flowing properties and the strength of joints made with them.

Applications

Electrical. Transformer leads and taps are brazed with silver alloys because of the low temperatures at which strong, shock-resistant joints of high conductivity can be made. Joints in bus bar installations of all kinds are made with these alloys because of the high strength, corrosion resistance, and elimination of voltage drop. Ground connections and cable joints are also made with this process.

In the manufacture of electric motors, end rings are bonded to rotor bars; and many small parts in the manufacture of electrical equipment are brazed with silver alloys. Lacing wires and shrouding are joined to turbine blades, and in certain types of turbines, the blades are silver-alloy brazed to packing pieces.

Refrigerators and Air Conditioning. One of the largest uses of silver brazing alloys is in the manufacture of refrigeration units, for both household and industrial plants. The low temperature at which they melt and the strong corrosion-resistant joints make them particularly desirable for joining the light metal sheets and tubing which are used in this industry.

Piping. Standard pipe and fittings up to 25 cm (10 in.) or more in diameter are joined with these alloys, and tests on joints show no failure in the pipe or fitting when the work is done properly. Special fittings are being made with rings of silver brazing alloy fitted into grooves cut in the fittings, and this type of joint has been specified for marine and navy piping, and piping in buildings.

Other Uses. Articles for home, such as cooking utensils, hot water tanks, water heaters, and metal furniture are brazed. Industrial equipment such as chemical equipment and containers, dairy equipment, and innumerable products in the electrical, automotive and aerospace industries are brazed with silver-base metal fillers. *See also* BRAZING, FURNACES, INDUCTION HEATING, *and* SALT BATH.

SILVER SOLDERING

A nonstandard term for brazing with a silver-base filler metal.

SINGLE-BEVEL EDGE SHAPE

A type of bevel edge shape having one prepared surface. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-BEVEL-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-FLARE-BEVEL-GROOVE WELD

A weld in a groove formed by a member with a curved surface in contact with a planar member. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-FLARE-V-GROOVE WELD

A weld in a groove formed by two members with curved surfaces. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-GROOVE WELD, Fusion Welding

A groove weld that is made from one side only. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE IMPULSE WELDING

A resistance welding process variation in which spot, projection, or upset welds are made with a single pulse. See STANDARD WELDING TERMS. *See* Figure H-6.

SINGLE-J EDGE SHAPE

A type of J-edge shape having one prepared surface. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-J-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-OPERATOR WELDING POWER SUPPLY

A motor generator, or transformer type welding power supply which will provide current for only one arc welding circuit at a time.

SINGLE PHASE

A generator or circuit in which only one alternating-current voltage is produced.

SINGLE-PORT NOZZLE

A constricting nozzle of the plasma arc torch that contains one orifice, located below and concentric with the electrode. See STANDARD WELDING TERMS.

SINGLE-SPLICED BUTT JOINT

See STANDARD WELDING TERMS. *See* Figure S-16. *See also* SPLICED JOINT.

SINGLE-SPLICED JOINT

See STANDARD WELDING TERMS. *See* Figure S-16. *See also* SPLICED JOINT.

SINGLE-SQUARE-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-U-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

SINGLE-V-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

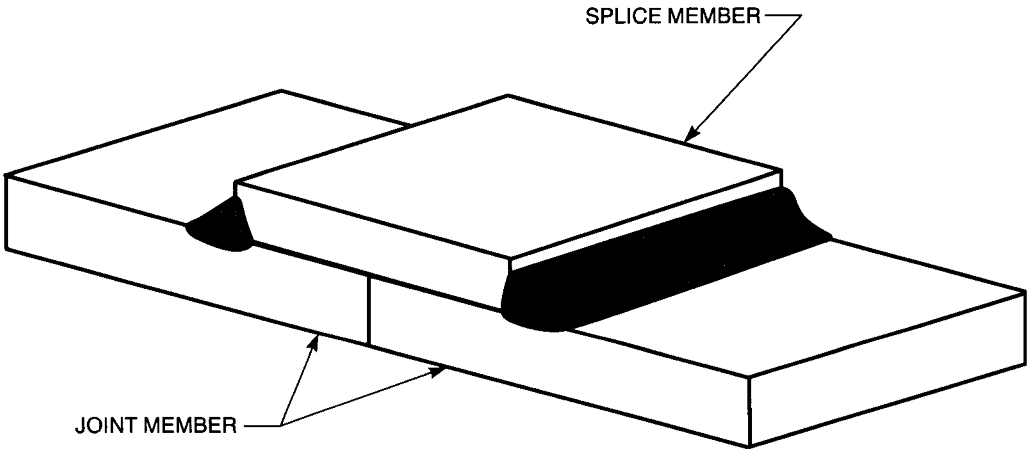


Figure S-16—Single-Spliced Butt Joint

SINGLE-WELDED JOINT, *Fusion Welding*

A joint that is welded from one side only. See STANDARD WELDING TERMS. *See* Appendix 6.

SINTERING

A process of compacting a mass of metallic (or ceramic) powder into solid form by heat, with or without pressure, and with or without melting. If intimate contact can be established by the particles, and if the temperature is sufficiently high, they will grow together even in the solid state; that is, there is an actual union and growth of grain structure by diffusion. This phenomenon makes it is possible to make solid blocks of metals with high melting points. Sintering is used extensively to join hard particles of tungsten and tantalum carbides for making tool bits, the cement being metallic cobalt.

The temperature used in sintering may be far below the normal melting point of the metal, and the joining occurs by the action of surface cohesive force of the solid particles and not by partial fusion.

Sintered metals are often porous, but can be made nearly 100% dense compared to the theoretical density of the solid if high pressures are used during solid-phase sintering, or if a liquid phase, even if transient, is formed. The porosity depends strongly on the screen analysis of the powder and the presence or absence of vibration during packing of the mold. The pressure used before or during sintering also affects porosity. Although they may be very hard, sintered masses are usually not very strong, that is, the usual hardness-tensile relationship associated with steel does not hold. *See* POWDER METALLURGY *and* FRITTING.

6F

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in flat, vertical, and overhead welding positions. The pipe remains fixed until welding is complete. See STANDARD WELDING TERMS. *See* Appendix 4.

6G

A welding test position designation for a circumferential groove weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. The pipe remains fixed until welding is complete. See STANDARD WELDING TERMS. *See* Appendix 4.

6GR

A welding test position designation for a circumferential groove weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. A restriction ring is added, adjacent to the joint, to restrict access to the weld. The pipe remains fixed until welding is complete. See STANDARD WELDING TERMS. *See* Appendix 4.

SIZE OF WELD

See STANDARD WELDING TERMS. *See also* WELD SIZE *and* Appendix 11.

SKATE WELDER

A lightweight, motorized travel carriage on which seam tracking equipment, a wire feed system and automatic head are mounted.

Straight or curved track sections are attached directly to the workpiece, either by suction cups or bolting. This permits movement of the welding carriage in a continuous path along the weld seam. The skate welder makes it possible to do precision welding on massive structures that cannot be handled on conventional rotating positioners and longitudinal seamers. Skate carriages can be operated in horizontal and vertical directions to make out-of-position welds.

SKIP CUTTING

A method of splitting narrow materials, such as flat bar stock and structural l-beams and channels to prevent warpage. In this method, the cut is made at several intervals, depending on the width of the material, leaving a series of uncut sections along the line of cut, each about 12 to 25 mm (1/2 to 1 in.) long. These uncut ligaments hold the material in line until cooled, then the material is cut through to separate the pieces.

SKIP SEQUENCE

See SKIP WELDING.

SKIP WELDING

A welding technique in which a series of tack welds are made at intervals a few inches apart. The operator welds the first interval, skips to the fourth, then to the seventh, continuing this sequence until the end of the joint is reached. Then the welder goes back to the second, fifth, eighth, and so on. This method allows the welding to be done on a comparatively cool area of the workpiece, and the distortion caused by expansion and contraction is greatly reduced. *See* INTERMITTENT WELD.

SKULL

The unmelted residue from a liquated filler metal. See STANDARD WELDING TERMS.

SLAG

A nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in some welding and brazing processes. See STANDARD WELDING TERMS.

This term is used to describe the oxides and nonmetallic solids that sometimes are entrapped in weld metal, between adjacent beads, or between the weld metal and the base metal. During deposition and subsequent solidification of the weld metal, many chemical reactions occur. Some of the products of these reactions are solid nonmetallic compounds which are insoluble in the molten metal. Because of their lower specific gravity, these compounds will rise to the surface of the molten metal unless they become entrapped within the weld metal.

In shielded metal arc welding, flux cored arc welding, and submerged arc welding, a slag is also formed over the molten metal, protecting it from the air and slowing down the rate of cooling. By this means, varying in detail with different electrodes and fluxes, the air surrounding the arc is deoxidized and the metal is protected, or shielded, from the oxygen and nitrogen which would otherwise be present. The result is greater tensile strength and ductility of the weld metal.

This term is also applied to the scale blown out of the kerf when cutting with a torch.

SLAG-COVERED ELECTRODE

The electrode heavily coated with slag used in shielded metal arc welding. The slag covers the weld and cools in the form of a brittle mass, which can be chipped off when the weld is completed. *See* COVERED ELECTRODE.

SLAG (CHIPPING) HAMMER

A hammer with a chisel point used to remove slag from a weld deposit.

SLAG INCLUSION

Nonmetallic material entrapped in a weld. *See* SLAG.

SLAKED LIME

The residue calcium hydroxide, $Ca(OH)_2$ in an acetylene generator. *See* CALCIUM CARBIDE.

SLOPE

A term describing the shape of the static volt-ampere curve of a constant potential welding machine. Slope is caused by impedance and is usually introduced by adding substantial amounts of inductive reaction to the welding power circuit. The amount of slope can be controlled by a variable reactor in the a-c portion of the welding. It should be remembered that a reactor inherently opposes change in the welding current.

As more reactance is added to a welding circuit, there is a steeper slope to the volt-ampere curve. The addition of reactance does two things: (1) it limits the available short circuit current and (2) it slows the rate of response of the welding machine to changing arc conditions. These factors assist in decreasing the current surge when the electrode makes short-circuiting contact with the base metal. The result is decreased spatter from the welding arc.

It makes no difference whether the reactor is in the primary or secondary a-c circuit, since there will be no significant change in the performance characteristics either way. Resistance may be added to either the a-c or d-c circuit to accomplish the same purpose, but it is a more expensive method. Resistance will introduce more slope with less slow-down of response time. *See* CONSTANT VOLTAGE POWER SOURCE.

SLOT WELD

A weld made in an elongated hole in one member of a joint fusing that member to another member. The hole may be open at one end. A fillet welded slot is not to be construed as conforming to this definition. See STANDARD WELDING TERMS. *See* Figure S-17.

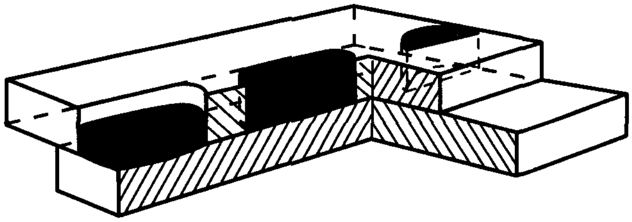


Figure S-17—Slot Welds

SLOT WELD SIZE

The width and length of the weld metal in the plane of the faying surfaces. See STANDARD WELDING TERMS.

SLUDGE

A term often applied to the accumulation of slaked carbide and water in the bottom of an acetylene generator.

SLUGGING

The unauthorized addition of metal, such as a length of rod, to a joint before welding or between passes, often resulting in a weld with incomplete fusion. See STANDARD WELDING TERMS.

Slugging is a dishonest welding technique used to simulate increased production.

SMOOTHING BEAD

A weld bead made to correct an undesirable weld profile, but not to enhance weld appearance. See STANDARD WELDING TERMS. *See also* COSMETIC PASS.

SMOOTHING PASS

A weld pass that results in a smoothing bead. See STANDARD WELDING TERMS.

SODIUM SILICATE (Waterglass)

A binder used in the manufacture of welding electrode coatings. It holds the particles of electrode coating material on the rod until melted in the heat of the arc.

SOFT SOLDER

A nonstandard term for SOLDER.

SOLDER

The metal or alloy used as a filler metal in soldering, which has a liquidus not exceeding 450°C (840°F) and below the solidus of the base metal. See STANDARD WELDING TERMS.

Solders are generally referred to as being "hard" or "soft." These terms do indicate relative hardness (or strength), but more generally indicate relative melting points; with the hard solders melting at higher temperatures, often above 450°C (840°F), thereby making them actually braze fillers.

Solders are based on low-melting metals such as lead, cadmium, bismuth, zinc, indium or tin, and their low-melting (virtually always eutectic) alloys. *See* SOLDERING.

SOLDERABILITY

The capacity of a material to be soldered under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service. See STANDARD WELDING TERMS.

SOLDERING (S)

A group of welding processes that produces coalescence of materials by heating them to the soldering temperature and by using a filler metal having a liquidus not exceeding 450°C (840°F) and below the solidus of the base metals. The filler metal is distributed between closely fitted faying surfaces of the joint by capillary action. See STANDARD WELDING TERMS.

The soldered joint is generally considered to be a metallurgical bond between the solder filler metal and the base metals being joined. Strength of the joint can be enhanced by mechanical configuration of the joint. Some solder joints do not have a metallurgical bond, but are held together by adhesion properties of the interface.

The metallurgical solder joint is produced by reaction of the base metals and the filler metal. The solder alloy is applied as a liquid metal that wets and spreads in the joint, and generally forms a layer of an intermetallic compound with a small amount of the base metal. On solidification, the joint is held together by the same attraction between adjacent atoms that holds a piece of solid metal together.

A sound soldered joint is achieved by the selection and use of specific materials and processes. There are many soldering filler metals, processes, methods, procedures, and types of equipment, and many metal alloys that can be joined. Specific applications require consideration of all these factors to obtain the optimum manufacturing and service results. Filler metal selection, joint design, metal cleaning, heating methods, fluxes, and joint properties are variables. Temperature ranges of commonly used soldering alloys are compared with base metal melting points in Figure S-18.

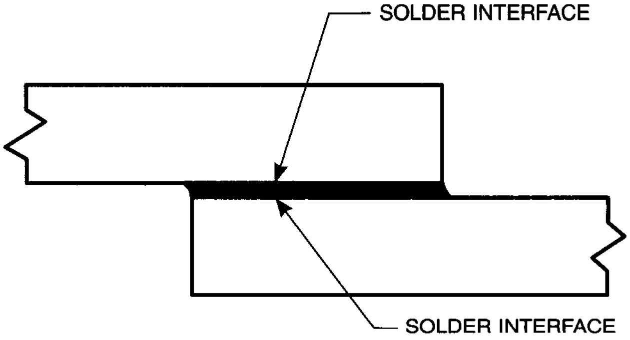


Figure S-18—Soldered Joint

Advantages of Soldering. A major factor in the popularity of soldering is that it is a low-temperature process and therefore has minimum effect on base metal properties. The low temperature used for joining requires little energy input and allows precise control of the process. A wide range of heating methods can be adopted, giving flexibility in design and manufacturing procedures. Modern automation produces large numbers of joints in electrical and electronic circuits. Highly reliable joints can be obtained with carefully controlled procedures. The occasional defective soldered joint can easily be repaired.

Chemistry, physics, and metallurgy are the main disciplines involved in soldering. Wetting and spreading solder filler metals on metallic surfaces are conditioned by the surface tension properties of the materials involved and the degree of alloying taking place during the soldering action. Soldering normally requires the presence of a flux. The flux cleans the metal to be joined and lowers the surface tension between the molten metal and the solid substrate. The flux improves the wetting and spreading of the solder metal.

Wetting takes place when the solder leaves a continuous permanent film on the base metal surface. Alloying depends on the solubility of the base metal in molten solder metal. A high level of alloying between the base metal and solder metal can retard spreading, therefore, good solder filler metals usually dissolve only a moderate amount of metal. Intermetallic compounds may form, depending of the metal systems involved.

Many solder joints are designed with gaps that require capillarity between the solder and base metal. Capillary action is improved by lowering surface tension, narrowing the gap in the joint, and using a highly compatible displacement flux.

Surfaces of the materials to be joined must be cleaned of dirt, oxides, or other contaminants. One function of a flux is to provide a final cleaning by chemical reaction with the metal surface. This attack should be slight but effective. Covering the surface with flux is no substitute for prior cleaning.

When heated, the flux is activated; it cleans contacted surfaces and protects the cleaned areas from oxidation during soldering. The solder filler metal is applied when the joint has been heated to the soldering temperature. The surfaces are protected by the activated flux during soldering action. When soldered joints have been cooled, some residual flux may be present that needs to be removed to prevent early joint deterioration.

Physical problems affecting wetting, spreading, and capillary action can result in unsatisfactory joints. They generally result from poor surface condition or improper flux. Some metals, for example, chromium, cannot be readily wet by most known solder filler metals. De-wetting is the retraction of solder on an already wetted surface which leaves areas of incomplete coverage. Inadequate cleaning, poor flux selection, and wrong solder composition are the main causes of de-wetting.

Basic Steps

Base Metal Selection. Base metals are usually selected for specific properties that are needed for the component or part design. These include strength, ductility, electrical conductivity, weight, and corrosion resistance. The solderability of the base materials must also be considered because the selection of flux and surface preparation will depend on the base materials.

Solder Selection. The solder is selected to provide good flow, penetration and wetting capability in the soldering operation, and the desired joint properties in the finished product.

Flux Selection. Flux is intended to enhance the wetting of base materials by the solder by removing tarnish films from precleaned surfaces, and by preventing oxidation during the soldering operation. The selection of the type of flux usually depends on the solderability of the base materials. Rosin fluxes are used with base metals in electrical and electronic applications, or with metals that are precoated with a solderable finish. Inorganic fluxes are often used in industrial soldering such as plumbing and vehicle radiators. The flux requirements for soldering a number of alloys and metals are indicated in Table S-4.

Joint Design. Joints should be designed to fulfill the requirements of the finished assembly and to permit application of the flux and solder by the soldering process that will be used. Joints should be designed so that proper clearance is maintained during heating. Special fixtures may be necessary, or the components can be crimped, clinched, wrapped, or otherwise held together.

Precleaning. All metal surfaces to be soldered should be cleaned before assembly to facilitate wetting of the base metal by the solder. Flux should not be considered as a substitute for precleaning. Precoating

Table S-4
Flux Requirements for Metals, Alloys, and Coatings

Base Metal, Alloy, or Applied Finish	Rosin	Organic	Inorganic	Special Flux and/or Solder	Soldering Not Recommended*
Aluminum	—	—	—	X	—
Aluminum-bronze	—	—	—	X	—
Beryllium	—	—	—	—	X
Beryllium-copper	—	X	X	—	—
Brass	X	X	X	—	—
Cadmium	X	X	X	—	—
Cast iron	—	—	—	X	—
Chromium	—	—	—	—	X
Copper	X	X	X	—	—
Copper-chromium	—	—	X	—	—
Copper-nickel	X	X	X	—	—
Copper-silicon	—	—	X	—	—
Gold	X	X	X	—	—
Inconel	—	—	—	X	—
Lead	X	X	X	—	—
Magnesium	—	—	—	—	X
Manganese-bronze (high tensile)	—	—	—	—	X
Monel	—	X	X	—	—
Nickel	—	X	X	—	—
Nickel-iron	—	X	X	—	—
Nichrome	—	—	—	X	—
Palladium	X	X	X	—	—
Platinum	X	X	X	—	—
Rhodium	—	—	X	—	—
Silver	X	X	X	—	—
Stainless steel	—	—	X	—	—
Steel	—	—	X	—	—
Tin	X	X	X	—	—
Tin-bronze	X	X	X	—	—
Tin-lead	X	X	X	—	—
Tin-nickel	—	X	X	—	—
Tin-zinc	X	X	X	—	—
Titanium	—	—	—	—	X
Zinc	—	X	X	—	—
Zinc die castings	—	—	—	—	X

*With proper procedures, such as precoating, most metals can be soldered.

may be necessary for base materials that are difficult to solder.

Soldering Process. The soldering process should be selected to provide the proper soldering temperature, heat distribution, and rate of heating and cooling required for the product being assembled. Application of the solder and flux will be dictated by the selection of the soldering process.

Flux Residue Treatment. Flux residue should be removed after soldering unless the flux is specifically designed to be consumed during the process.

Solders

Solders have melting points or melting ranges generally below 425°C (800°F). A wide range of solder filler metals designed for use with most industrial metals and alloys are commercially available. These generally flow satisfactorily with the appropriate fluxes to produce good surface wetting, and result in joints with satisfactory properties. Tin-lead alloys are the most widely used solder filler metals.

Historical Background

Soldering is a technology that has been in continuous development from ancient times. Many artifacts discovered in archeological excavations were joined by soldering. The technology seems to have existed for several thousand years, with changes as metallurgical knowledge and new metals were discovered.

Copper and lead alloys were the first to be joined. Early metallurgists learned to identify eutectics in binary systems. The use of eutectic alloys permitted soldering to join simple shapes into complex items of jewelry and utensils. The industrial revolution promoted widespread use of soldered joints. Advancements in alloy joining, processing techniques, and applications continue today. Soldering is now used in industrial applications, satellite communications, computers, and the space program.

The following is excerpted from the Welding Encyclopedia, First Edition, edited by L. B. Mackenzie, Welding Engineer Publishing Company, Chicago, 1921.

"Fusible alloys are used to join metals by soldering. The types of soldering are distinguished by self-descriptive names: hard, soft, silver, gold, aluminum, copper, tin, pewter, and spelter. The kind of solder used depends on the metals to be joined; in all cases, the solder should be more fusible than the metals to be joined.

"Hard solders are called *spelter*, and hard soldering is called *brazing*. Brazing produces greater strength than soldering with the soft solders. Hard solders will also withstand more heat than soft solders. Hard solders contain metals such as copper, zinc, or silver, and require a red heat to melt them.

"Soft solders are made of such metals as lead, tin, or bismuth. They are used for applications in which the articles to be soldered must be air- or water-tight, but are not exposed to high temperatures, and when strength is not a factor. It is a much simpler operation to join metals with soft solder than with hard solder, and soft soldering is used when possible in place of brazing.

"The ordinary good grade of solder is made of tin and lead in equal parts. Fine solder: two parts tin, one part lead; cheap solder: one part tin, two parts lead.

"Mixing Solders. By varying the proportions and adding bismuth, a solder can be made that will melt in boiling water. In mixing solders, the least fusible metal should be melted first and the more easily fusible metals added. Mixing soft solders should be done under melted tallow and agitated by thrusting a stick of green wood or raw potato under the molten metal. The escaping steam stirs and mixes the metals very thoroughly. They can be then run out in molds. A small channel of angle iron will serve in mixing hard solders. They should be melted under a coating of powdered charcoal or borax. Hard solders may be reduced to granulated form (the most convenient form for use) by casting into small strips or ingots and filing with a coarse file.

"Silver solder should be rolled or hammered into thin strips or sheets and cut to suitable size. A silver coin hammered thin makes a very satisfactory solder for iron, copper and hard brass. Copper to which is added 10% of silver is suitable for soldering sheet steel.

Soldering

"To prepare for soldering, the surfaces must be cleaned, either by scraping or filing, or by using a suitable acid, or a combination of both. In the case of sheet iron covered with scale, one method is to scrape or file the surface, or scratch it with a wire brush and coat it with strong muriatic (hydrochloric) acid, letting the acid act for 5 or 10 minutes, and then wiping it dry and applying cut acid (hydrochloric acid to which an excess of zinc has been slowly added).

"In the soldering process, the metals must be heated above the melting point of the solder, and since metals readily oxidize when heated, a flux is necessary to coat the surfaces after they are cleaned, to prevent their oxidation. Cast iron may be soldered by using a flux made by adding zinc chloride to melted tallow and heating until it foams and turns a reddish brown. Zinc chloride solution also is satisfactory. It is very important, however, to clean the surface very thoroughly and solder immediately after cleaning.

"**Selection of Flux.** For hard soldering, borax is used as a flux. For silver soldering, finely powdered borax mixed with water to the consistency of paste is very effective. However, this flux should be allowed to dry after applying. For soldering galvanized iron, raw hydrochloric acid is used as a flux.

"For soldering copper, brass, or gunmetal, a flux of zinc chloride, ammonium chloride, or rosin is used. For soldering zinc, galvanized iron and steel, hydrochloric acid or ammonium chloride (Sal-ammoniac) is used. For soldering tinware, pewter or lead, a flux of rosin, turpentine, or Russian tallow is used.

Jewelry Soldering

"If acids are used to clean the soldered joint, it should be thoroughly washed to remove all excess acid to prevent subsequent corrosion. When soldering jewelry, zinc chloride should be used. For soldering small pieces, tin foil cut to size and moistened with a solution of Sal-ammoniac placed between the pieces to be soldered may be used. The pieces should be made flat and smooth at the joint, the tin foil inserted and the pieces gently heated. For soldering gold articles, a solder made of two grams silver, one gram copper, and one pennyweight gold may be used with success. A good solder for general use contains 18 parts gold, 4 parts silver, six parts copper, and two parts zinc.

"Antimony, arsenic, tin and lead should not be used in soldering gold.

"**Burnt Borax Flux.** The flux used is usually borax, but it should be properly prepared. This is done by covering the bottom of a pan with a thin, even layer of ordinary commercial borax and heating it over a slow fire until it will crumble in the fingers to a fine dry powder. An hour's heating should be sufficient.

"**Brazing Solders.** The brazing solder and the burnt borax are thorough mixed in suitable proportions, and water is added to bring the supply, for later use, to the consistency of putty. This is mixed with more water, as required, to a mixture like grout in cement work, and applied to the parts to be soldered. For brass and steel tubes, a proportion of 10 parts solder to one part burnt borax is used. Other mixtures are used for other metals. The melting points of the metals being soldered must be taken into account in selecting the grade of solder to be used."

SOLDERING BLOWPIPE

A device used to obtain a small, accurately directed flame for fine work. A portion of any flame is blown to the desired location by the blowpipe, which is usually mouth operated. See STANDARD WELDING TERMS.

SOLDERING FLUX

A compound that dissolves the oxide from the surface being soldered. Flux enhances the wetting of base materials by the solder by removing tarnish films from precleaned surfaces, and by preventing oxidation during soldering. *See* SOLDERING, Flux Selection.

SOLDERING GUN

An electrical soldering iron with a pistol grip and a quick-heating, relatively small bit. See STANDARD WELDING TERMS.

SOLDERING IRON

A soldering tool having an internally or externally heated metal bit usually made of copper. See STANDARD WELDING TERMS.

The soldering iron accomplishes several tasks:

(1) Provides a source of heat to the joint to melt the solder

(2) Provides a means of transporting molten solder to the joint, if needed

(3) Provides a means of withdrawing excess solder from the joint, if required.

SOLDER INTERFACE

The interface between solder metal and base metal in a soldered joint. See STANDARD WELDING TERMS. *See* Figure S-18.

SOLDERING PASTE

A soldering flux in paste form, or, alternatively, a paste consisting of a mixture of flux and powder solder alloy. The latter is often called *solder* paste or *paste solder.*

SOLENOID

A coil of insulated wire wound in the form of a spring or on a spool, used to induce a magnetic field to cause an action, such opening or closing a switch.

SOLDER METAL

That portion of a soldered joint that has been melted during soldering. See STANDARD WELDING TERMS.

SOLID-PHASE WELDING

A non-fusion welding process that produces welds by applying heat, usually with pressure, to the base metal, at a temperature below the melting point of the base metal, with or without filler metal. Also known as non-fusion welding. *See* SOLID-STATE WELDING.

SOLID-STATE WELDING (SSW)

A group of welding processes that produces coalescence by the application of pressure at a welding temperature below the melting temperatures of the base metal and the filler metal. See STANDARD WELDING TERMS.

Examples of solid state welding are friction welding, explosion welding, diffusion welding and ultrasonic welding.

SOLID SOLUTION

An alloy in which in the solid state the items of the various component metals are formed with a single lattice. *See* METALLURGY.

SOLIDUS

The highest temperature at which a metal or an alloy is completely solid. See STANDARD WELDING TERMS.

SORBITE

A late stage in the tempering of martensite when the carbide particles have grown to the extent that the structure has a distinctly granular appearance. Further tempering causes globular carbides to appear. *See* METALLURGY.

SPACE-LATTICE

When a liquid solidifies, or "freezes," the atoms are no longer free to move, but arrange themselves in regular patterns or definite forms. These forms consist of a three-dimensional latticework *(space lattice)* of imaginary lines connecting the atoms.

SPACER

See STANDARD WELDING TERMS. *See also* JOINT SPACER *and* SPACER STRIP.

SPACER STRIP

A metal strip or bar prepared for a groove weld and inserted in the joint root to serve as a backing and to maintain the root opening during welding. It can also bridge an exceptionally wide root opening due to poor fit. See STANDARD WELDING TERMS. *See* Figure S-19.

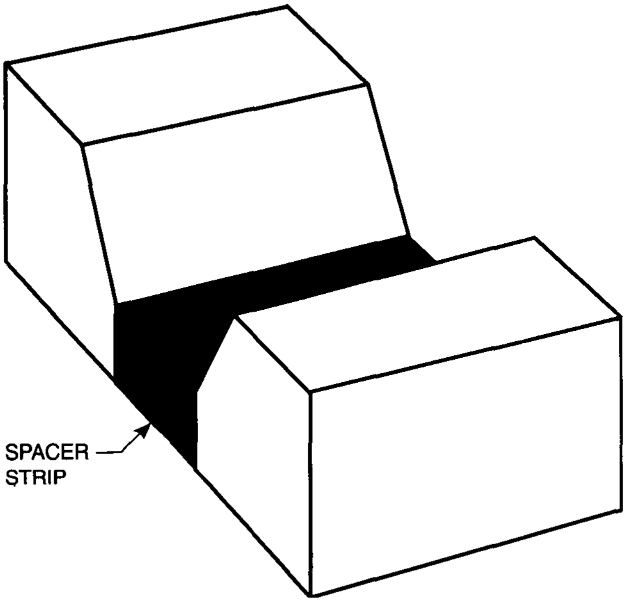


Figure S-19—Spacer Strip Used to Maintain the Root Opening During Welding

SPARK LIGHTER

See LIGHTER.

SPARK SHIELD

A nonstandard term for a safety shield.

SPARK TEST

An elementary but fairly accurate test for the identification of steel by observation of the spark pattern produced during grinding.

When a steel bar is held against an emery wheel, the end of the bar is heated by friction. As the small particles, or sparks, are thrown from the wheel, they will follow a straight line which becomes broader and more luminous some distance from the source of heat before disappearing. This is probably due to the exposure of the heated particles to the oxygen in the air, which requires some time to react. Note: Touch the material lightly to the wheel; observe individual spark. Use black background.

SPATTER

The metal particles expelled during fusion welding that do not form a part of the weld. See STANDARD WELDING TERMS.

Causes of spatter: The inherent properties of certain electrodes; excessive welding current; the type or diameter of rod used; an excessively long arc; arc blow.

Corrections: Use correct type of electrode; check for correct welding current and arc length; reduce arc blow; use anti-spatter on parts adjacent to the weld to prevent spalls from adhering to the work.

SPATTER LOSS

Metal lost due to spatter. See STANDARD WELDING TERMS.

Spatter loss can be determined from the difference in weight between the weight of the electrode actually deposited on the workpiece and the weight of the electrode consumed (melted).

SPECIFICATIONS

Documents which clearly and accurately describe all of the pertinent technical information necessary for a material, product, system, or service, then ascertain that the requirements have been met. *See* STANDARDS, Welding.

SPECIFIC GRAVITY

The relative density of materials, i.e., the weight as compared with an equal volume of some other material. Solids and liquids are usually compared with water, and gases are usually compared with air.

SPECIFIC HEAT

The ratio of the quantity of heat required to raise the temperature of a material one degree to that required to raise the temperature of an equal mass of water one degree. The heat in calories required to raise the temperature of one gram of a substance one degree Centigrade.

SPECIFIC RESISTANCE

The electrical resistance of a one-centimeter cube of any material.

SPEED CONTROL VALVE

A combination check valve and needle valve which restricts the flow of air or liquid in one direction, and allows unrestricted passage in the opposite direction.

SPHEROIDIZING

Long-term heating of high-carbon steels at or near the critical temperature, followed by slow cooling throughout the upper part of the cooling range, for the purpose of spheroidizing the cementite in the steel.

SPIKING, Electron Beam Welding and Laser Beam Welding

A condition where the joint penetration is nonuniform and changes abruptly over the length of the weld. See STANDARD WELDING TERMS.

The cause of spiking is the intermittent and random loss of the vapor cavity produced in the keyhole mode used in processes with high energy density. Liquid falling back into the vapor cavity causes a momentary loss of penetration when it briefly blocks beam energy.

SPINNING

A mechanical process for shaping shallow vessels from metal disks by rotating a lathe while pressing a tool against the peripheral zone. It is sometimes necessary to carry out this process in several stages, due to work hardening. If this occurs, an annealing operation is undertaken between spinning stages.

SPIT

A nonstandard term when used for FLASH and EXPULSION during resistance welding by various processes.

SPLICE

A nonstandard term when used for a welded, brazed, or soldered joint.

SPLICED BUTT JOINT

See STANDARD WELDING TERMS. *See* SPLICED JOINT. *See* Figure S-16.

SPLICED JOINT

A joint in which an additional workpiece spans the joint and is welded to each joint member. See STANDARD WELDING TERMS. *See* Figure S-16. *See also* SPLICE MEMBER.

SPLICE MEMBER

The workpiece that spans the joint in a spliced joint. See STANDARD WELDING TERMS. *See* Figure S-16.

SPLIT LAYER TECHNIQUE

A welding technique in which more than one weld is applied to a single layer. See STANDARD WELDING TERMS.

SPLIT PHASE

An electrical circuit arrangement in which currents of different phases are obtained from a single-phase source by using reactances of different values in parallel circuits.

SPLIT PIPE BACKING

A pipe segment used as a backing for welding butt joints in round bars. See STANDARD WELDING TERMS. *See* Figure S-20.

SPOOL

A filler metal package consisting of a continuous length of welding wire in coil form wound on a cylinder (called a barrel), which is flanged at both ends. The flange contains a spindle hole of smaller diameter than the inside diameter of the barrel. See STANDARD WELDING TERMS.

SPOON

A small instrument or "flatter" used in finishing the surface of an aluminum weld.

SPOT WELD

A weld made between or upon overlapping members in which coalescence may start and occur on the faying surfaces or may proceed from the outer surface of one member. The weld cross section (plan view) is approximately circular. See STANDARD WELDING TERMS. *See* Figure S-21. *See also* ARC SPOT WELD *and* RESISTANCE SPOT WELDING.

SPOT WELDING

A resistance welding process in which the fusion is confined to a relatively small area, approximating the shape or contour of one or both welding electrodes. This is generally a small portion of the lapped surfaces of the workpieces being joined. *See* RESISTANCE WELDING.

SPOT WELDING, INERT ARC

A variation of the gas tungsten arc welding process, often done manually with a pistol-like holder that has a vented, water-cooled gas nozzle, a tungsten electrode that is concentrically positioned relative to the gas nozzle, and a trigger switch for controlling the operation. Figure S-22 illustrates manual gas tungsten arc spot welding.

Spot welding may be done with either ac or DCEN. Sequencing controls automatically establish the preweld gas and water flow, start the arc, time the arc duration, and provide the required postweld gas and water flow.

SPOT WELD SIZE

The diameter of the weld metal in the plane of the faying surfaces. See STANDARD WELDING TERMS. *See* Appendix 11.

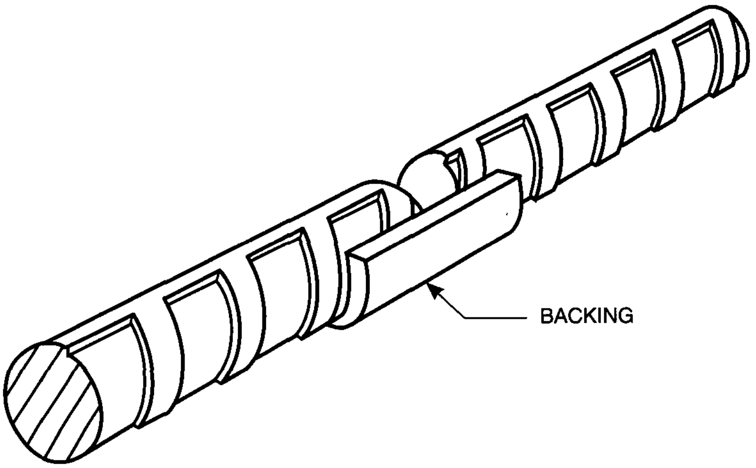


Figure S-20—Split Pipe Backing

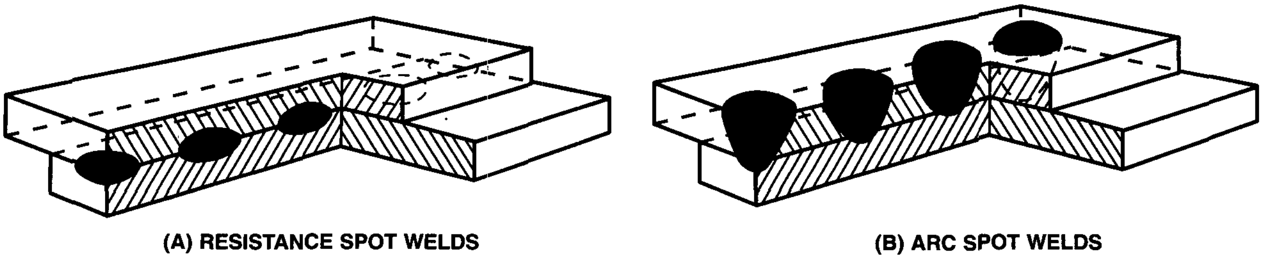


Figure S-21—Types of Spot Welds

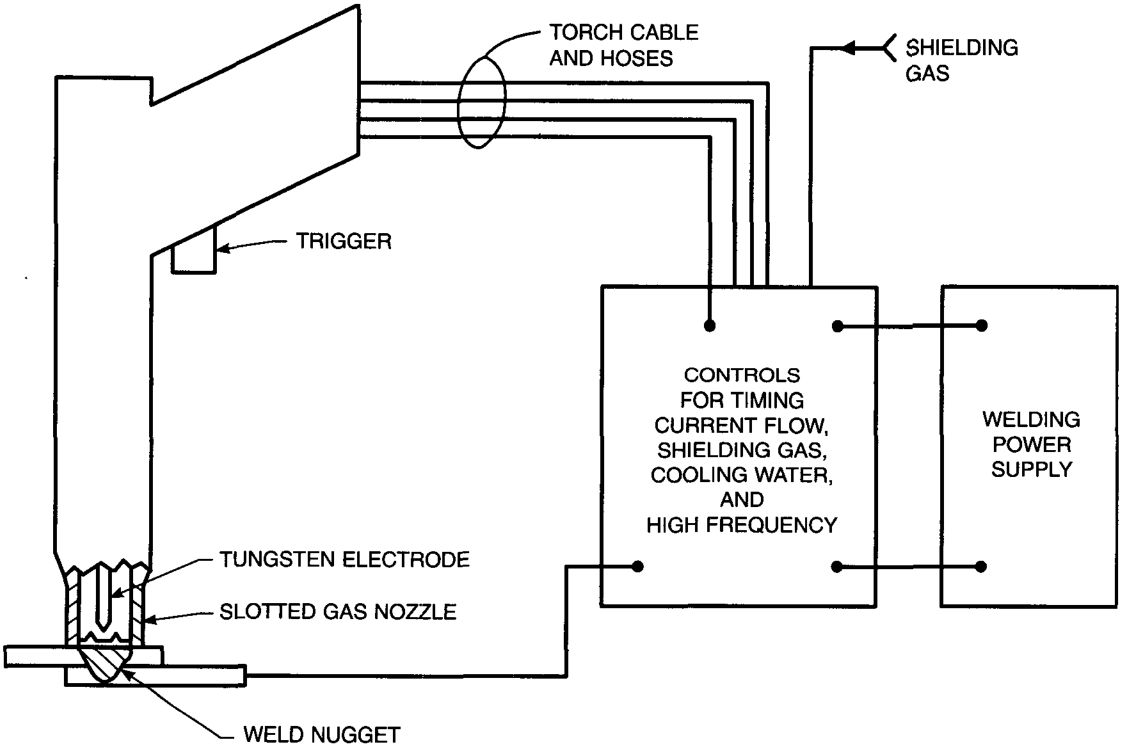


Figure S-22—Schematic of Manual Gas Tungsten Arc Spot Welding

SPRAY ARC

A nonstandard term for SPRAY TRANSFER.

SPRAY DEPOSIT

See STANDARD WELDING TERMS. *See* THERMAL SPRAY DEPOSIT.

SPRAY DEPOSIT DENSITY RATIO

See STANDARD WELDING TERMS. *See* THERMAL SPRAY DEPOSIT DENSITY RATIO.

SPRAYER

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYER.

SPRAYING BOOTH

An exhaust booth where thermal spraying is performed. See STANDARD WELDING TERMS.

SPRAYING OPERATOR

See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING OPERATOR.

SPRAYING RATE, Thermal Spraying

The rate at which surfacing material passes through the gun. See STANDARD WELDING TERMS.

SPRAYING SEQUENCE, Thermal Spraying

The order in which layers of materials are applied, such as overlapped, superimposed, or at various angles. See STANDARD WELDING TERMS.

SPRAY TAB, Thermal Spraying

A small piece of additional material that is thermally sprayed concurrently with the workpiece, and used to evaluate the quality of the thermal spray deposit. See STANDARD WELDING TERMS.

SPRAY TRANSFER, Arc Welding

Metal transfer in which molten metal from a consumable electrode is propelled axially across the arc in small droplets. See STANDARD WELDING TERMS. *See* Figure S-23. *See also* GLOBULAR TRANSFER *and* SHORT CIRCUITING TRANSFER.

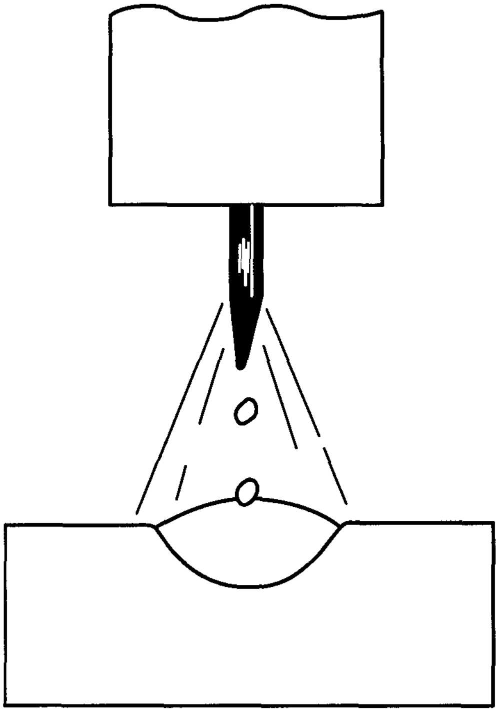


Figure S-23—Axial Spray Transfer

When using argon, or an argon and oxygen mixture, as a shielding gas with the gas metal arc welding (GMAW) process, spray transfer is the result of a *pinch effect* on the molten tip of the consumable welding wire. The pinch effect physically limits the size of the molten ball that can be formed on the end of the welding wire, and therefore only droplets of metals are transferred rapidly through the welding arc from the wire to the workpiece. The droplets produced in the spray transfer method are equal to or smaller than the diameter of the wire being used. *See* PINCH EFFECT, GLOBULAR TRANSFER, *and* GAS METAL ARC WELDING.

SPRAY WELDING

A group of thermal spraying processes used primarily for surfacing, but also for producing shapes in molds. These processes involve spraying a finely divided material (e.g., particles of metal, ceramic, or polymer) through a heat source and depositing it on a surface using the kinetic energy of the particle. *See* THERMAL SPRAYING.

SQUARE EDGE SHAPE

A type of edge shape in which the prepared surface lies perpendicular to the material surface. See STANDARD WELDING TERMS. *See* Appendix 6.

SQUARE-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

SQUEEZE TIME, Resistance Welding

The time between the initiation of the welding cycle and first application of current in spot, seam, or projection and some types of upset welds. See STANDARD WELDING TERMS. *See* Figure H-6.

STACK CUTTING

Thermal cutting of stacked metal plates arranged so that all the plates are severed by a single cut. See STANDARD WELDING TERMS. *See also* THERMAL CUTTING.

The stack cutting technique is often used to cut sheet material that is too thin for ordinary oxyfuel cutting methods. Sheet thicknesses of 0.9 mm (20 gauge) and over are the most practical. Stack cutting is used in place of shearing or stamping, particularly where volume does not justify expensive dies. The flame cut edges are square and free of burrs.

Stack cutting is usually limited to sheet and plate up to 13 mm (1/2 in.) thick because of the difficulty in clamping heavier material in a tight stack. A stack cutting operation is shown in Figure S-24.

Figure S-24—Typical Stack Cutting Operation with the Plates Clamped by Vertical Welds

Successful stack cutting requires clean, flat sheet or plate. Dirt, mill scale, rust, and paint may interrupt the cut and reduce cut quality. The stack must be securely clamped, particularly at the cut location, with the edges aligned at the point where the cut is to start.

Piercing of stacks with the oxyfuel torch to start a cut is impractical. Holes must be drilled though the stacks to start an interior cut.

The total thickness of the stack is determined by the cutting tolerance requirement and the thickness of the top piece. With a cutting tolerance of 0.8 mm (1/32 in.), stack height should not exceed 50 mm (2 in.); with a 1.6 mm (1/16 in.) tolerance, the thickness may be up to 100 mm (4 in.). The maximum practical limit of thickness is about 150 mm (6 in.).

When stack cutting material less than 4.8 mm (3/16 in.) thick, a waster plate 6 mm (1/4 in.) thick is used on top. It insures better starting, a sharper edge on the top production piece, and no buckling of the top sheet.

Plasma Arc Cutting (PAC). The plasma process has been used for stack cutting of carbon steel, stainless steel, and aluminum. The plates to be stack-cut should preferably be clamped together. PAC can tolerate wider gaps between plates than OFC.

STAGGERED INTERMITTENT WELD

An intermittent weld on both sides of a joint in which the weld increments on one side are alternated with respect to those on the other side. See STANDARD WELDING TERMS. *See* Figure S-25.

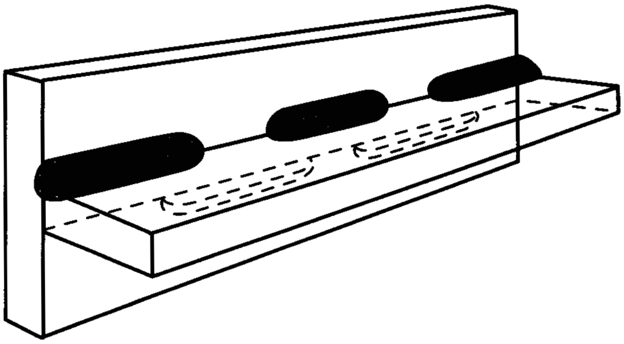


Figure S-25—Staggered Intermittent Fillet Weld

STAINLESS STEEL

Stainless steels are alloys of iron base metals, highly resistant to acids, except sulfuric and hydrochloric acids. They are also resistant to oxidation and scaling at high temperatures and retain their physical properties well under heat. Stainless steels are used in the chemical, oil, dairy, food, paper and other industries requiring material with unusual resistance to corrosion and heat. The stainless steels are supplied in plates, sheets, bars, strip, tubing, bolts, nuts, rivets, and wire, and can be rolled, drawn, formed, or worked into almost any specific shape or apparatus, merely by following the correct procedure for the particular alloy at hand.

Usually, the resistance of stainless steels to corrosive attack is primarily due to chromium content, which is 10% or higher in most types of stainless steel. Nickel is also used as an alloying element, ranging in content from 2 to 35%. Consequently the stainless steels are grouped into two main categories: straight chromium (or nearly so) and chromium-nickel (with the remainder essentially iron).

The straight chromium alloys contain about 12% chromium. Various others contain chromium in increasing amounts, but the majority are the austenitic class, consisting of iron alloyed with about 18% chromium and 8% or more of nickel.

In addition to the recognized corrosion resistance, certain types of stainless steels have a number of other useful properties, such as toughness at sub-zero temperatures, good strength at elevated temperatures, and the ability to remain nonmagnetic under a variety of conditions. Some alloys are hardened by simple, low-temperature precipitation heat treatments, thus avoiding quenching operations. The reasons for selecting a stainless steel must justify its higher cost. However, when all aspects of fabricating, treating, and service performance are considered, stainless steel components are often incorporated in many kinds of welded construction.

The American Iron and Steel Institute (AISI) standards for stainless steels, their type numbers and composition ranges for the 300 Series stainless steels are shown in Table S-5.

Stainless steels in the form of castings have been given designations and composition limits by the Alloy Casting Institute (ACI), a division of Steel Founders Society of America (SFSA). Reference: Linnert, George E, *Welding Metallurgy*, Vol. 1, 4th Edition. American Welding Society, Miami, Florida. 1994.

STAINLESS STEEL, Brazing

Stainless steels may be brazed by all processes, but with tighter process controls than required to braze carbon steels. The most rigorous requirements are imposed by inherent chemical characteristics of the stainless steels and the generally more arduous service environments. Success in brazing stainless steel components depends on a knowledge of the properties of stainless steels and rigid adherence to the appropriate process controls.

Base Metals. Stainless steels may be grouped into five categories: (1) austenitic (nonhardenable) steels, (2) ferritic (nonhardenable) steels, (3) martensitic

Table S-5
Stainless Steel Chemical Requirements Composition, %[a]

UNS Designation	Type	Carbon[b]	Manganese	Phosphorus	Sulfur	Silicon	Chromium	Nickel	Molybdenum	Nitrogen	Copper	Other Elements[c]
S30100	301	0.15	2.00	0.045	0.030	0.75	16.00–18.00	6.00–8.00	...	0.10	...	...
S30200	302	0.15	2.00	0.045	0.030	0.75	17.00–19.00	8.00–10.00	...	0.10	...	...
S30400	304	0.08	2.00	0.045	0.030	0.75	18.00–20.00	8.00–10.50	...	0.10	...	...
S03403	304L	0.030	2.00	0.045	0.030	0.75	18.00–20.00	8.00–12.00	...	0.10	...	...
S30500	305	0.12	2.00	0.045	0.030	0.75	17.00–19.00	10.50–13.00	...	...	...	...
S30815	308	0.05–0.10	0.80	0.040	0.030	1.40–2.00	20.00–22.00	10.00–12.00	...	0.14–0.20	...	Ce 0.03–0.08
S30908	309S	0.08	2.00	0.045	0.030	0.75	22.00–24.00	12.00–15.00	...	...	...	...
S30909	309H	0.04–0.10	2.00	0.045	0.030	0.75	22.00–24.00	12.00–15.00	...	...	...	...
S30940	309Cb	0.08	2.00	0.045	0.030	0.75	22.00–24.00	12.00–16.00	...	...	...	Cb 10 × C min, 1.10 max
S31008	310S	0.08	2.00	0.045	0.030	1.50	24.00–26.00	19.00–22.00	...	...	...	...
S31009	310H	0.04–0.10	2.00	0.045	0.030	0.75	24 00–26.00	19.00–22.00	...	...	...	...
S31040	310Cb	0.08	2.00	0.045	0.030	1.50	24 00–26.00	19.00–22.00	...	...	...	Cb 10 × C
S31050	310MoLN	0.030	2.00	0.030	0.010	0.50	24 00–26.00	21.00–23.00	2.00–3.00	0.10–0.16	...	...
S31600	316	0.08	2.00	0.045	0.030	0.75	16.00–18.00	10.00–14.00	2.00–3.00	0.10	...	...
S31603	316L	0.030	2.00	0.045	0.030	0.75	16.00–18.00	10.00–14.00	2.00–3.00	0.10	...	...
S31635	316Ti	0.08	2.00	0.045	0.030	0.75	16.00–18.00	10.00–14.00	2.0–3.0	0.10	...	Ti 5 × (C + N) min, 0.70 max
S31640	316Cb	0.08	2.00	0.045	0.030	0.75	16.00–18.00	10.00–14.00	2.0–3.0	0.10	...	Cb 10 × C min, 1.10 max
S31700	317	0.08	2.00	0.045	0.030	0.75	18.00–20.00	11.00–15.00	3.00–4.00	0.10	...	...
S31703	317L	0.030	2.00	0.045	0.030	0.75	18.00–20.00	11.00–15.00	3.00–4.00	0.10	...	...
S32100	321	0.08	2.00	0.045	0.030	0.75	17.00–19.00	9.00–12.00	...	0.10	...	Ti 5 × (C + N) min, 0.70 max
S34700	347	0.08	2.00	0.045	0.030	0.75	17.00–19.00	9.00–13.00	...	...	...	Cb 10 × C min, 1.00 max
S34709	347H	0.04–0.10	2.00	0.045	0.030	0.75	17.00–19.00	9.00–13.00	...	...	...	Cb 8 × C min, 1.00 max

a. Maximum, unless range or minimum is indicated.

b. Carbon analysis shall be reported to nearest 0.01% except for the low-carbon types, which shall be reported to nearest 0.001%.

c. The terms Columbium (Cb) and Niobium (Nb) both relate to the same element.

(hardenable) steels, (4) precipitation hardening steels, and (5) duplex stainless steels. All these alloys are iron based and contain chromium, the basic element that imparts corrosion resistance. The corrosion resistance of the stainless steels varies from one alloy to another, and for any given alloy, varies from one corrosive medium to another. If doubt exists about the correct stainless steel to use in a given environment, standard reference works or manufacturer's representatives should be consulted.

Filler Metals. Factors to be considered in selecting a filler metal for a particular application include the following:

(1) Service conditions, including operating temperature, stresses, and environment

(2) Heat treatment requirements for martensitic or precipitation hardening steels

(3) Brazing process

(4) Cost

(5) Special precautions, such as sensitization of unstabilized austenitic steels at certain temperatures.

Commercially available brazing filler metals used for joining stainless steels are commonly the copper, silver, nickel, cobalt, platinum, palladium, and gold based alloys.

Process and Equipment. Stainless steels can be brazed with any brazing process. Much controlled-atmosphere brazing is performed on stainless steels, and the acceptability of this technique is attributed to the ready availability of reliable atmospheres and vacuum furnaces. The primary requirements are that the furnaces have good temperature control, plus or minus 8°C (15°F), at brazing temperature and be capable of fast heating and cooling. All gases used in atmosphere furnaces must be of high purity (>99.995% pure). Commercial vacuum brazing equipment operates at pressures varying from 0.0015 to 13.5 Pa (10^{-5} to 10^{-1} torr). The necessary vacuum level depends on the particular grade of stainless steel, with those containing titanium or aluminum requiring better vacuums.

Precleaning and Surface Preparation. Stainless steels require more stringent precleaning than carbon steels. During the heating cycle, residual contaminants often form tenacious films which are difficult to remove by fluxes or reducing atmospheres. These films form as a direct reaction between the contaminant and stainless steel surface.

Precleaning for brazing should include a degreasing operation. The joint surfaces should also be cleaned mechanically or with an acid pickling solution. Wire brushing should be avoided, but if necessary, stainless steel brushes should be used. Cleaned surfaces should be protected to prevent soiling by dirt, oil or fingerprints. The parts should be brazed immediately after cleaning. When this is not practical, the cleaned parts should be enclosed in containers such as sealed polyethylene bags or desiccator jars to exclude moisture and other contaminants until the part can be brazed.

Fluxes and Atmospheres. Stainless steel assemblies are routinely furnace brazed in atmospheres of dry hydrogen, argon, helium, dissociated ammonia, or vacuum, without the aid of flux. When fluxes are required, there are a number of special compositions available for use with stainless steels. There are many special requirements for brazing stainless steels; appropriate references should be consulted.

Postbraze Operations. The major stainless steel postbraze operations that may be necessary are removal of flux or stopoff residues, and any required postbraze heat treatment.

Depending on the materials used, flux or stopoff residues can be removed by water rinsing, chemical cleaning, or mechanical means. With abrasive cleaning, the grit should be sand or another nonmetallic material. Metallic shot, other than stainless steel, should be avoided because particles may become embedded in the stainless steel surface and cause rusting or pitting corrosion in service.

Unless the brazing cycle is compatible with the heat treating requirements of the base metal, heat treatment after brazing will be required for assemblies which are made with martensitic or precipitation hardening stainless steels. Since treatments vary so widely, no general rules can be made except that supplier recommendations should be followed.

Repair Methods. When furnace brazed assemblies contain many joints, minor defects may occur that are beyond acceptance limits, but which are not economically or technically feasible to repair by rebrazing the entire assembly. In some cases, repairs can be made by localized rebrazing using oxyacetylene or gas tungsten arc torches. The manual gas tungsten arc method is useful for braze fillet repairs on applications like turbine engine stators. Filler metal is added, as required. Prototype work on a mock-up with proper evaluation prior to actual repair work is recommended. Reference: American Welding Society, Brazing Handbook, 4th Edition, Miami, Florida. 1991.

STAINLESS STEEL, Cutting

See OXYFUEL GAS CUTTING, METAL POWDER CUTTING, *and* PLASMA ARC CUTTING.

STAINLESS STEEL, Silver Brazing

Stainless steel can be satisfactorily brazed using silver brazing filler metal with the proper fluxes. Ordinary steel flux or borax will not successfully remove the scale formed on the surface when heated, and so will prohibit any bond between the braze material and the steel. The filler metal will ball up, resembling water drops on an oiled surface, and will not adhere. Special fluxes for stainless steel are available which, when used dry or in a water paste applied to the surface before heating, will eliminate this difficulty because they fuse and protect the steel from the formation of an oxide on the surface.

Low-melting silver braze alloy is preferred over those melting at higher temperatures because it reduces the tendency to form scale and also reduces warping. It is advisable to heat the rod and apply dry flux in addition to the original paste or dry powder on the steel itself. When brazing sheet metal, overheating the metal must be carefully avoided, because copper brazing alloys will penetrate entirely through the sheet following the grain boundaries, resulting in checks or cracks upon cooling. *See* SILVER ALLOY BRAZING.

STAINLESS STEEL WELDING

When welding stainless steels the process and procedures must be selected in consideration of the alloying elements of the two general types of steels: straight chromium, and chromium-nickel.

Straight Chromium Stainless Steel. These steels, especially those containing 18% chromium or more, are subject to a rapid grain growth when heated to a high temperature, and do not respond satisfactorily to heat treatment. They can be softened to a certain extent, provided proper control is maintained after welding by annealing for eight hours or so at about 790°C (1450°F). This may or may not be not be satisfactory, as much depends on the actual welding. As a rule, numerous small beads will produce the best results when followed by annealing.

These alloys, when welded, have very little ductility; the welds are likely to crack on deformation, or bending. Therefore they are not recommended when the product will be subjected to movement or shock at room temperature. However, if a little heat is applied, or the operating temperature is about 95°C (200°F) or more, the welds will be much tougher, and at 200 or 260°C (400 or 500°F), some bending will occur before breaking. These factors should be considered before welding straight chromium steels.

Chromium-Nickel Stainless Steels. The chromium-nickel group is highly recommended for welding. These metals, being of an austenitic nature, are extremely tough and ductile in the as-welded condition. A straight chromium weld will probably snap as soon as it is bent, but a chromium-nickel weld will bend back flat on itself with no sign of fracture.

Chromium-nickel alloys can be welded with any of the commonly used processes, such as gas metal arc welding (GMAW), shielded metal arc welding (SMAW) or gas tungsten arc welding (GTAW). Forge welding is not recommended because scale is formed on the surface and prevents proper fusion.

In addition to being very fluid in the molten state, the 18-8 type has a high thermal expansion, about 60% more than that of carbon steel; a low heat conductivity (about 1/3 to 1/2 that of carbon steel), and a lower melting point. These same characteristics apply to the straight chromium type, except that the coefficient of expansion is about 10% less than that of carbon steel. These factors should be considered in the design of any welded equipment to prevent difficulties which might arise from undue strains, or warpage.

Carbide Precipitation. While welds in alloys of the chromium-nickel group are far more satisfactory from the standpoint of physical tests, they do, under certain conditions, exhibit a tendency toward "weld decay," or lack of corrosion resistance. When an 18-8 stainless steel with more than 0.08% carbon is heated between 540 and 800°C (1000 and 1500°F) and cooled slowly, excess carbon is precipitated, or segregated out of solution, and deposited along the grain boundaries in the form of carbides. These carbides are less resistant to corrosion than the iron-chromium-nickel alloy, with the result that wherever they are present, more rapid attack will occur when exposed to corrosive conditions.

In making a weld, the metal deposited and the joint itself are heated to the melting or fusing temperature, which is around 1475°C (2690°F), and the body of the work remains cold. Hence, there will be a zone near the weld and parallel to it which will be heated between 540 and 800°C (1000 and 1500°F), and in which area carbides will be precipitated. This region may be wide or narrow, near or some distance from the weld, depending on the type of joint and method of welding, which determines the total amount of heat applied. If welding is rapid, the zone will be narrow and close; if welding is slow, it will be wide and further away. This carbide can be put into solution again by heating to a temperature about 480°C (900°F) or higher, and cooling rapidly through the critical range. Air cooling will be sufficiently rapid if the weldment is thin, 1.6 mm (1/16 in.) or less, but a water quench is advised if the weldment is thick. If the material contains less than 0.08% carbon, such as a modified Type 302, this carbide segregation will be practically negligible, simply because there is not much carbon present and the small amount available remains in solid solution in the alloy itself. This carbide precipitation will not seriously affect the physical properties until it becomes quite extensive, but it will reduce the corrosion resistance considerably, if present even in small quantities. For this reason, only a modified Type 302 is recommended for welded equipment which is to be subjected to highly corrosive attack and which cannot be conditioned after welding. It is also recommended for equipment operating at elevated temperatures, such as 540°C (1000°F) or higher. While reducing the carbon content to below 0.07% will practically eliminate precipitation of carbides during the short time of welding, it will not necessarily stop this condition in equipment operating continuously between 540 to 815°C (1000 to 1500°F). Additions of such alloys as niobium, titanium, or molybdenum to the low carbon stainless steel will further reduce this tendency. Where only heating is the factor, niobium or titanium is satisfactory. If corrosion resistance is of most importance, then molybdenum is preferred. This intergranular corrosion is characteristic of the chromium-nickel alloys of higher alloy content as well as those containing only 18-8, provided the carbon is over 0.08. While corrosion will occur under highly corrosive conditions such as would be produced by an acid attack commonly found in the chemical industries, it should not be assumed that low-carbon alloys are essential for all welded products. Alloys with medium carbon content have proven entirely satisfactory in manufacturing other products, such as food handling apparatus, dairy equipment, architectural trim, or heat-resisting units. Hence, unless the service environment is severely corrosive, the regular 18-8 type will be found to be satisfactory.

No attempt will be made here to comprehensively cover the subject of stainless steel welding and brazing; however, some general information is provided. Suggested references are the *Welding Handbook*: Vol. 1, 8th Edition, 1987 Volume 2, 8th Edition, Welding Processes, 1992; and Volume 3, 8th Edition, Materials and Applications, 1996; published by the American Welding Society, Miami, Florida.

Arc Welding

Arc welding produces highly satisfactory results on stainless steels. Direct current, electrode positive (DCEP) should be used, the same as when welding the non-ferrous metals such as bronze, aluminum, or copper, and similar to the practice followed when welding carbon steel with heavy flux-coated electrodes. While direct current electrode positive (DCEP) will generally give best results, it cannot be considered a hard-and-fast rule. In some instances, especially when heavy plates were involved, direct current electrode negative (DCEN) produced better fusion and penetration.

Plate Preparation. Scarfing the edges is not necessary on plate up to 3.2 mm (1/8 in.) thickness. For 4.8 mm (3/16 in.), if only one bead is to be laid from one side, it is advisable to scarf the edges on a 45° angle to within 1.6 to 2.4 mm (1/16 to 3/32 in.) of the bottom. With 6 mm (1/4 in.) or heavier, it is best to use two or more beads, scarfing from either one or both sides and leaving about 2.4 mm (3/32 in.) unbeveled at either the bottom or center, as the case may be.

The 18-8 stainless has a high coefficient of expansion, about 60% greater than mild steel. In setting up any job, allowance must be made for this expansion. If automatic arc welding is used, the edges should be clamped parallel in the same way as carbon steel, with extra allowance made only when movement is calculated. If a ring is to be welded to a flat circular sheet and a corner weld used, the sheet will bulge at the center due to contraction around the outside on cooling. For this reason, it is more important than with steel to turn a 25 or 50 mm (1 or 2 in.) flange around the sheet and then butt weld the ring or shell to it; this permits the weld to move slightly without producing a buckle. For the same reason, it is advisable to have proper fixtures for holding the work in place while welding to prevent localized strains pulling at the joints and drawing them out of line. This is almost sure to happen if an attempt is made to weld a curved seam without support from a jig or fixture.

Welding Current. The 18-8 alloy can be welded with a lower welding current than required for steel, because this alloy has lower heat conductivity and a lower melting point than steel. These characteristics tend to keep the heat of the arc localized at the point of contact rather than allowing it to travel rapidly back into the plate, so less heat is required for the same size plate and wire than is ordinarily used. For example, if 110 to 120 amperes were used with 3.2 mm (1/8 in.) steel wire, only about 90 to 100 amperes would be needed for 18-8 stainless steel. Stainless will penetrate much better than steel because it is very fluid when molten, while ordinary carbon steel tends to be more viscous and sluggish.

Flux Coating on Electrodes. Chromium and nickel are the chief elements in the stainless steel alloys; the balance is iron. These alloys are highly resistant to heat, that is, they will not scale appreciably at high temperatures as long as they remain in solid form, but will oxidize as soon as molten if exposed to the air. The iron and nickel will remain practically unaffected, but chromium will oxidize rapidly, so it is necessary to protect the molten metal from contact with the air. In shielded metal arc welding (SMAW), this is accomplished by applying a flux coating on the outside of the electrode which will fuse along with the wire. This protects the metal while going through the arc and covers over the deposited metal, excluding any air until the weld has solidified. If the type of flux coating does not afford the required protection, an imperfect or badly oxidized weld will result.

In addition to protecting the metal, the flux coating should also have a stabilizing effect to assist in maintaining a steady arc. As the weld cools, this slag covering will crack off to a large extent, due to the difference in contraction rates between it and the metal. However, if a weld of more than one bead is to be made, all slag should be removed with an air-operated cleaning tool, or by a similar method, to guard against slag which might be entrapped by further layers. The flux has a low melting point, and any small particles remaining will generally be fused and floated to the surface by the heat of the next beads, but this does not always happen. This cleaning procedure will produce welds which will not show any blowholes, gas pockets or slag inclusions on a ground and polished specimen.

When welding stainless steels, the welding rod should have higher chromium and nickel content than the plate to be welded, to compensate for alloying elements lost across the arc. This will provide similar corrosion, physical and chemical characteristics between the two.

In the straight chromium field, the alloy containing 18% chromium is the most common. This type requires the same procedure in welding as the chromium-nickel variety, the differences being that less warpage is likely to occur, due to its lower expansion, and the welds will be hard and comparatively brittle, due to its martensitic structure. In the lower chromium alloys, for example, 12% chromium, the welds can be toughened by annealing, but in the higher alloys with 18% or more chromium, they do not respond satisfactorily to annealing or heat treating. However, if a proper welding procedure is followed, they can be softened to some extent by annealing for eight hours or so at 790°C (1450°F). These alloys are so brittle at room temperature in the as-welded state that they will snap at the slightest deformation.

Discoloration. The high temperature employed in welding, whether on chromium steel or chromium-nickel steel, will discolor the metal for a short distance on each side of the weld. This is an oxide and is only a surface condition; that is, the oxide on the surface does not affect the metal beneath it. The discoloration can be removed easily by some form of pickling, or by grinding and polishing with abrasive wheels and grits. After grinding and polishing, the metal underneath will be in the same condition as before welding. If this oxide is not removed and the surface becomes wet and dry, it will change from a blue color to a brown, resembling iron rust, along these areas. This is also a surface condition only.

Oxyfuel Gas Welding

Oxyfuel gas welding with acetylene can be used on stainless steel, especially in the lighter gauges, such as 18 gauge or thinner. Gas welding, of course, is slower than the electric arc method and therefore apt to produce considerably more buckling and warping.

Neutral Flame. A neutral flame should be used for welding stainless steel; the flame should be as small as possible, supplying only sufficient heat to produce good fusion. Any excess heat will simply aggravate buckling.

Flux. Although the neutral flame will protect the upper side of the weld, it will have no effect on the underside. It is necessary, therefore, to apply a flux along the underside near the edges. The flux may also be applied on the top of the weld as well as on the bottom, or on the wire itself. However, it has been found that the best results are obtained by applying it only to the underside, using as a filler rod a bare wire with the same analysis as the plate.

The flux is generally easiest to apply if it is mixed with water and made into a paste about the consistency of molasses. After applying the paste, it should be allowed to dry long enough to permit it to become fairly solid before welding. As soon as the heat is applied, this flux will fuse, forming a sort of molded cover for the bead and protecting it on the underside. This will produce a smooth, neat-appearing bead; without the flux it will be rough and irregular, and will generally present a burned or bad appearance.

Resistance Welding

Stainless steels are particularly adapted to resistance welding because the inherently high electrical resistance is a fixed property of the steel and is a constant. Stainless steels present a clean surface, free from oxide and scale, and unlike plate stock, there is no zinc or lead coating. This tends to reduce the contact resistance. Contact resistance varies with the pressure, the condition of the electrodes, and the condition of the surfaces of the materials to be welded. The inherent resistance of the steel itself is high, so that this proportion of the total resistance is higher than in other weldable materials.Thus, the variable portions of the total resistance are reduced to a minimum and welding control is greatly simplified.

The capacity of the welding machine required to make a weld in stainless steel is likewise materially reduced. This is due to the high resistance of the metal and its low heat conductivity. Low heat conductivity prevents too rapid a dissipation of heat and allows a greater proportion of the heat to go to the weld.

Spot Welding. Spot welding, in principle, is produced by holding two sheets in close contact between two copper electrodes, and passing a low-voltage, high current through the circuit for a short period of time. Fusion immediately takes place between the two sheets, while the excess heat is rapidly carried away from the outside surfaces by water-cooled electrodes. *See* RESISTANCE WELDING.

While the total heat applied will be determined by adjusting the welding control, the area of the electrode points should be maintained as constant as possible. Any increase in area will tend to reduce the heat per unit area, resulting in an improperly or poorly fused joint. A decrease in area will increase the unit heat and will usually burn a hole entirely or partly through the sheet to be welded, other factors remaining constant. The pressure exerted by the electrodes is generally produced by the compression of helical springs, and can be adjusted by a lock nut on a shaft through the center of the spring. Variable pressures will also affect the quality of the weld. Too much pressure will reduce the resistance of the joint and tend to decrease the heat generated. The pressure generally determines the amount of upset displacement directly following the fusing period, producing an indentation on each side of the welded sheets. In addition to these variables, the time of current flow is of great importance. Too long a period gives the same result as too much heat. Too short a period will produce no weld.

It is evident, therefore, that spot welding depends on the following four variables:

(1) Current

(2) Diameter of electrode contact points

(3) Pressure (controlled by spring or pneumatic pressure)

(4) Length of time the current is allowed to flow.

If both electrodes are the same diameter, a depression will occur on both sides. While not serious when a pickle finish is used, the depression can be objectionable on a polished surface. This depression can be reduced by placing a copper block about 23 mm (1/2 in.) thick and 50 mm (2 in.) square between the electrode and the polished side, thus putting the major depression on the underside. An aluminum block 3.2 to 6.4 mm (1/8 to 1/4 in.) thick works well in some cases, but due to the lower melting point of aluminum, will tend to pit if a slight arc is drawn. This procedure will reduce the depression but will not eliminate it entirely, because the depression is due to shrinkage of the molten metal in the center of the weld, which pulls the base material from both surfaces. If the work is to be polished, the remaining indentation will have to be ground out.

Spot welding, like any other type of welding requiring a high temperature, will cause a blue oxide to be formed on the surface which will change to a brown color resembling rust if exposed to the weather or moist conditions. This is only a surface condition, affecting the original oxide only. If the welds are to be exposed to the atmosphere, they should be cleaned with acid, as in pickling. In the ground and polished state, spot welds have withstood several hundred hours of salt spray without the least sign of attack.

Shot Welding. Shot welding is also a form of spot welding, but uses a higher voltage and shorter time, which produces less heat on the surface. It tends to confine the heat more completely to the junction of the two sections being welded, with the result that there is less oxide or discoloration on the surface than that produced with spot welding.

Seam Welding. Seam welding is similar to spot welding in principle. Instead of using two electrodes in making one weld at a time, rollers are substituted for electrodes and the work is fed between these, and a continual series of intermittent welds is produced. Various machines employ different methods of producing this intermittent effect but in nearly all cases the resulting weld is a series of overlapping spot welds, as can be noted by a stitch effect on the surface. The adjustment or manipulation is similar to that for spot welding. It should be remembered, however, that the range for welding the chromium and chromium-nickel stainless steels is considerably narrower than for common steel and because of this, a closer adjustment is of vital importance.

Flash Welding. Stainless steel can be flash welded much like ordinary steel products, provided certain conditions noted previously are observed. In flash welding, the two sheets or bars to be joined are held in clamps approximately 12.3 mm (1/2 in.) or so from the edges, depending on the section. The current is turned on, the edges brought together and a certain amount flashed off, during which time the temperature of the metal is rising to welding heat. At the proper time, the current is shut off and the two edges squeezed together, or upset, producing a burr along the outside which, when ground or chipped off, shows a solid weld beneath.

In producing the actual upset, the first stage should be very rapid, followed by a slower movement than with steel. This will keep the very fluid, nearly molten metal from dropping away at first, and the slower and final movement will allow the metal to upset evenly instead of crawling irregularly from one side to the other. When conditions are right, this joint will be solid. It is necessary, therefore, that all stages are automatically controlled. The two edges along the joint should be as uniform and straight as possible in order to start heating or flashing along the entire section simultaneously. This will prevent overheating or loss of metal at any one point, as would be the case if contact were made at one end of the joint much earlier than at the other. The grips should also be in good mechanical condition to prevent climbing, especially with thin sections. In general, as in spot welding, less heat or shorter time will be required than with common steel of the same section.

STAKE WELDER

A longitudinal fixture designed for straight-line welding applications on metal from 0.13 mm (0.005 in.) and thicker. These fixtures are used for welding cones, tubes, cylinders, or flat sheets, and are available in models capable of producing welds from 0.6 to 3.65 m (24 to 144 in.) in length. They produce fusion butt welded joints free of meltout, burnbacks, extreme shrinkage or distortion.

STANDARD RESISTANCE

Known resistance that is used for comparison with unknown resistance.

STANDARDS, Welding

The term *Standard* applies collectively to codes, specifications, recommended practices, classifications, methods, and guides for a welding process or application that have been prepared by a sponsoring committee of the American Welding Society (AWS), and approved and adopted in accordance with established procedures. Standards for welding are published in cooperation with the American National Standards Institute (ANSI).

The American Welding Society maintains more than 125 technical committees and sub-committees which prepare and publish approximately 140 documents to serve the welding industry. All AWS standards are voluntary consensus standards because they are adopted voluntarily by users. Volunteers from every sector of the welding industry pool their knowledge and expertise to produce these standards, which are essential to industry and the progress of technology.

Code. A code is a standard consisting of a set of conditions and requirements relating to a particular subject, and indicating appropriate procedures by which it can be determined that the requirements have been met. It is a standard that is suitable for adoption by a governmental authority as a part of a law or regulation, or as specified by other mandatory documents. A code is intended to be mandatory, and it should be used when so required by a governmental authority or specified by other mandatory documents. Other mandatory documents could be documents issued by agencies such as purchasing departments, trade associations, or insurance companies.

Specification. A specification is a standard that clearly and accurately describes the essential technical requirements for a material, product, system or service. It indicates the procedures, methods, qualifications, or equipment by which it can be determined that the requirements have been met. A specification is intended to be mandatory when referenced by other mandatory documents, such as those for procurement purposes, or when mutually agreed upon by the parties involved.

Recommended Practice. A recommended practice is a standard that describes general industry practice for some particular process, material, technique, or method, as well as other factors and items that should be considered before using that process, material, technique, or method.

Classification. A classification is a standard intended primarily to establish an arrangement or division of materials or products into groups based on similar characteristics such as origin, composition, properties, or use.

Method. A method is a standard consisting of a set of requirements relating to the manner in which a particular kind of test, sampling, analysis, or measurement is conducted to determine the properties, composition, or performance of some item. A method does not include numerical limits for the properties, composition, or performance, and is invoked, not by itself, but by other standards.

Guide. A guide is a standard that provides information to the user as to the best practical methods to accomplish the task described. A guide usually provides several different methods.

Standards Development

The Technical Activities Committee (TAC) of the American Welding Society has oversight of the technical committees and subcommittees responsible for writing standards.

AWS subcommittees consist of volunteers who provide the technical input to the documents and prepare the standards. Committee membership must be balanced to ensure that all interests are properly represented. A committee ideally consists of one-third suppliers (producers or distributors of any product or service specified in the Standard), one-third consumers (those directly concerned with the use of any product specified in the Standard, but not with its production or distribution), and one-third general interest members, (others who are interested, i.e., the academic community).

Committee meetings are open to the public; committee meeting schedules are published in the *Welding Journal* each month.

After subcommittee agreement on the content of the document, it is reviewed by the specific technical committee to which the subcommittee reports. The draft approved by the technical committee is sent to the Technical Activities Committee, which consists of the chairmen of all of the technical committees, and three at-large members. Members of the TAC vote on two aspects of the document:

(1) Conformance with the rules for preparation of the Standard

(2) Adequacy of the technical content of the document.

The next step is review by the Technical Council, which consists of ten members of the AWS Board of Directors. Technical Council members verify by vote that ANSI/AWS rules and procedures were followed during the preparation and balloting of the document. Technical Council members may comment on the technical content of a document, but they do not vote on technical content.

When the Standard is submitted to the Technical Council, it is opened to public review. Availability of the document for review is advertised in the *Welding Journal* and ANSI's publication, *Standards Action.* Anyone concerned with the document has 60 days to obtain a copy and make comment. All comments received are considered and the commentator is notified of the results. If there are no negative responses to the draft, or when negative responses have been resolved, ANSI's Board of Standards Review approves the document as an American National Standard and it is published.

Standards development and maintenance is an ongoing process. Every five years these documents must be revised, reaffirmed or withdrawn to comply with ANSI requirements. *See* Appendix 16.

STANDARD WELDING PROCEDURE SPECIFICATION (SWPS)

A welding procedure specification (WPS) prepared by the Welding Research Council (WRC) Welding Procedures Committee. The committee uses procedure qualification reports (PQRs) which it develops or those developed by industries and donated. After the standard welding procedure specifications are prepared by the WRC committee, they are sent to the American Welding Society (AWS) B2 Committee on Qualification. The documents then proceed through the AWS ballot sequence, and after approval at all levels, become American National Standards. *See also* Appendix 16.

STANDARD WELDING TERMS

A glossary of terms and definitions developed by the American Welding Society (AWS) to standardize the oral and written communication of the details of welding, brazing, soldering, thermal spraying, and thermal cutting processes and applications.

Standard terms and definitions are identified in this edition of the Welding Encyclopedia. All standard terms are referenced to STANDARD WELDING TERMS. *The standard definitions are in italics.* Nonstandard terms are identified as such.

The American Welding Society publishes this glossary of the technical terms used in the welding industry in the document, *ANSI/AWS A3.0, Standard Welding Terms and Definitions.* This document, in dictionary form, was prepared by the AWS Committee on Definitions and Symbols, and is a comprehensive compilation of welding terminology. The document establishes each term as standard or non-standard to reflect the accuracy of the term. Nonstandard terms are also included because of common usage. The document is an American National Standard, developed in accordance with the rules of the American National Standards Institute (ANSI).

There are 1253 terms and definitions in A3.0-94, with 53 illustrations to support and clarify the definitions, as well as classification charts and corollary information for the welding processes. To preserve an understanding of old documents and literature, welding terms believed to be no longer significant in the welding industry are included in A3.0. Obsolete or seldom used processes are listed separately.

The first AWS document containing welding definitions was published January 18, 1940. The latest publication, ANSI/AWS 3.0-94, was published May 23, 1994.

STANDOFF DISTANCE

The distance between a nozzle and the workpiece. See STANDARD WELDING TERMS. *See* Appendix 10.

START CURRENT

The current value during start time interval. See STANDARD WELDING TERMS. *See* Appendix 19.

STATIC ELECTRODE FORCE

See ELECTRODE FORCE.

STARTING WELD TAB

Additional material that extends beyond the beginning of the joint, on which the weld is started. See STANDARD WELDING TERMS.

START TIME

The time interval prior to weld time during which arc voltage and current reach a preset value greater or less than welding values. See STANDARD WELDING TERMS. *See* Appendix 19.

STATIC ELECTRODE FORCE

The force exerted by electrodes on the workpieces in making spot, seam, or projection welds by resistance welding under welding conditions, but with no current flowing and no movement in the welding machine. See STANDARD WELDING TERMS.

STATIONARY SHOE

A backing shoe that remains in a fixed position during welding. See STANDARD WELDING TERMS.

STATOR

The stationary part of an induction motor or generator on which the field windings are placed.

STEEL

A hard, strong, durable iron-carbon alloy which may or may not contain other alloying elements besides those which appear as impurities. Steel always contains less than 1.7% carbon. Steel is malleable when suitable conditions are provided.

STEEL, Acid

Steel melted under a slag which has an acid reaction and in a furnace with an acid bottom and lining. See STEEL, Basic.

STEEL, Alloy

A plain carbon steel to which another element, other than iron and carbon, has been added in a percentage large enough to alter the characteristics and properties of the steel. These elements may be chromium, manganese, nickel, tungsten, or vanadium, and are added to produce or increase certain specific physical properties, such as hardness, toughness, ductility, strength, resistance to corrosion or resistance to wear.

The various kinds of steel are most often identified by a type designation or a specification number.

SAE (formerly Society for Automotive Engineers) and the American Society for Testing Materials developed a unified system for designating metals and alloys. *See* UNIFIED NUMBERING SYSTEM.

The American Iron and Steel Institute and SAE published a system for designating carbon and alloy steels using the UNS identifications. *See* Table S-6.

Table S-6
AISI-SAE System for Designation of Carbon and Alloy Steels*

Description	AISI-SAE Designation	UNS Identifier Number**
Low-Carbon Steels for Wire and Rods	100X	G100XO
Carbon Steels	10XX	G10XXX
Carbon Steels, Resulfurized (Free Machining)	11XX	G11XXX
Carbon Steels, Resulfurized and Rephosphorized	12XX	G121XX
Manganese Alloy Steels with Mn 1.60 to 1.90%	13XX	G13XXX
Manganese Steels with Mn Maximum over 1.0%	15XX	G15XXX
Nickel Alloy Steels	2XXX	
Nickel-Chromium Alloy Steels	31XX	G31XXX
High Nickel-Chromium Alloy Steels	33XX	G33XXX
Carbon-Molybdenum Alloy Steels	40XX	G40XXX
Chromium-Molybdenum Alloy Steels	41XX	G41XXX
Chromium-Nickel-Molybdenum Alloy Steels	43XX	G43XXX
Nickel-Molybdenum Alloy Steels	46XX	G46XXX
Nickel-Chromium-Molybdenum Alloy Steels	47XX	G47XXX
High Nickel-Molybdenum Alloy Steels	48XX	G48XXX
Low-Chromium Alloy Steels	50XX	G50XXX
Chromium Alloy Steels	51XX	G51XXX
High-Carbon Chromium Alloy Steels	51X00	G51986
High-Carbon Chromium Alloy Steels	52100	G52986
Chromium-Vanadium Alloy Steels	61XX	G61XXX
Chromium-Vanadium-Aluminum Alloy Steels	E71400	G71406
Nickel-Chromium-Molybdenum-Boron Alloy Steel	81B45	G81451
Low Nickel-Chromium-Molybdenum Alloy Steels	86XX	G86XXX
Low Nickel-Chromium-Molybdenum Alloy Steels	87XX	G87XXX
Nickel-Chromium-Molybdenum Alloy Steels	8822	G88220
Silicon-Manganese Spring Steels	92XX	G92XXX
Silicon-Manganese-Chromium Spring Steels	92XX	G92XXX
Nickel-Chromium-Molybdenum Alloy Steels	93XX	G93XXX
Nickel-Chromium-Molybdenum Alloy Steels	98XX	G98XXX
Boron Containing Steels	XXBXX	
Boron-Vanadium Containing Steels	XXBVXX	
Lead Containing Steels (Free Machining)	XXLXX	

*Categories of Composition, Ranges, and Limits for Elements

**All "X" marks shown in the UNS Identifier Number following the alphabetical identification of each series are replaced by a digit when a specific steel in the series is singled out.

STEEL, Austenitic

See MANGANESE STEEL *and* STAINLESS STEEL.

STEEL, Basic

Steel melted under a slag with a basic reaction, and in a furnace with a basic bottom and lining.

In specific steelmaking processes, the matter of acid versus basic steelmaking should be examined, because an understanding of these two terms is metallurgically important to both steelmaking and welding. The terms *acid* and *basic* are derived from the kind of refractory lining and the slag used in a process. Most of the nonmetallic compounds that are used in making refractory furnace linings or employed as a flux or slag can be classified as having either acid or basic (alkaline characteristics when heated to the temperatures encountered in steelmaking. A material is classified by noting any tendency on its part to react with a strongly basic material like lime (CaO) or a decidedly acid material like silica (SiO_2). Dissimilar materials will react or attack each other while similar materials will not. A furnace operating with a basic-type slag will have a refractory lining made of basic materials, whereas a furnace using an acid-type slag will have a lining of acid materials. If an acid slag is used in a basic-lined furnace, the slag would quickly attack and damage the furnace lining. The common acid materials involved in steel-melting are silica (SiO_2) and phosphorus pentoxide (P_2O_5), while the basic materials are lime (CaO), burnt dolomite (MgO, CaO), iron oxide (FeO), and manganese oxide (MnO).

The important difference between acid and basic steelmaking processes is in their respective ability to rid the molten metal bath of residual phosphorus and sulfur. In the acid steelmaking furnace, there is no significant removal of phosphorus and sulfur because the acid slag cannot react chemically with these two elements. The charge of raw materials as a whole must meet the same maximum requirements specified for these two elements in the finished steel. This means high-grade ore and steel scrap must be used. For the most part, an acid-lined furnace functions mainly as a furnace to melt a charge, remove carbon, and hold the molten bath while nonmetallics rise from it and become part of the slag.

STEEL, Capped

See STEEL, Rimmed.

STEEL, Carbon

See CARBON STEEL.

STEEL, Cast

Cast steel can be welded using the same electrodes and procedures used to weld wrought steel.

In a very complicated or thin cast steel section, the heat should be distributed as widely as possible, and in extreme cases the welding operation should be carried on intermittently to allow the heat to be distributed over the workpiece, so that a sufficient amount of heat is not concentrated at one point to cause undue or harmful expansion of the metal.

Wear-Resistant Surface. For a manganese steel casting used, for example in railway crossovers, satisfactory welding can be done using a 12% manganese steel electrode.

Wherever possible, a weld made in a steel casting should be reinforced so that the section of the weld is larger than the original adjacent section. This is needed due to the low degree of ductility compared with the ductility of the original casting.

Fatigue Failures. Cast steel is generally presumed to have less resistance to fatigue than rolled steel. Castings subjected to alternating stresses of tension and compression will provide service for a given length of time but may eventually fail. The initial failure due to breakage may be repaired by welding, but in a comparatively short length of time, another failure may occur in some other part of the casting. One explanation for this reaction is that at the time of initial failure, the metal of the casting had undergone its limit of fatigue. If the casting had been annealed, the later failures would probably have been eliminated. Frequently steel castings which have been repeatedly subjected to high temperatures cannot be welded. This occurs particularly in the case of annealing pots and annealing boxes. In such a case it is impossible to get a reasonable degree of fusion between the added metal and the metal of the original piece.

STEEL, Clad

A thin solid overlay section bonded to the surface of a heavier section of steel plate to provide corrosion resistance or an improved mechanical property. Steel plate can be clad by overlay welding, explosion welding, or by roll welding two or more solid sections together. *See* STAINLESS STEEL WELDING.

STEEL, High-Alloy

A steel alloy with a content of chromium, nickel, or manganese of 10% or higher.

STEEL, High-Carbon

Steel containing 0.45% or more carbon.

STEEL, High-Speed

A name commonly applied to certain tool steel alloys. The most common of these are the 18-4-1 steels, with a chemical composition of 18% tungsten, 4% chromium, and 1% vanadium. Molybdenum high-speed steels are another type. They are usually composed of approximately 9% molybdenum, 4% chromium, 1.6% tungsten, and 1% vanadium. High-speed steels usually contain from .75 to .80% carbon, and for this reason are difficult to weld by processes other than arc welding. *See also* TOOL BRAZING.

STEEL, High Strength Low Alloy (HSLA)

Steels with less than 0.25% carbon and with an alloy content less than 5% are considered high-strength, low-alloy steels.

STEEL, Killed

Killed steel is made by removing or tying up the oxygen that saturates the molten metal prior to its solidification to prevent effervescence or rimming action during cooling. The molten steel is held in the ladle, furnace or crucible, (and usually treated with aluminum, silicon, or manganese), until no more gas is evolved and the metal is perfectly quiet.

STEEL, Low-Carbon

A classification of carbon steel with a carbon content less than 0.15%. Only residual quantities of other elements are present, except for small quantities of silicon and manganese which are added for deoxidation during the steel making process.

STEEL, Manganese

See MANGANESE STEEL.

STEEL, Medium Carbon

Steel that contains between 0.30 and 0.45% carbon.

STEEL PLATE

A term applied to steel that is more than 3.2 mm (1/8 in.) thick.

STEEL, Rimmed

An incompletely deoxidized steel usually containing less than 0.25% carbon and having the following characteristics:

(1) During solidification, an evolution of gas occurs sufficient to maintain a liquid ingot top ("open" steel) until a side and bottom rim of substantial thickness has formed. If the rimming action is intentionally stopped shortly after the mold is filled, the product is termed *capped steel.*

(2) After complete solidification, the ingot consists of two distinct zones: A rim somewhat more pure than when poured, and a core containing scattered blowholes, with a minimum amount of pipe, and having an average metalloid somewhat higher than when poured, and markedly higher in the upper portion of the ingot.

STEEL, SAE

Steels which conform to the specifications of the Society of Automotive Engineers.

STEEL, Sheet

A term usually applied to steel under 3.2 mm (1/8 in.) thick. *See* SHEET METAL WELDING.

STEEL, Stainless

See STAINLESS STEEL.

STEEL, Structural

See STRUCTURAL WELDING.

STEEL, Zinc Coated

See GALVANIZED IRON, Welding.

STEPBACK SEQUENCE

A nonstandard term for BACKSTEP SEQUENCE.

STEP BRAZING

The brazing of successive joints on a given part with filler metals of successively lower brazing temperatures so as to accomplish the joining without disturbing the joints previously brazed. See STANDARD WELDING TERMS.

STEP DOWN

The reducing of electric current or voltage from a higher to a lower value.

STEP SOLDERING

The soldering of successive joints on a given part with solders of successively lower soldering temperature so as to accomplish the joining without disturbing the joints previously soldered. See STANDARD WELDING TERMS.

STEP UP

Increasing or changing electric current or voltage from a lower to a higher value.

STETHOSCOPIC TESTING

A technique used during the late 1920's for testing welds for porosity by evaluating the sound produced with the tapping of a hammer. A stethoscope with a rubber tip made contact on the surface of the plate. This apparatus excluded extraneous sounds and minimized damping of the oscillations at the contact point on the metal. The drum, pipe or plate being tested is tapped with a small hammer at the spot to be tested. The presence of a serious defect in a vessel could often be determined by its ring. A "flat" or dull sound indicated to the trained ear the presence of a defect.

In past times, blacksmiths used this principle when hammering metal cold on the anvil to test it. In "sounding" a tank, however, this technique was difficult due to the forced and natural vibrations of the tank, and the tendency for the natural vibration to drown out all other sounds. This technique has been superseded by radiographic and other nondestructive testing technologies, except perhaps in cases where this equipment is not available.

STICK ELECTRODE

A nonstandard term for COVERED ELECTRODE.

STICK ELECTRODE WELDING

A nonstandard term for SHIELDED METAL ARC WELDING.

This term is often applied to manual arc welding, in which a bare or coated electrode, often referred to as a "stick," is used.

STICKOUT, Gas Tungsten Arc Welding

The length of the tungsten electrode extending beyond the end of the gas nozzle. See STANDARD WELDING TERMS. *See* Appendix 10.

STICKOUT, Gas Metal Arc Welding and Gas Shielded Flux Cored Arc Welding

The length of unmelted electrode extending beyond the end of the gas nozzle. See STANDARD WELDING TERMS. *See* Appendix 10.

STITCH WELD

A nonstandard term for INTERMITTENT WELD.

STOPOFF

A material used on the surfaces adjacent to the joint to limit the spread of soldering or brazing filler metal. See STANDARD WELDING TERMS.

STORED ENERGY WELDING

A resistance welding process variation in which welds are made with electrical energy accumulated electrostatically, electromagnetically, or electrochemically at a relatively low rate and made available at the required welding rate. See STANDARD WELDING TERMS.

STRAIGHT POLARITY

A nonstandard term for DIRECT CURRENT ELECTRODE NEGATIVE (DCEN).

This term describes the arrangement of welding leads in which the electrode is the negative pole and the workpiece is the positive pole of the arc circuit. *See* DIRECT CURRENT ELECTRODE NEGATIVE.

STRAIN

Distortion or deformation of a metal structure due to stress. *See* DISTORTION.

STRAIN AGING

See AGING.

STRAIN HARDENING

An increase in elastic limit, hardness, and tensile strength of metals produced by straining. Further increases, particularly in elastic limit, occur on aging at ordinary or slightly elevated temperatures. For mild steel, the maximum aging effects are obtained by heating between 200 to 300°C (390 to 570°F).

STRAIN GAUGE

An instrument used to measure a material's elastic deformation produced by stresses created when loads are applied to the material.

A popular type of strain gauge is the Berry strain gauge, a hand-held instrument with a prepared gauge showing length before and after a known load is applied. Based on the relationship of the strain of deformation to the stress in the test material, the stress in the test structure is determined when the difference in gauge length is found.

The usual gauge length is 50.8 mm (2 in.) for standard test specimens. Instruments adjusted to 203 mm (8 in.) are almost as common, and for structural tests on long members, a 508 mm (20 in.) instrument is used. All of them indicate changes of length in 0.025 mm (.001 in.).

STRANDED ELECTRODE

A composite filler metal electrode consisting of stranded wires that may mechanically enclose materials to improve properties, stabilize the arc, or provide shielding. See STANDARD WELDING TERMS.

STRANDED WIRES

Wires or cables composed of a number of small wires twisted or braided together. *See* CABLE AND CABLE CONNECTORS.

STRAP WELD

A reinforcement band (or any shape) of metal welded across two adjoining plates or surfaces on the underside of the plate or joint to add strength and stability. After welding the underside reinforcements, the two edges on the upper side of the reinforcement are then welded.

STRENGTH

The ability of a material to resist strain.

STRESS

Force producing or tending to produce deformation of a metal. *See* DISTORTION.

STRESS-CORROSION CRACKING

Failure of metals by cracking under combined action of corrosion and stress, residual or applied. In brazing, the term applies to the cracking of stressed base metal due to the presence of a liquid filler metal. See STANDARD WELDING TERMS.

Stress-corrosion cracking was once and is still occasionally called *chloride ion cracking, halogen-induced stress cracking,* or *halide contamination cracking*.

There are believed to be two different sets of conditions present in a material in which stress corrosion cracking occurs: active path corrosion and hydrogen embrittlement. In active path corrosion, cracking is caused by localized corrosion at the crack tip, which then proceeds along a path which is electrochemically active with respect to the surrounding metal. In hydrogen embrittlement, cracking results from the entry of hydrogen into the metal, which reduces the capability of the metal to deform plastically.

The following conditions promote corrosion cracking: (1) a susceptible metal, (2) a specific environment, and (3) a tensile stress. Metal susceptibility and environment specificity depend on the particular metal-environment combination. A metal may be susceptible to stress corrosion cracking in only a few specific environments, and conversely, a particular environment may induce cracking in only certain metals. Usually, the tensile stress must exceed a specific level, depending on the particular metal-environment combination, to produce stress corrosion cracking.

The sequence of events generally leading to failure of a metal by stress corrosion cracking begins with localized chemical attack of the metal surface. A crack then initiates at a sharp intrusion produced by this attack, and grows slowly. When the crack reaches a size at which the metal can no longer support the load, rapid fracture occurs. If a crack-like flaw is already present in the metal surface, localized attack is not necessarily the cause; slow crack growth proceeds from the flaw.

The process of stress corrosion cracking involves a complex interaction of metallurgical, chemical, and mechanical factors. Since these three factors correspond to the three conditions which produce stress corrosion cracking, the role of each factor in this phenomenon must be considered.

Stress Corrosion Cracking in Stainless Steel. Experimental data indicates that as little as 5 ppm of available chloride is sufficient to cause stress corrosion cracking in stainless steel. To minimize the possibility, every precaution must be taken to ensure that all possible sources of halogen contamination are kept away from the base metal. Materials used in purging dams and related items should be only those known to be free of halogens. Several types of commercially available metal marking pens are known to contain significant quantities of available halogens and are capable of causing cracking. Perspiration from hand prints sometimes contains sufficient available chloride to cause stress corrosion cracking, so clean cotton gloves should be used in handling stainless steel.

STRESS-RELIEF CRACKING

Intergranular cracking in the heat-affected zone or weld metal as a result of the combined action of residual stresses and postweld exposure to an elevated temperature. See STANDARD WELDING TERMS.

This phenomenon is most prevalent in age-hardenable alloys. It is also referred to as *reheat cracking* or *strain age cracking*.

STRESS-RELIEF HEAT TREATMENT

Uniform heating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling. See STANDARD WELDING TERMS.

The mechanism of stress relief is yield (with or without some degree of creep) by residual stresses that exceed the flow (or creep) strength of the material at the heat treating temperature. Stress relief is the most common reason heat treatment is used in welding. *See* HEAT TREATMENT.

A gas-fired car bottom furnace used for stress-relieving steel forgings is shown in Figure S-26. The furnace is 1.5 m (5 ft) wide by 3 m (10 ft) deep by 1.5 m (5 ft) high. The furnace door is pneumatically lifted overhead to gain entrance to the furnace chamber. The car is electrically driven.

STRIKE

See STANDARD WELDING TERMS. *See also* ARC STRIKE.

STRINGER BEAD

A type of weld bead made without appreciable weaving motion. See STANDARD WELDING TERMS. *See also* WEAVE BEAD.

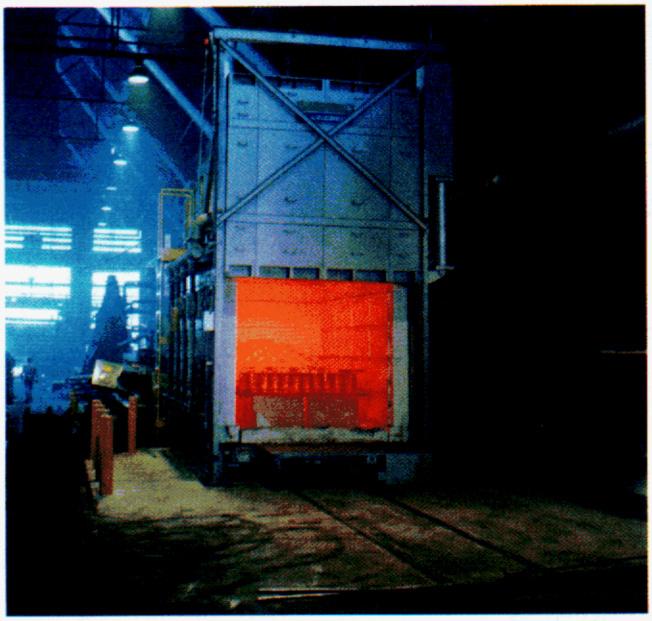


Figure S-26—A Gas-Fired Car Bottom Furnace Used for Stress-Relieving Steel Forgings up to a Maximum Operating Temperature of 1000°C (1800°F)

Photo courtesy of Lindberg Unit of General Signal Company

STRIP WELDER

A flash-butt welding machine used in steel mills to join the ends of sheet steel to produce a continuous strip.

STRONGBACK

A device attached to both sides of a weld joint to maintain alignment of the members during welding. See STANDARD WELDING TERMS.

STRUCTURAL WELDING

Any welded assembly requiring resistance to externally applied forces or moments but not intended to resist pressures above 103 kPa (15 psig) and requiring resistance to externally applied forces or moments is considered a structure.

Structural welding has progressed from its original application in the building and bridge industries to a wide spectrum of industrial uses. Fabrications as diverse as offshore oil and gas platforms, grain silos, missile launchers, crane booms, and amusement rides depend on welding for strength and integrity. There are three essential phases to any engineering and construction project: design, fabrication or erection, and inspection.

Structural Design. Design typically involves the arrangement of structural elements to adequately resist external loads. A major aspect of design therefore involves the calculation of stresses and sizing of members and connections. Computer models and hand calculations, used in conjunction with design specifications, are used by the structural engineer to accomplish this task. An additional aspect of design that is important to the structural engineer, fabricator and erector is the selection of base metal. The engineer should be aware of several properties necessary for adequate service and construction qualities.

Construction Steels. Yield strength is the property of most interest to engineers. A steel's yield strength primarily depends on its carbon content, alloy content, heat treatment, mechanical processing, or any combination of these. High carbon or alloy content can produce steel with high hardenability, which can result in hydrogen cracking.

This susceptibility can necessitate special welding requirements, such as high preheat and interpass temperatures or even postweld heat treatment. The "conventional" construction steels, such as ASTM A36 and ASTM A572 Grade 50, have an excellent history of ready weldability when welded in accordance with prescribed limits, such as are found in the ANSI/AWS D1.1, *Structural Welding Code—Steel.* Such steels use carbon or low alloys (such as vanadium) or both to provide strength in the as-rolled or normalized condition. Modern steelmaking techniques have created a new generation of steels with optimum weldability, because of low carbon and alloy contents. In order for such steels, such as ASTM A841, ASTM A913 or API 2W, to achieve the strength levels expected of the more traditional construction steels, controlled rolling and thermal processing (i.e., thermomechanical processing) are used in the steel mill to finish the wrought material. Weldability of the materials, as measured by their relatively low hardenability, and resistance to hydrogen cracking, is excellent; low preheat is required (or frequently none) to produce high yield strength welds with excellent notch toughness and low cracking sensitivity.

While weldability and yield strength are always considerations for any type of welded structure, notch toughness typically is a primary concern for dynamically loaded structures. Dynamic loads can range from low stress cyclically applied over a long period of time to a single impact at high velocity. Bridges and offshore platforms exemplify the first category, making fatigue a primary consideration in design. In order to minimize the probability of fracture under dynamic stress and in the presence of a discontinuity, a specified notch toughness is usually required for base metal, filler metal, deposited weld metal, base metal heat-affected zone (HAZ) or any combination of these.

Base metal notch toughness is a metallurgical property usually obtained through control of chemistry, deoxidizing (killing), heat treatment (e.g., normalizing), or thermomechanical processing. Filler metals usually rely on alloys, such as nickel, for enhancing toughness as demonstrated by the electrode manufacturer's certification tests.

For deposited weld metal and the heat-affected zone (HAZ), a filler metal and base metal with a specified notch toughness obviously must be employed, but technique also becomes important in ensuring that the fused joint has the required minimum toughness. This is demonstrated in the welding procedure specification (WPS) qualification test. Typical techniques include low heat input and the use of small weld beads that temper or grain-refine previously deposited passes.

Although the science of fracture mechanics has introduced mathematical rigor to the subject of fracture resistance, the Charpy-V notch test remains the method of choice for assessing notch toughness. Typically expressed as impact energy required for specimen fracture at a specified test temperature, Charpy V-notch values are a qualitative assessment of toughness.

It is important for designers to understand the relative nature of these values; whereas it can be stated with confidence that a material tested at 27 joules at –18°C (20 ft-lbs at 0°F) is tougher than a material tested at 27 joules at 21°C (20 ft-lbs at 70°F), it would not be appropriate to assume that the 27 joules at –18°C (20 ft-lb at 0°F) material could successfully resist an impact of 27 joules at –18°C (20 ft-lb at 0°F) in actual service. This is because several factors influence notch toughness which are not accurately reflected in the Charpy V-notch test. Temperature, loading rate, severity of stress risers and degree of restraint against plastic flow are all key factors in degrading fracture resistance, and it is the interaction of these factors that is critical to this property.

Fracture mechanics has attempted to rationalize these factors through the use of formulae and tests, which are generally expensive and time-consuming. However, even fracture mechanics methods cannot exactly replicate actual service conditions. The engineer must still use judgement in assessing how much toughness is adequate for any given application.

Service Environments. The bridge and offshore industries have long histories with their particular structures and dynamic loading environments; therefore, the incidences of brittle fracture that occur now in these applications are usually due to poor design details or fabrication that allows severe stress concentration sites for cracking to initiate. Until the Northridge, California, and Great Hanshin (Kobe), Japan, earthquakes of 1994 and 1995, respectively, steel moment frame buildings designed to resist seismic loading had a flawless track record of fracture-free survivability. However, these two earthquakes severely undermined confidence in many assumptions about seismic structural design, material properties and testing methods.

Many welded connection and base metal fractures were observed in buildings, though no fracture resulted in structural collapse. As a result, extensive research and debate continues as to the best method of resisting fracture in a seismic event. Earthquakes, representing nature's power at its most awesome, will continue to challenge all assumptions and predictions. However, the performance of welded steel structures, while also not conforming to predicted behavior, have succeeded in their most vital requirement, the preservation of human life. In comparison to structures of other materials that collapsed and did result in deaths, welded steel is still viewed by many as the optimum seismic material.

Material Selection. Though steel constitutes the bulk of structural metal used by industry, aluminum is the second most popular structural metal, primarily because of its low weight to strength ratio and resistance to corrosion. The marine and aerospace industries in particular find welded aluminum to be an attractive alternative to steel. Alloys such as 6061 are readily weldable and frequently used in the as-welded condition, even though the joint strength is less than the base metal strength. When higher strengths as well as corrosion resistance are requirements, stainless steel competes with other metals such as nickel and titanium. These metals have their own peculiar weldability requirements that challenge engineers and fabricators. Other materials may be introduced into the structural markets of the future, posing fabricators with the challenge of welding with a variety of processes.

Welding Processes. Process selection is, in fact, a vital concern of fabricators faced with production and quality demands as well as the need to control costs. In the past, the flexibility offered by the SMAW process made it an overwhelming favorite for shop, field and repair welding alike. Although the cellulosic and rutile SMAW electrodes (e.g., E6010) have traditionally been popular for their contribution to weldability, the large quantity of diffusible hydrogen contained within their deposited weld metal can promote hydrogen cracking unless strictly controlled.

With the productivity improvements made in automatic and semi-automatic processes, the popularity of shielded metal arc welding (SMAW) has declined significantly. Shop welding provides an ideal environment to make the gas metal arc welding (GMAW) and flux cored arc welding (FCAW) processes popular for welding sheet steels as well as structural thicknesses, 3.2 mm (0.125 in.) and up.

Thick materials, on the order of 50 mm (2 in.) and greater, are more efficiently shop welded with the submerged arc welding (SAW), electroslag welding (ESW) or electrogas welding (EGW) processes. The ESW process offers the highest potential productivity, but extra care must be taken to avoid mid-welding stoppages and excessive HAZ grain growth. While SMAW is still frequently used in shop welding, its use is declining for general production welding.

Field welding, with its exposure to wind and differing accessibility situations, limits the process types available to a contractor. Here again SMAW has been the process of choice and remains popular; however, the improved reliability, productivity and portability of the FCAW-S process have made significant inroads into SMAW's popularity. The self-shielded flux core process is, in fact, very often selected in the building and marine industries because of its high arc duty cycle, high productivity and lower defect rejection rate than SMAW. Repair welding remains the one area where SMAW will probably maintain its popularity.

Procedure Qualification. Qualification of welding procedure specifications (WPS) and personnel (welders, welding operators and tack welders) is an essential aspect of any fabricator's quality assurance and quality control (QA/QC) program. Fabricators can economize by promoting the use of prequalified WPSs which are exempt from mechanical testing when performed in accordance with ANSI/AWS D1.1. This requires staying within prescribed limits which could constrain a fabricator from maximizing productivity. It is frequently more efficient to take the expense of qualifying a WPS in order to use parameters that are more productive than permitted for WPS prequalification.

Welder Qualification. Whereas WPS tests are intended to demonstrate metallurgical and mechanical compatibility between base metal and filler metal, personnel qualification tests the welder's skill and competence to deposit sound weld metal. Qualified personnel are the first line of defense against welding defects. Fabricators can benefit by ensuring that their welding personnel are well trained for their job function.

Inspection. Inspection occurs before, during and after welding to ensure conformance with contract requirements (e.g., drawings, specifications). The owner of a structure may choose to select a verification inspector, who is typically a third party agency, to oversee a fabricator's work. The fabricating company will have its own inspectors to supervise qualifications, material certifications, joint fit-ups, electrode and base metal preparation, and all other activities required to deliver a quality product.

Inspection is sometimes an area much neglected by engineers, who should take into account the diversity of available inspection methods. The engineer should ascertain prior to bid document release what kinds of welds require which type of inspections. Typically, critical connections subject to tension require a nondestructive testing (NDT) method suitable for probing below the weld surface. Radiographic testing (RT) and ultrasonic testing (UT) are the most popular methods for this task, with RT competing with UT in the shop environment, but with UT being overwhelmingly popular in the field. Both methods can detect discontinuities within the volume of the weld, through visual indications on exposed film (RT) or acoustic reflections displayed on a screen (UT).

For less critical connections, such as joints in compression or shear, surface NDT methods are less expensive and easier to implement. Magnetic particle testing (MT) and liquid penetrant testing (PT) are the preferred methods, though MT is limited to steels with a predominantly ferritic or martensitic microstructures. Only surface or near-surface discontinuities are visually detectable, but since it is usually surface defects that result in crack initiation, these NDT methods are adequate for non-tension welds.

Repair welding is necessitated when unacceptable discontinuities are discovered by the inspection. If the

Engineer of Record refuses to accept the defective weld, gouging out of the offending discontinuity is required, followed by cleaning of the gouged area, rewelding and reinspection. However, it is always the Engineer's prerogative to accept a Code-defective weldment if the intended design application is not adversely affected. Frequently, the prospects of successfully rewelding are poor, and this may influence the Engineer's decision.

Fitness-for-purpose methods are available that attempt to couple the NDT-detected discontinuities with fracture-mechanics analyses to ascertain crack sensitivity. Since many codes, such as ANSI/AWS D1.1, are primarily workmanship-based rather than service load-based, requirements that are not complied with in construction do not necessarily imply that a weld will not adequately resist their design loads. It is up to the Engineer to determine this acceptability if he or she so chooses. Otherwise, Code requirements prevail and potentially costly weld repair will be required.

Cost and Structural Integrity. Economy is an important factor in any engineering project, of course, but the Engineer's primary concern is structural integrity and safety, reflected by adherence to quality requirements. It is the harmonious marriage of these virtues that make structural welding such a popular method of providing civilization with safe, affordable structures within which we can work, play and enjoy life in general.

References. Specific information on structural welding is available from the American Welding Society (AWS) in its document, ANSI/AWS D1.1-96, *Structural Welding Code—Steel.* Computerized access to this document is available on a compact disk, (CD-ROM), and one version includes full-page images of the 25 AWS publications referenced in the document.

STUB

The short length of filler metal electrode, welding rod, or brazing rod that remains after its use for welding or brazing. See STANDARD WELDING TERMS.

STUBBING

A condition in a gas metal arc welding machine in which the electrode dips into the weld puddle and then is "frozen" in place, due to the lack of short circuit current. This produces a definite weld defect that may be minimized by using a constant voltage welding machine.

STUD ARC WELDING

A nonstandard term for ARC STUD WELDING.

STUD WELDING

A general term for joining a metal stud or similar part to a workpiece. Welding may be accomplished by arc, resistance, friction, or other process with or without external gas shielding. See STANDARD WELDING TERMS.

The three common stud welding methods are electric arc, capacitor-discharge, and drawn-arc/capacitor-discharge. All are adaptable to automatic and semiautomatic uses. *See also* ARC STUD WELDING and CAST IRON STUDDING.

STUDDING, Cast Iron

Distributing steel studs along the face of cast iron parts to be welded with the shielded metal arc process so that the weld cannot pull away from the cast iron. A steel electrode is used. *See* CAST IRON STUDDING.

SUBMERGED ARC WELDING (SAW)

An arc welding process that uses an arc or arcs between a bare metal electrode or electrodes and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the workpieces. The process is used without pressure and with filler metal from the electrode and sometimes from a supplemental source (welding rod, flux, or metal granules). See STANDARD WELDING TERMS. *See also* HOT WIRE WELDING *and* SERIES SUBMERGED ARC WELDING.

In submerged arc welding, the arc is covered by a flux. This flux plays a main role in that (1) the stability of the arc is dependent on the flux, (2) mechanical and chemical properties of the final weld deposit can be controlled by flux, and (3) the quality of the weld may be affected by the care and handling of the flux.

Submerged arc welding is a versatile production welding process capable of making welds with currents up to 2000 amperes, ac or dc, using single or multiple wires or strips of filler metal. Both a-c and d-c power sources may be used on the same weld at the same time.

Principles of Operation

In submerged arc welding, the end of a continuous bare wire electrode is inserted into a mound of flux that covers the area or joint to be welded. An arc is initiated using one of six arc-starting methods (*See* ARC STARTING METHODS). A wire-feeding mechanism then begins to feed the electrode wire toward the joint at a controlled rate, and the feeder is moved manually or automatically along the weld seam. For machine or automatic welding, the work may be moved beneath a stationary wire feeder.

Additional flux is continually fed in front of and around the electrode, and continuously distributed over the joint. Heat evolved by the electric arc progressively melts some of the flux, the end of the wire, and the adjacent edges of the base metal, creating a pool of molten metal beneath a layer of liquid slag. The melted bath near the arc is in a highly turbulent state. Gas bubbles are quickly swept to the surface of the pool. The flux floats on the molten metal and completely shields the welding zone from the atmosphere.

The liquid flux may conduct some electric current between the wire and base metal, but an electric arc is the predominant heat source. The flux blanket on the top surface of the weld pool prevents atmospheric gases from contaminating the weld metal, and dissolves impurities in the base metal and electrode and floats them to the surface. The flux can also add or remove certain alloying elements to or from the weld metal.

As the welding zone progresses along the seam, the weld metal and then the liquid flux cool and solidify, forming a weld bead and a protective slag shield over it.

It is important that the slag is completely removed before making another weld pass. The submerged arc process is illustrated in Figure S-27.

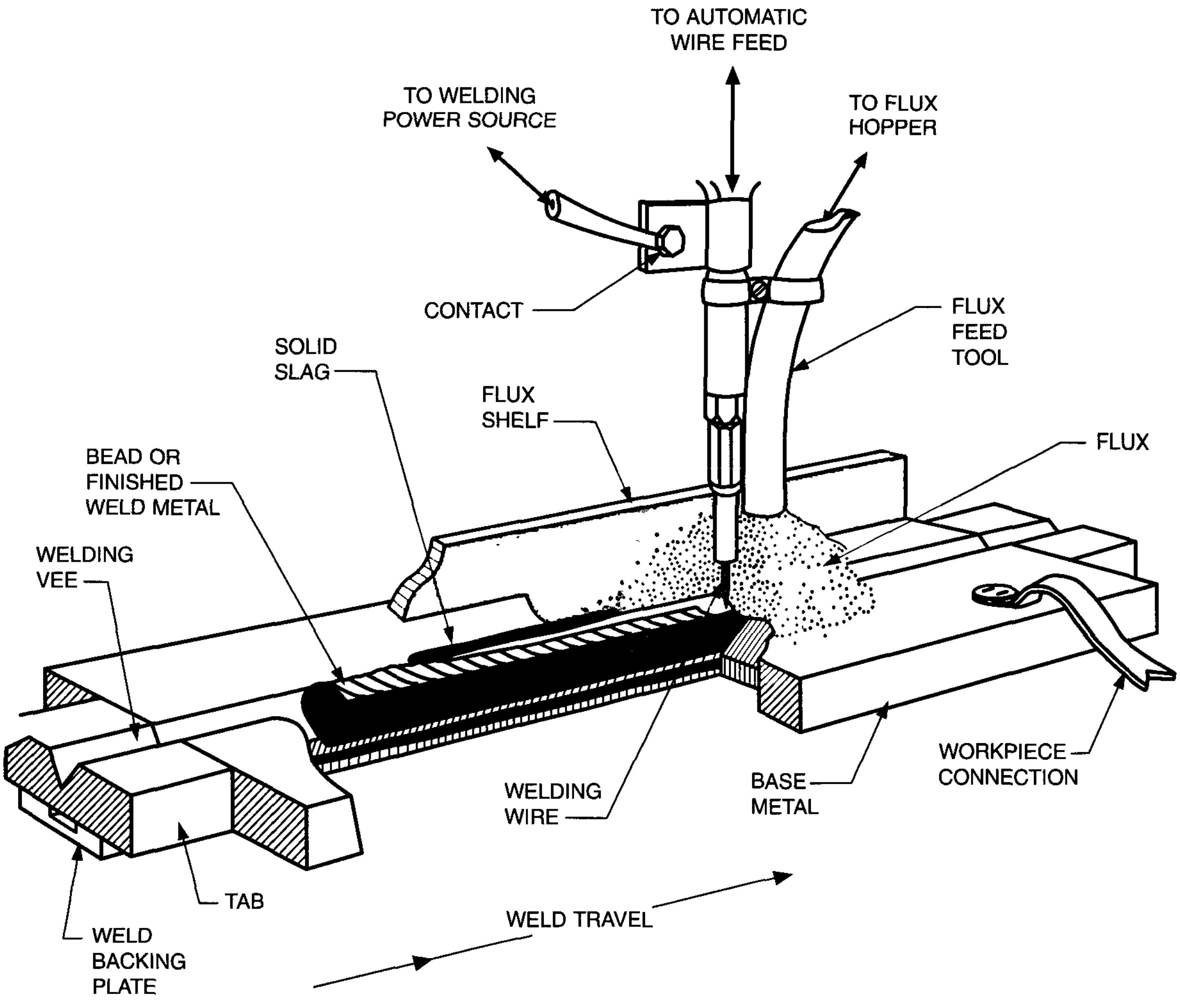


Figure S-27—Schematic View of Submerged Arc Welding Process

Factors that determine whether to use submerged arc welding include:

(1) The chemical composition and mechanical properties required of the final deposit

(2) Thickness of base metal to be welded

(3) Joint accessibility

(4) Position in which the weld is to be made

(5) Frequency or volume of welding to be performed.

Submerged arc welding can be applied in three different modes: semiautomatic, automatic, and machine. Each method requires that the work be positioned so that the flux and the molten weld pool will remain in place until they have solidified. Many types of fixtures and positioning equipment are available or can be built to satisfy this requirement.

Semiautomatic Welding. Semiautomatic welding is done with a hand-held welding gun, which delivers both flux and the electrode. The electrode is driven by a wire feeder. Flux may be supplied by a gravity hopper mounted on the gun or pressure fed through a hose. This method features manual guidance using relatively small diameter electrodes and moderate travel speeds. The travel may be manual or driven by a small gun-mounted driving motor. *See* Figure S-28.

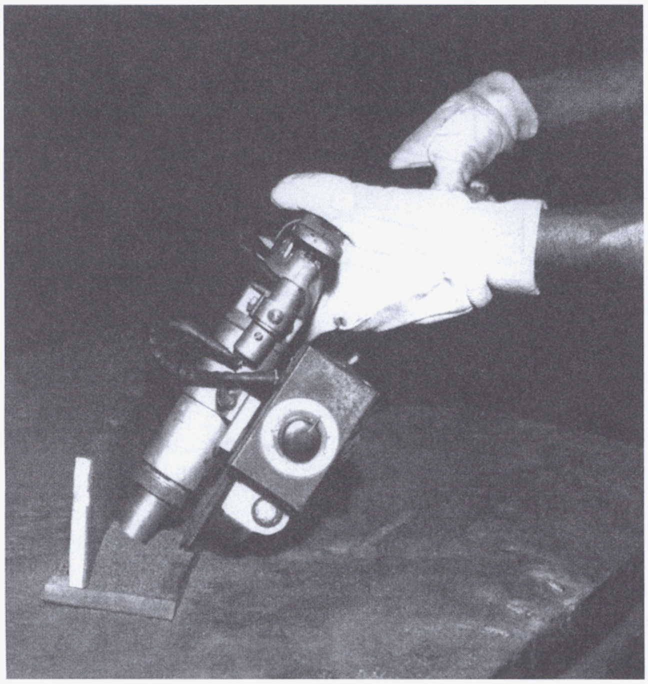


Figure S-28—Hand-Held Submerged Arc Welding Gun. Note Flux on Plate.

Automatic Welding. Automatic welding is done with equipment that performs the welding operation without requiring a welding operator to continually monitor and adjust the controls. The expense of self-regulating equipment can be justified in order to achieve high production rates. Automatic submerged arc hardfacing of a caster roll is shown in Figure S-29.

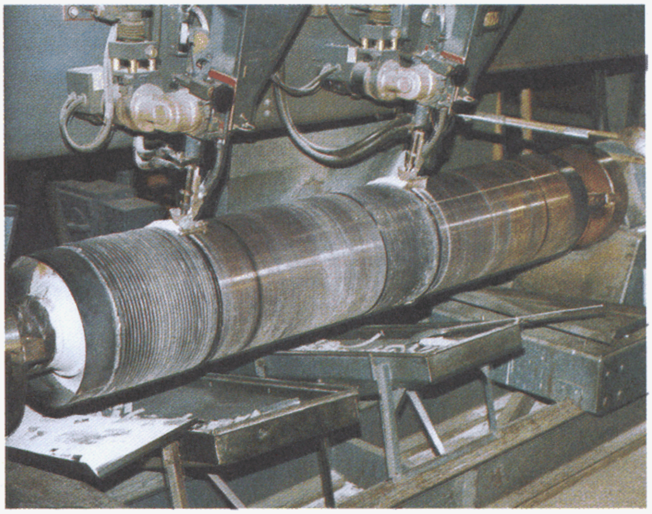


Figure S-29—Automatic Dual-Head Submerged Arc Hardfacing of a Caster Roll

Photo courtesy of Lincoln Electric Company

Machine Welding. Machine welding employs equipment that performs the complete welding operation. However, it must be monitored by a welding operator to position the work, start and stop welding, adjust the controls, and set the speed of each weld. A typical machine welding operation is shown in Figure S-30.

Process Variations

Submerged arc welding lends itself to a wide variety of wire and flux combinations, single and multiple electrode arrangements, and use of a-c or d-c welding power sources. The process has been adapted to a wide range of materials and thicknesses. Various multiple arc configurations may be used to control the weld profile and increase the deposition rates over single arc operation. Weld deposits may range from wide beads with shallow penetration for surfacing, to narrow beads with deep penetration for thick joints. Part of this versatility is derived from the use of a-c arcs. The principles which favor the use of ac to minimize arc blow in single arc welding are often applied in

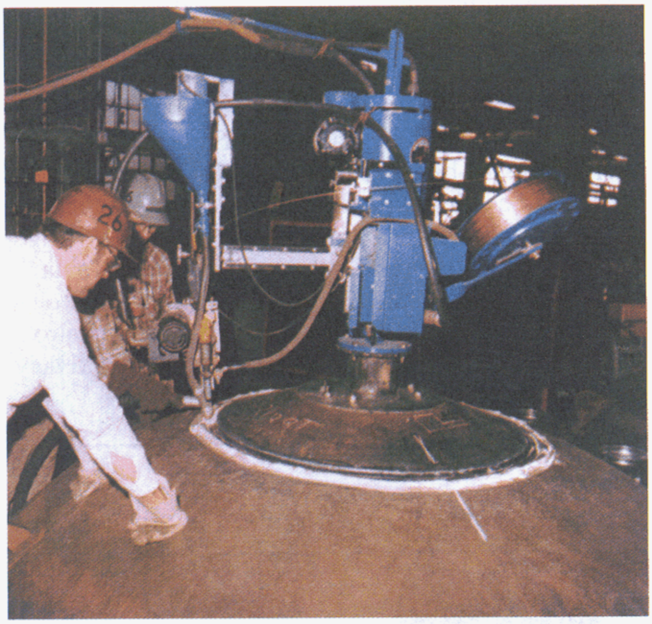


Figure S-30—Mechanized Submerged Arc Weld Made on a Vessel Head

multiple arc welding to create a favorable arc deflection. The current flowing in adjacent electrodes sets up interacting magnetic fields that can either reinforce or diminish each other. In the space between the arcs, these magnetic fields are used to produce forces that will deflect the arcs (and thus distribute the heat) in directions beneficial to the intended welding application.

Equipment

The equipment required for submerged arc welding consists of (1) a power supply, (2) an electrode delivery system, (3) a flux distribution system, (4) a travel arrangement, and (5) a process control system. Optional equipment includes flux recovery systems and positioning or manipulating equipment.

Power Sources

Several types of power supplies are suitable for submerged arc welding. A d-c power supply may provide a constant voltage (CV), constant current (CC), or a selectable CV/CC output. A-C power supplies may provide either a CC output or a CV square wave output. Because SAW is generally a high-current process with high-duty cycle, a power supply capable of providing high amperage at 100% duty cycle is recommended.

D-C Constant-Voltage Power Sources. D-C constant-voltage power supplies range in size from 400 A to 1500 A models. The smaller supplies may also be used for GMAW and FCAW. These power sources are used for semiautomatic SAW at currents ranging from about 300 to 600 A with 1.6, 2.0, and 2.4 mm (1/16, 5/64, and 3/32 in.) diameter electrodes. Automatic welding is done at currents ranging from 300 to over 1000 A, with wire diameters generally ranging from 2.4 to 6.4 mm (3/32 to 1/4 in.). However, applications for d-c welding at over 1000 A are limited because severe arc blow may occur at such high current.

A constant-voltage power supply is self-regulating, so it can be used with a constant-speed wire feeder. No voltage or current sensing is required to maintain a stable arc, so very simple wire feed speed controls may be used. The wire feed speed and wire diameter control the arc current, and the power supply controls the arc voltage.

Constant-voltage d-c power supplies are the most commonly used supplies for submerged arc welding. They work well for most applications where the arc current does not exceed 1000 A, and may work without a problem at higher currents. The CV d-c power supply is the best choice for high-speed welding of thin steel.

Constant-Current Power Sources. Constant-current d-c power sources are available in both transformer-rectifier and motor-generator models, with rated outputs up to 1500 A. Some CC d-c power sources may also be used for GTAW, SMAW, and air carbon arc cutting. With the exception of high-speed welding of thin steel, CC d-c sources can be used for the same range of applications as CV d-c supplies.

Constant-current sources are not self-regulating, so they must be used with a voltage-sensing variable wire feed speed control. This type of control adjusts the wire feed speed in response to changes in arc voltage. The voltage is monitored to maintain a constant arc length. With this system, the arc voltage is dependent upon the wire feed speed and the wire diameter.

Combination Power Sources. Power sources that can be switched between CV and CC modes are also available. Sources rated at up to 1500 A are available, but machines rated at 650 A or less are much more common. The value of these power sources lies in their versatility, since they can be used for SMAW, GMAW, GTAW, FCAW, air carbon arc cutting, and stud welding, in addition to submerged arc welding.

Alternating-Current Power Sources. Alternating-current welding power sources rated for 800 to 1500 A at 100% duty cycle are available. If higher amperages are required, these machines can be connected in parallel.

Conventional a-c power sources are the constant-current type. The output of these machines drops to zero with each polarity reversal, so a high open circuit voltage (greater than 80 V) is required to ensure re-ignition of the arc. Even at that high open circuit voltage, arc re-ignition problems are sometimes encountered with certain fluxes. Because these power supplies are the constant-current type, the speed controls must be voltage sensing, variable wire feed type.

The constant-voltage square wave a-c power source is a relatively new type. Both the output current and the output voltage from these supplies approximate square waves. Because polarity reversals are instantaneous with square wave supplies, as is shown in Figure S-31, arc re-ignition problems are not as severe as those encountered with conventional a-c supplies. Hence, some fluxes that do not work with conventional a-c sources will work with square wave a-c supplies. Relatively simple constant wire feed speed controls can be used with square wave supplies, since they supply constant voltage.

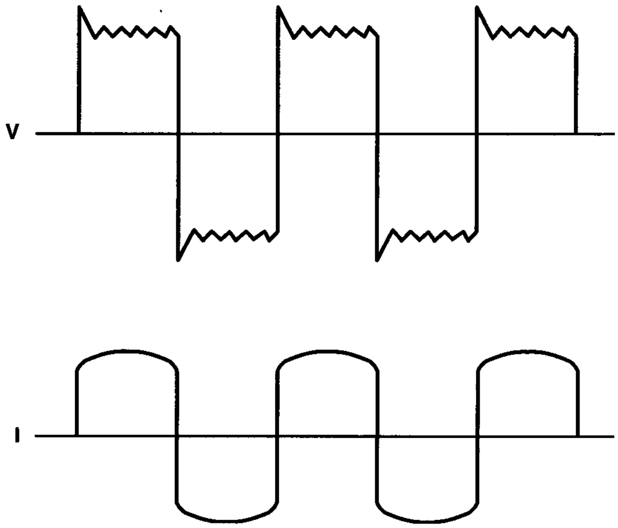


Figure S-31—Square Wave AC Waveforms

The most common uses of a-c power for SAW are high-current applications, multiwire applications, narrow-gap welding, and applications where arc blow is a problem.

Controls

The state-of-the-art wire feeders used for automatic SAW, such as the one shown in Figure S-32, have microprocessor-based digital controls. These controls have feed-back loops interfaced with the power supply and wire feed motor, to maintain the welding voltage and wire speed at preset values. The great advantage of digital controls is their precise control of the welding process. The disadvantages are that the controls are not compatible with some power supplies, and they are not as rugged as most analog controls.

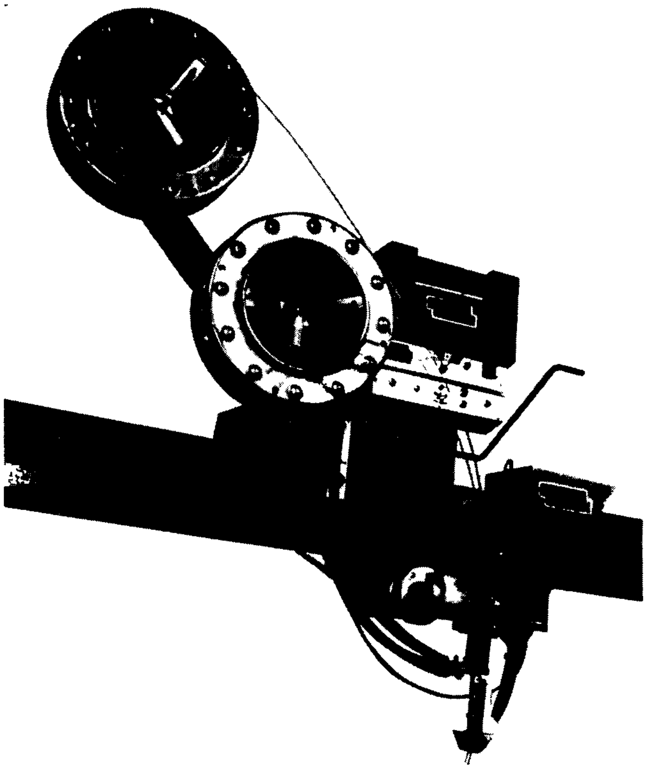


Figure S-32—Digital Control for Two-Wire Submerged Arc Welder

Weld Heads and Torches

A submerged arc welding head comprises the wire feed motor and feed roll assembly, the torch assembly and contact tip, and accessories for mounting and positioning the head. A flux nozzle is usually mounted on the weld head, to deposit the flux either slightly ahead of or concentric with the welding wire.

Wire feed motors are typically heavy duty, permanent magnet-type motors with an integral reducing gearbox, feeding wire at speeds in the range of 8 to 235 mm/sec (20 to 550 in./min.).

The feed roll assembly may have one drive and one idler roll, two drive rolls, or four drive rolls. Four-roll drive assemblies are reported to provide positive feeding with the least wire slippage. Feed rolls may be knurled-V or smooth-V type; knurled-V rolls are the most common. In some cases, where the wire is being pushed through a conduit, smoother feeding will result if smooth V-groove rolls are used.

The torch assembly guides the wire through the contact tip to the weld zone, and also delivers welding power to the wire at the contact tip.

Special equipment is needed for narrow groove (SAW-NG) and strip electrode SAW. Parallel wire SAW uses special feed roll and torch assemblies that provide positive feeding of two wires through one torch body. Strip electrode SAW also requires a special feed roll and torch assembly. Torches that feed strip are generally adjustable to accommodate several sizes of strip, typically 30, 45, 60, 90 mm (1.2, 1.8, 2.4, 3.5 in.) wide, and up to 1 mm thick (0.04 in.) thick. The assemblies for parallel wire and strip electrode SAW are generally designed for mounting on standard welding heads with little or no modification.

The special SAW-NG equipment has long narrow torch assemblies and long narrow flux nozzles to deliver the flux and wire to the bottom of deep narrow grooves. These systems may also have some means to bend the wire to assure good side wall fusion in the narrow groove. Simple SAW-NG adaptors can be mounted directly on standard weld heads; more complex systems are available as complete weld head assemblies.

For semiautomatic SAW, the weld head may be a GMAW-type wire feeder that pushes the electrode through a conduit to the torch assembly. Such wire feeders accept any of the drive roll systems previously described, and are generally capable of feeding wire up to 2.4 mm (3/32 in.) in diameter at wire feed speeds over 235 mm/s (550 in./min). The torch-conduit assembly allows for welding up to 4.6 m (15 ft) from the wire feeder. Flux feed is provided either by a small 1.8 kg (4 lb) gravity feed flux hopper mounted on the torch, or from a remote flux tank that uses compressed air to convey the flux to the weld zone. In both cases, the flux is delivered through the torch surrounding the welding wire. A typical semiautomatic SAW system is shown in Figure S-28.

Accessory Equipment

Accessory equipment commonly used with SAW includes travel equipment, flux recovery units, fixturing equipment, and positioning equipment.

Travel Equipment. Weld head travel in SAW is generally provided by a tractor-type carriage, a side beam carriage, or a manipulator.

A tractor-type carriage, as shown in Figure S-33, provides travel along straight or gently curved weld joints by riding on tracks set up along the joint, or by riding on the workpiece itself. Trackless units use guide wheels or some other type of mechanical joint-tracking device. The weld head, control, wire supply, and flux hopper are generally mounted on the tractor. Maximum travel speeds possible with tractors are about 45 mm/s (100 in./min). Tractors find the most use in field welding where their relative portability is necessary because the workpiece cannot be moved.

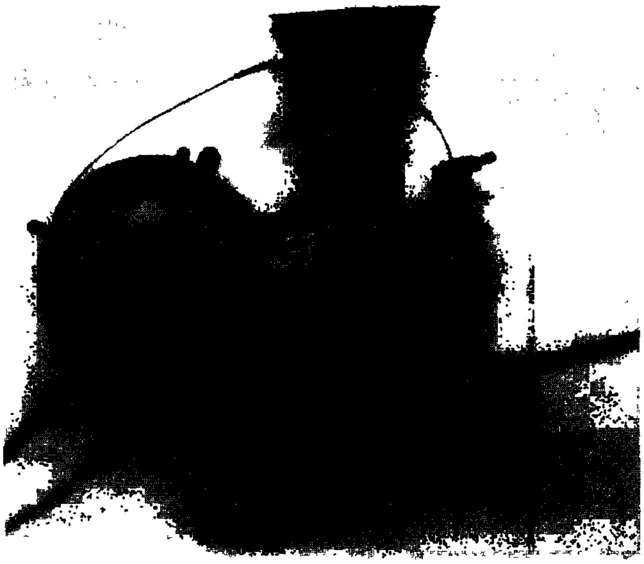


Figure S-33—Submerged Arc Welding Head, Control, Wire Supply, and Flux Hopper Mounted on a Tractor Type Carriage

Side beam carriages provide linear travel only, and are capable of travel speeds in excess of 85 mm/s (200 in./min). Because side beam systems are generally fixed and the workpiece must be brought to the weld station, their greatest use is for shop welding. The weld head, wire, flux hopper, and sometimes the control are mounted on the carriage.

Manipulators are similar to side beams, in that they are fixed and the workpiece must be brought to the welder. Manipulators are more versatile than side beams in that they are capable of linear motion in three axes. The weld head, wire, flux hopper, and often the control and operator ride on the manipulator.

Flux Recovery Units

Flux recovery units are frequently used to maximize flux utilization and minimize manual clean-up. Flux recovery units may do any combination of the following:

(1) Remove unfused flux and fused slag behind the weld head

(2) Screen out fused slag and other oversized material

(3) Remove magnetic particles

(4) Remove fines

(5) Recirculate flux back to a hopper for reuse

(6) Heat flux in a hopper to keep it dry.

Pneumatic flux feeding is commonly used in semiautomatic SAW and frequently in automatic SAW.

Positioners and Fixtures. Because SAW is limited to flat position welding, positioners and related fixturing equipment find widespread use. Commonly used positioners include:

(1) Head-tailstock units, turning rolls, or both, to rotate cylindrical parts under the weld head

(2) Tilting-rotating positioners, to bring the area to be welded on irregular parts into the flat position

Custom fixturing often includes positioners to aid in setting up, positioning, and holding the workpiece. Turnkey systems are available.

Materials

Submerged arc welding is used to fabricate most materials in general use, from "plain" carbon steels to exotic nickel-base alloys. Most steels and alloys are readily weldable with commercially available wires and fluxes.

Electrodes

Submerged arc electrodes produce weld deposits matching carbon steel, low- alloy steel, high-carbon steels, special alloy steels, stainless steels, nickel alloys, and special alloys for surfacing applications. These electrodes are supplied as bare solid wire and as composite metal-cored electrodes (similar to flux-cored arc welding electrodes).

Electrodes are normally packaged as coils or drums ranging in weight from 11 to 454 kg (25 to 1000 lb). Large electrode packages are economical because they increase operating efficiency and eliminate end-of-coil waste.

Submerged arc welding electrodes vary in size from 1.6 to 6.4 mm (1/16 to 1/4 in.) in diameter. General guidelines for amperage range selection are presented in Table S-7. The wide amperage ranges are typical of submerged arc welding. Refer to ANSI /AWS A5.17, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding.*

Table S-7
Submerged Arc Wires—
Diameters vs. Current Range

Wire Diameter		Current Range (Amperes)
mm	in.	
2.3	5/64	200–500
2.4	3/32	300–600
3.2	1/8	300–800
4.0	5/32	400–900
4.8	3/16	500–1200
5.6	7/32	600–1300
6.4	1/4	600–1600

Welding Fluxes

Fluxes are granular mineral compounds mixed according to various formulations. Based on the choice of several manufacturing methods, the different types of fluxes are fused, bonded (also known as agglomerated), and mechanically mixed.

Fused Fluxes. The raw materials of a fused flux are mixed dry and melted in an electric furnace. After melting, the furnace charge is poured and cooled. Cooling may be accomplished by shooting the melt through a stream of water or by pouring it onto large chill blocks. The result is a product with a glassy appearance which is then crushed, screened for size, and packaged.

Fused fluxes have the following advantages:

(1) Good chemical homogeneity

(2) Easy removal of the fines without affecting the flux composition

(3) Normally will not absorb moisture, which simplifies handling, storage, and welding problems

(4) Readily recycled through feeding and recovery systems without significant change in particle size or composition.

Their main disadvantage is the difficulty of adding deoxidizers and ferro-alloys to them during manufacture without segregation or extremely high losses. The high temperatures needed to melt the raw ingredients limit the range of flux compositions.

Bonded Fluxes. To manufacture a bonded flux, the raw materials are powdered, dry mixed, and bonded with either potassium silicate, sodium silicate, or a mixture of the two. After bonding, the wet mix is pelletized and baked at a temperature lower than that used for fused fluxes. The pellets are then broken up, screened to size, and packaged. The advantages of bonded fluxes include the following:

(1) Easy addition of deoxidizers and alloying elements; alloying elements are added as ferro-alloys or as elemental metals to produce alloys not readily available as electrodes, or to adjust weld metal compositions
(2) Usable with thicker layer of flux when welding
(3) Color identification

The disadvantages are the following:

(1) Tendency for some fluxes to absorb moisture in a manner similar to coatings on some shielded metal arc electrodes
(2) Possible gas evolution from the molten slag
(3) Possible change in flux composition due to segregation or removal of fine mesh particles.

Mechanically Mixed Fluxes. To produce a mechanically mixed flux, two or more fused or bonded fluxes are mixed in any ratio necessary to yield the desired results.The advantage of mechanically mixed fluxes is that several commercial fluxes may be mixed for highly critical or proprietary welding operations. The following are disadvantages of mechanically mixed fluxes:

(1) Segregation of the combined fluxes during shipment, storage, and handling
(2) Segregation occurring in the feeding and recovery systems during the welding operation
(3) Inconsistency in the combined flux from mix to mix

Flux Usage. In applications where low hydrogen considerations are important, fluxes must be kept dry. Fused fluxes do not contain chemically bonded H_2O, but the particles hold surface moisture. Bonded fluxes contain chemically bonded H_2O, and may hold surface moisture as well. Bonded fluxes need to be protected in the same manner as low-hydrogen shielded metal arc electrodes. The user should follow the directions of the flux manufacturer for specific baking procedures.

Fluxes are identified as chemically basic, chemically acid, or chemically neutral. The basic or acid quality of a flux is related to the ease with which the component oxides of the flux ingredients dissociate into a metallic ion with a positive charge and a negatively charged oxygen ion. Chemically basic fluxes are normally high in MgO or CaO, while chemically acid fluxes are normally high in SiO_2.

The basicity or acidity of a flux is often referred to as the ratio of CaO or MgO to SiO_2. Fluxes having ratios greater than one are called *chemically basic*. Ratios near unity are *chemically neutral*. Those less than unity are *chemically acidic*.

Welding of Carbon Steel Materials

Carbon steel materials are usually welded with electrode and flux combinations classified under AWS Standard A5.17, *Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*. Typical steels that are welded with these consumables are listed in ANSI/AWS D1.1, *Structural Welding Code-Steel*, as Group I and II classifications. These steels include ASTM A106 Grade B, A36, A516 Grades 55 to 70, A537 Class 1, A570 Grades 30 to 50, API 5LX Grades X42 to X52, and ABS Grades A to EH36. These steels are usually supplied in the as-rolled or the normalized condition.

Table S-8 lists minimum mechanical properties for various wire/flux combinations. When selecting SAW consumables, it is required that both the minimum tensile and minimum yield strengths as well as the notch toughness properties (when required) of the weld metal be matched with the base metal. AWS *Filler Metal Comparison Charts* show the commercial products that meet the AWS wire-flux classifications listed in Table S-8. In special applications, particularly carbon steel weldments subject to long term postweld heat treatment, low-alloy submerged arc welding consumables covered by ANSI/AWS A5.23, *Specifications for Low Alloy Steel Electrodes and Fluxes*, may be required to meet tensile properties of the base metal. Table S-9 shows the classification system for flux-electrode combinations. Fluxes are classified on the basis of weld metal properties obtained when used with specific electrodes.

ANSI/AWS A5.23 lists welding consumables used with carbon steel base materials to meet special notch toughness requirements. Actual mechanical properties obtained may significantly exceed minimum values shown.

Table S-8
Minimum Mechanical Properties with Carbon Steel Consumables Covered by AWS A5.17

AWS Classification	Welding Condition	Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	% Elongation in 2 inches	Charpy Impact Values (Joules)	Charpy Impact Values (Ft-Lbs)	Charpy Impact Values Test Temp.
F6A2-EL12	AW	414	60	331	48	22	27	20	–29°C (–20°F)
F6A6-EL12	AW	414	60	331	48	22	27	20	–51°C (–60°F)
F7A2-EL12	AW	483	70	400	58	22	27	20	–29°C (–20°F)
F6P4-EM12K	SR	414	60	331	48	22	27	20	–40°C (–40°F)
F7A2-EM12K	AW	483	70	400	58	22	27	20	–29°C (–20°F)
F7A6-EM12K	AW	483	70	400	58	22	27	20	–51°C (–60°F)
F7A2-EH14	AW	483	70	400	58	22	27	20	–29°C (–20°F)

1. Actual mechanical properties obtained may significantly exceed minimum values shown.
2. Type of welding flux (manufacture) greatly influences CVN impact properties of the weld metal.
3. Caution should be used when these weld deposits are stress relieved, they may fall below base metal strengths.
4. Test data on 25.4 mm (1 in.) thick plate (ASTM A36 plate).
5. Stress relieved condition: 620°C (1150°F) for 1 hour.

The type of welding flux (manufacture) greatly influences CVN impact properties of the weld metal. Caution should be used when these weld deposits are stress relieved; they may fall below base metal strengths.

Special Service Conditions. Some carbon steel components that are submerged arc welded will be used in special service conditions where the hardness of the weld metal, heat-affected zone, and plate must not exceed a specified maximum level. This is usually required in the oil industry, where the component will be exposed to wet hydrogen sulfide gas. It has been found that if the hardness is kept below a prescribed level, depending on the type of material and the service conditions, stress corrosion cracking will generally not occur.

Stainless Steels

Stainless steels are capable of meeting a wide range of properties, such as corrosion resistance, strength at elevated temperatures, and toughness at cryogenic temperatures, and are selected for a broad range of applications.

The stainless steels most widely used for welded industrial applications are classified as follows:

(1) Martensitic
(2) Ferritic
(3) Austenitic
(4) Precipitation hardening
(5) Duplex or ferritic-austenitic.

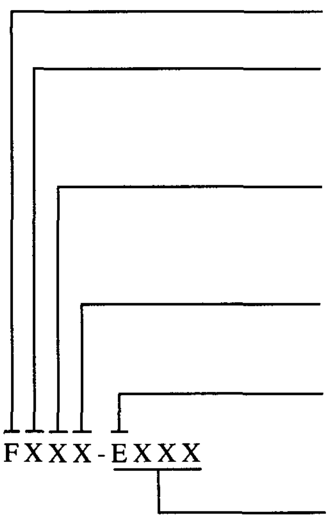
Filler metals for fabricating these steels are specified in ANSI/AWS A5.9, *Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Bare and Composite Metal Cored and Stranded Welding Electrodes and Welding Rods.*

Not all stainless steels are readily weldable by the submerged arc process, and some require that special considerations be followed. In stainless steels and nickel base alloys the main advantage of submerged arc welding (its high deposition rates), sometimes becomes a disadvantage. As deposition rates increase, so does heat input, and in stainless alloys high heat inputs may cause deleterious microstructural changes. Comments about each class of stainless steels and pertinent welding considerations are presented in Volume 4 of the *Welding Handbook*, 8th Edition, published by the American Welding Society, Miami, Florida.

Stainless Steel Electrodes and Fluxes

ANSI/AWS A5.9 covers filler metals for welding corrosion or heat resisting chromium and chromium-nickel steels. This specification includes steels in which chromium exceeds 4% and nickel does not exceed 50% of the composition. Solid wire electrodes are classified on the basis of their chemical composition, as manufactured, and composite electrodes on the basis of the chemical analysis of a fused sample. The

Table S-9
Classification System for Flux-Electrode Combination
See AWS Publication A5.17 (Latest Edition) for Additional Information



Indicates flux

Indicates the minimum tensile strength [in increments of 69 MPa (10 000 psi)] of weld metal made in accordance with the welding conditions given, and using the flux being classified and the specific classification of electrode indicated.

Designates the condition of heat treatment in which the tests were conducted: "A" for as-welded and "P" for postweld heat treated. The time and temperature of the PWHT are as specified.

Indicates the lowest temperature at which the impact strength of the weld metal referred to above meets or exceeds 27 J (20 ft-lb).

E indicates a solid electrode; EC indicates a composite electrode.

Classification of the electrode used in producing the weld referred to above.

Examples

F7A6-EM12K is a complete designation. It refers to a flux that will produce weld metal which, in the as-welded condition, will have a tensile strength no lower than 480 MPa (70 000 psi) and Charpy V-notch impact strength of at least 27 J (20 ft-lb) at –51°C (–60°F) when produced with an EM12K electrode under the conditions called for in this specification.

F7A4-EC1 is a complete designation for a flux when the trade name of the electrode used in classification is indicated as well. It refers to a flux that will produce weld metal with that electrode, which in the as-welded condition, will have a tensile strength no lower than 480 MPa (70 000 psi) and Charpy V-notch energy of at least 27 J (20 ft-lb) at –40°C (–40°F) under the conditions called for in this specification.

American Iron and Steel Institute numbering system is used for these alloys.

Fluxes for stainless steel SAW are proprietary. Manufacturers of fluxes should be consulted for recommendations. Submerged arc fluxes are available in fused and bonded types for welding stainless alloys. Some bonded fluxes contain chromium, nickel, molybdenum, or niobium to replace elements lost across the arc. The newer chemically basic fluxes have shown more consistent element recovery than earlier, less basic or acid types. Performance of fluxes for stainless steel weldments may depend on the user's care in flux handling and reuse. Over-recycled fluxes will become depleted in compensating elements. Refer to the manufacturer's recommendation for handling and recycling of flux.

General Process Applications

SAW is used in a wide range of industrial applications. High weld quality, high deposition rates, deep penetration, and adaptability to automatic operation make the process suitable for fabrication of large weldments. It is used extensively in pressure vessel fabrication, ship and barge building, railroad car fabrication, pipe manufacturing, and the fabrication of structural members where long welds are required. Automatic SAW installations manufacture mass produced assemblies joined with repetitive short welds.

The process is used to weld materials ranging from 1.5 mm (0.06 in.) sheet to thick, heavy weldments. Submerged arc welding is not suitable for all metals and alloys. It is widely used on carbon steels, low-alloy structural steels, and stainless steels. It joins some high-strength structural steels, high-carbon steels, and nickel alloys. However, better joint properties are obtained with these metals by using a process with lower heat input to the base metal, such as gas metal arc welding.

Submerged arc welding is used to weld butt joints in the flat position, fillet welds in the flat and horizontal positions, and for surfacing in the flat position. With special tooling and fixturing, lap and butt joints can be welded in the horizontal position.

Operating Variables

Control of the operating variables in submerged arc welding is essential if high production rates and welds of good quality are to be obtained. These variables, in their approximate order of importance, are the following:

(1) Welding amperage
(2) Type of flux and particle distribution
(3) Welding voltage
(4) Welding speed
(5) Electrode size
(6) Electrode extension
(7) Type of electrode
(8) Width and depth of the layer of flux.

Welding Amperage. Welding current is the most influential variable because it controls the rate at which the electrode is melted and therefore the deposition rate, the depth of penetration, and the amount of base metal melted. If the current is too high at a given travel speed, the depth of fusion or penetration will be too great. The resulting weld may tend to melt through the metal being joined. High current also leads to waste of electrodes in the form of excessive reinforcement. This over welding increases weld shrinkage and causes greater distortion. If the current is too low, inadequate penetration or incomplete fusion may result.

Welding Voltage. Welding voltage adjustment varies the length of the arc between the electrode and the molten weld metal. If the overall voltage is increased, the arc length increases; if the voltage is decreased, the arc length decreases.

Voltage has little effect on the electrode deposition rate, which is determined by welding current. The voltage principally determines the shape of the weld bead cross section and its external appearance. Increasing the welding voltage with constant current and travel speed will:

(1) Produce a flatter and wider bead
(2) Increase flux consumption.

Travel Speed. With any combination of welding current and voltage, the effects of changing the travel speed conform to a general pattern. If the travel speed is increased, (1) power or heat input per unit length of weld is decreased, and (2) less filler metal is applied per unit length of weld, resulting in less weld reinforcement. Thus, the weld bead becomes smaller.

Electrode Size. Electrode size affects the weld bead shape and the depth of penetration at a fixed current. Small diameter electrodes are used with semiautomatic equipment to provide flexibility of movement. They are also used for multiple electrode, parallel power equipment. Where poor fit-up is encountered, a larger diameter electrode is better than small ones for bridging large root openings.

Electrode size also influences the deposition rate. At any given current, a small diameter electrode will have a higher current density and a higher deposition rate than a larger electrode. However, a larger diameter electrode can carry more current than a smaller electrode, and produce a higher deposition rate at higher amperage.

Electrode Extension

In developing a procedure, an electrode extension of approximately eight times the electrode diameter is a good starting point. At current densities above 125 A/mm^2 (80 000 A/in.^{2}), electrode extension becomes an important variable. At high current densities, resistance heating of the electrode between the contact tube and the arc increases the electrode melting rate. The longer the extension, the greater is the amount of heating and the higher the melting rate. This resistance heating is commonly referred to as I^2R heating.

Deposition rates can be increased from 25% to 50% by using long electrode extensions with no change in welding amperage. With single electrode automatic SAW, the deposition rate may approach that of the two-wire method with two power sources.

Width and Depth of Flux. The width and depth of the layer of granular flux influence the appearance and soundness of the finished weld as well as the welding action. If the granular layer is too deep, the arc is too confined and the weld will have a rough, rope-like appearance. The gases generated during welding cannot readily escape, and the surface of the molten weld metal becomes irregularly distorted. If the granular layer is too shallow, the arc will not be entirely submerged in flux. Flashing and spattering will occur. The weld will have a poor appearance, and it may be porous.

An optimum depth of flux exists for any set of welding conditions. This depth can be established by slowly increasing the flow of flux until the welding arc is submerged and flashing no longer occurs.

Inclination of Work

The inclination of the work during welding can affect the weld bead shape. Most submerged arc welding is done in the flat position. However, it is sometimes necessary or desirable to weld with the work slightly inclined so that the weld progresses downhill or uphill. For example, in high-speed welding of 1.3 mm (0.050 in.) steel sheet, a better weld results when the work is inclined 15 to 18° and the welding is done downhill. Penetration is less than when the sheet is in a horizontal plane. The angle of inclination should be decreased as plate thickness increases to increase penetration.

Arc Starting Methods

The method used to start the arc in a particular application will depend on such factors as the time required for starting relative to the total setup and welding time, the number of pieces to be welded, and the importance of starting the weld at a particular place on the joint. There are six methods of starting:

Steel Wool Ball Start. A tightly rolled ball of steel wool about 10 mm (3/8 in.) in diameter is positioned in the joint directly beneath the welding electrode. The welding electrode is lowered onto the steel wool until the ball is compressed to approximately one-half its original height. The flux is then applied and welding is started. The steel wool ball creates a current path to the work, but it melts rapidly while creating an arc.

Sharp Wire Start. The welding electrode, protruding from the contact tube, is snipped with wire cutters to form a sharp, chisel-like configuration at the end of the wire. The electrode is then lowered until the end slightly contacts the workpiece. The flux is applied and welding is commenced. The chisel point melts away rapidly to start the arc.

Scratch Start. The welding electrode is lowered until it is in light contact with the work, and the flux is applied. Next, the carriage is started and the welding current is immediately applied. The motion of the carriage prevents the welding wire from fusing to the workpiece.

Molten Flux Start. Whenever there is a molten puddle of flux, an arc may be started by simply inserting the electrode into the puddle and applying the welding current. This method is regularly used in multiple-electrode welding. When two or more welding electrodes are separately fed into one weld pool, it is only necessary to start one electrode to establish the weld pool. Then the other electrodes will arc when they are fed into the molten pool.

Wire Retract Start. Retract arc starting is one of the most positive methods, but the welding equipment must be designed for it. It is cost effective when frequent starts have to be made and when starting location is important.

Normal practice is to move the electrode down until it lightly contacts the workpiece. Then the end of the electrode is covered with flux, and the welding current is turned on. The low voltage between the electrode and the work signals the wire feeder to withdraw the tip of the electrode from the surface of the workpiece. An arc is initiated as this action takes place. As the arc voltage builds up, the wire feed motor quickly reverses direction to feed the welding electrode toward the surface of the workpiece. Electrode feed speeds up until the electrode melting rate and arc voltage stabilize at the preset value.

If the workpiece is light gauge metal, the electrode should make only light contact, consistent with good electrical contact. The welding head should be rigidly mounted. The end of the electrode must be clean and free of fused slag. Wire cutters are used to snip off the tip of the electrode (preferably to a point) before each weld is made. The electrode size should be chosen to permit operation with high current densities since they provide more reliable starting.

High-Frequency Start. This method requires special equipment but requires no manipulation by the operator other than closing a starting switch. It is particularly useful as a starting method for intermittent welding, or for welding at high production rates where many starts are required.

When the welding electrode approaches to within approximately 1.6 mm (1/16 in.) above the workpiece, a high-frequency, high-voltage generator in the welding circuit causes a spark to jump from the electrode to the workpiece. This spark produces an ionized path through which the welding current can flow, and the welding action begins.

Run-On and Run-Off Tabs

When a weld starts and finishes at the abrupt end of a workpiece, it is necessary to provide a means of supporting the weld metal, flux, and molten slag so that spillage does not occur. Tabs are the method most commonly used. An arc is started on a run-on tab that is tack welded to the start end of the weld, and it is stopped on a run-off tab at the finish end of the weld. The tabs are large enough so that the weld metal on the work itself is properly shaped at the ends of the joint. When the tabs are prepared, the groove should be similar to the one being welded, and the tabs must be wide enough to support the flux.

A variation of the tab is a copper dam that holds the flux, which in turn supports the weld metal at the ends of the joint.

Slag Removal

On multiple pass welds, slag removal becomes important because no subsequent passes should be made where slag is present. The factors that are particularly important in dealing with slag removal are bead size and bead shape. Smaller beads tend to cool more quickly and slag adherence is reduced. Flat to slightly convex beads that blend evenly with the base metal make slag removal much easier than very concave or undercut beads. For this reason, a decrease in voltage will improve slag removal in narrow grooves. On the first pass of two-pass welds, a concave bead that blends smoothly to the top edges of the joint is much easier to clean than a convex bead that does not blend well.

Weld Surfacing

The term *surfacing*, as used with SAW, refers to the application by welding of a layer of material to a surface to obtain desired properties or dimensions, as opposed to making a joint.

The SAW process is often used to surface carbon steel with stainless steel as an economical way to obtain a corrosion resistant layer on a steel workpiece. To end up with an overlay of specified composition, the filler metal must be enriched sufficiently to compensate for dilution.

Clad Steels

Stainless clad carbon- or low-alloy steel plates are sometimes welded with stainless filler metal throughout the whole plate thickness, but usually carbon or low-alloy steel filler metal is used on the unclad side, followed by removal of a portion of the cladding and completion of the joint with stainless filler metal.

Inexperienced fabricators should consult the manufacturer of the clad steel for recommendations of detailed welding procedures and subsequent postweld heat treatments. Joining clad steel to unclad steel sections normally requires making the butt weld and restoring the clad section in a fashion similar to joining two clad plates.

Safety Recommendations

For detailed safety information, refer to the equipment manufacturer's instructions and the latest editions of ANSI Z49.1, *Safety in Welding and Cutting*. For mandatory federal safety regulations established by the U.S. Labor Department's Occupational Safety and Health Administration, refer to the latest edition of OSHA Standards, Code of Federal Regulations, Title 29 Part 1910, available from the Superintendent of Documents, U.S. Printing Office, Washington, DC 20402.

Operators should always wear eye protection to guard against weld spatter, arc glare exposure, and flying slag particles.

Power supplies and accessory equipment such as wire feeders should be properly grounded. Welding cables should be kept in good condition.

Certain elements, when vaporized, can be potentially dangerous. Alloy steels, stainless steels, and nickel alloys contain such elements as chromium, cobalt, manganese, nickel, and vanadium. Material safety data sheets should be obtained from the manufacturers to determine the content of the potentially dangerous elements and their threshold limit values.

The submerged arc process greatly limits exposure of operators to air contaminants because few welding fumes escape from the flux overburden. Adequate ventilation will generally keep the welding area clear of airborne hazards. The type of fan, exhaust, or other air movement system will be dependent on the work area to be cleared. The various manufacturers of such equipment should be consulted for a particular application.

Basic information about this equipment can be found in Chapter 10 of the *Welding Handbook*, Volume 1 (8th Edition), published by the American Welding Society, Miami, Florida.

SUBSTRATE

Any material to which a thermal spray deposit is applied. See STANDARD WELDING TERMS.

SUCK-BACK

A nonstandard term for UNDERFILL at the root surface.

SULFUR

(Chemical symbol: S). A pale yellow, odorless, brittle, nonmetallic element found underground either in the solid state or as molten sulfur. Sulfur is insoluble in water but is soluble in carbon disulfide.

Sulfur is an impurity which appears in steel. It is harmful because it produces hot shortness, although it is frequently added to stainless steel to improve machining qualities. Sulfur is also used in gunpowder, in the vulcanization of rubber and in industrial chemicals. Atomic weight, 87.63; melting point, 900°C (1652°F); specific gravity, 2.64.

SULFURIC ACID (H_2SO_4)

Vitriol, or oil of vitriol. Sulfuric acid is used to sensitize stainless steel and is also used as an etching agent in metallography.

SURFACE CHECKING

A condition consisting of shallow surface cracks that sometimes develops on cooling after heat is applied to the material. This condition usually occurs in high-carbon steels following a quenching operation.

SURFACE CLEANING

See FLAME CLEANING.

SURFACE EXPULSION

Expulsion occurring at an electrode-to-workpiece contact rather than at the faying surface. See STANDARD WELDING TERMS.

SURFACE HARDENING

Heating the surface layer (case) of a metal to a suitable temperature and cooling it so that the surface layer is harder than the core metal. Typical processes for surface hardening are cyaniding, nitriding, heating by flame or induction, and carburizing.

SURFACE PREPARATION

The operations necessary to produce a desired or specified surface condition. See STANDARD WELDING TERMS.

Cleanliness is extremely important in welding applications. Foreign material, oxide, oil or grease must be carefully removed from the surface prior to welding.

Nickel (also cobalt) alloys are embrittled by sulfur, phosphorus, and metals with low melting points such as lead, zinc, and tin. Lead hammers, solders and wheels or belts loaded with these materials are frequent sources of contamination. Detrimental elements are often present in oils, paint, marking crayons, cutting fluids, and shop dirt. When welding nickel (also cobalt) alloys, It is particularly important that adequate attention be given to cleaning before applying heat from any source. Unless proven safe, all foreign material must be considered harmful in the presence of heat.

SURFACE ROUGHENING

A group of methods for producing irregularities on a surface. See STANDARD WELDING TERMS. *See also* DOVETAILING, GROOVE AND ROTARY ROUGHENING, ROTARY ROUGHENING, ROUGH THREADING, *and* THREADING AND KNURLING, Thermal Spraying.

SURFACE TENSION

A phenomenon which causes liquids in contact with their own vapors to reduce to minimum area, as if covered by an invisible membrane. This effect is attributed to forces that arise across the surface of the liquid because the atoms or molecules at the exposed surface are subject to interatomic forces from within the liquid. Surface tension is measured in ergs/cm^2.

In welding, the phenomenon of surface tension comes into play when filler metal and slag globules come close to or in contact with the molten base metal in the weld crater, with or without the aid of gravity. Surface tension not only attracts the liquid filler metal and slag globules into the liquid crater, but makes it possible to deposit weld metal in a horizontal, vertical or overhead position. At the same time, the surface tension determines the shape of weld contours. If it were not for surface tension, it would be impossible to deposit weld metal in any position other than flat. *See* OVERHEAD WELDING POSITION *and* GLOBULAR TRANSFER.

SURFACING

The application by welding, brazing, or thermal spraying of a layer of material to a surface to obtain desired properties or dimensions, as opposed to making a joint. See STANDARD WELDING TERMS. *See also* BUILDUP, BUTTERING, CLADDING, *and* HARDFACING.

Combustion surfacing processes include subsonic flame spraying and hypersonic flame spraying. Electric processes include arc spraying and plasma spraying. *See also* THERMAL SPRAYING.

SURFACING MATERIAL

The material that is applied to a base metal or substrate during surfacing. See STANDARD WELDING TERMS.

SURFACING METAL

The metal or alloy that is applied to a base metal or substrate during surfacing. See STANDARD WELDING TERMS.

SURFACING WELD

A weld applied to a surface, as opposed to making a joint, to obtain desired properties or dimensions. See STANDARD WELDING TERMS.

SWEATING

When steel is heated with a carburizing flame, it becomes red, and as the heating continues, the color of the steel becomes progressively lighter, until the thin carbonized surface layer begins to melt. This takes place at approximately a white heat, about 1200°C (2200°F). The welding rod is then melted and flowed over this sweating surface with the flame of the torch. No attempt should be made to puddle with the rod. It will flow and spread like solder when the surface is properly heated, and will adhere to the base metal, resulting in a weld that is actually stronger than the alloy itself.

SWEAT SOLDERING

A soldering process variation in which workpieces that have been precoated with solder are reheated and assembled into a joint without the use of additional solder. See STANDARD WELDING TERMS.

SWING GRINDER

A semi-portable grinder which is usually suspended from a crane, ceiling, or from a fixture to provide flexibility in grinding operations. The conventional type of swing grinder uses a snagging wheel which makes it possible to remove considerable metal very rapidly.

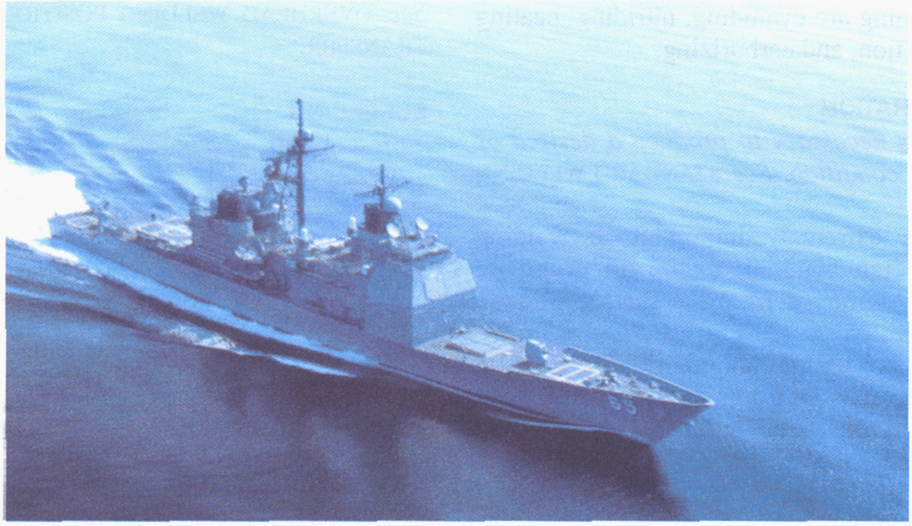
One of the disadvantages of the swing grinder fitted with a snagging wheel is that it is difficult to obtain a smooth surface. Abrasive belt swing grinders are available which combine the rapid moving features of the snagging wheel with the even surface grinding features of a disk grinder. An abrasive belt swing grinder removes a specific amount of metal, as required, resulting in a smooth and even surface. The abrasive belt is electrostatically coated with an aluminum oxide grinding material, and travels at a speed of about 1370 m/min (4500 ft/min).

SYNCHRONOUS INITIATION

In spot, seam, and projection welding, the initiation and termination of each half-cycle of welding-transformer primary current so that all half-cycles of such current are identical.

SYNCHRONOUS TIMING, Resistance Welding

The initiation of each half cycle of welding transformer primary current on an accurately timed delay with respect to the polarity reversal of the power supply. See STANDARD WELDING TERMS.



U.S. Navy frigate under way. The Naval Surface Warefare Center, Bethesda, Maryland, contributes welding technology used in the construction of these ships.

T

T

T: Abbreviation for temperature; **t**: abbreviation for time.

TTT CURVE

Abbreviation for Time-Temperature-Transformation Curve.

TAB

See STANDARD WELDING TERMS. *See also* RUNOFF WELD TAB, STARTING WELD TAB, *and* WELD TAB.

TACKER

A nonstandard term for TACK WELDER.

TACK WELD

A weld made to hold the parts of a weldment in proper alignment until the final welds are made. See STANDARD WELDING TERMS.

A tack weld is a short weld made at intermittent points to hold abutting edges together. The length of the weld, spacing between welds, and design of the tack weld should always be specified. Specifications usually include the length of each tack weld and the measurement from center to center of the tack welds. The particular design of the tack weld is often not specified.

TACKING

Welding at several points on the welding line to hold the workpieces together and prevent the pieces from shifting during the actual welding operation. *See* TACK WELD.

TANK WELDING

The American Society for Mechanical Engineers (ASME) maintains a Boiler and Pressure Vessel (B&PV) Code which contains material standards and specifications that cover tanks made from carbon and alloy steels. The ASME codes govern design, construction, maintenance, and inspection of power boilers, heating boilers, nuclear power plant components, pressure piping systems, and pressure vessels operating at 103 kPa (15 psi) and higher.

The American Petroleum Institute (API) has prepared material specifications for welding steel tanks, vessels, and tubular products used in the petroleum industry.

Persons involved in tank welding should become familiar with the ASME B&PV Code and API Standard 1104. Refer to American Welding Society, *Welding Handbook,* Volume 1, 8th Edition, American Welding Society, Miami, Florida. 1989.

Tank Repair. There are many types of tanks and piping systems which have contained hazardous substances. All are potentially dangerous. Information on safe practices for tank repair is found in ANSI/AWS F4.1, *Recommended Safe Practices for Preparation for Welding and Cutting of Containers and Piping.*

Metal storage tanks commonly located at the top of buildings to supply water for private fire protection are welded subject to rules and regulations of the American Water Works Association (AWWA) and the National Board of Fire Underwriters. These rules are set forth in ANSI/AWWA D100 (AWS D5.2), *AWWA Standard for Welded Steel Tanks for Water Storage.*

TANKS, SAFE PRACTICES

Tanks which contained flammable oil, gasoline, vapors or gas must be handled with caution when making repairs by welding. These tanks may contain sufficient air and residual fumes to cause an explosion when mixed with the gas used with a cutting or welding torch. The document, AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting Containers and Piping That Have Held Hazardous Substances,* should be consulted.

Before welding or cutting a tank with an arc or torch it is essential to clean the tank thoroughly and remove all possibility of a flammable mixture remaining in the tank.

TANTALUM

(Chemical symbol: Ta). A ductile, gray metallic element. It is known for its resistance to a wide variety of acids, alcohols, chlorides, sulfates, and other chemicals. Tantalum is used as an alloy in metals, and is also used in electrical capacitors and high-temperature furnace components. Atomic number, 73; atomic weight, 181; melting point, 2910°C (5270°F).

Although tantalum has an extremely high melting point, and readily combines with all but the inert gases, this reactive metal will produce strong, ductile welds when welded by the gas tungsten arc welding (GTAW) process. Welding is preferably done in a vacuum chamber. The thermal conductivity of tantalum is somewhat lower than that of steel; the thermal coefficient of expansion is about the same as steel.

TAPER DELAY TIME

The time interval after upslope during which the current is constant. See STANDARD WELDING TERMS. *See* Appendix 19.

TAPER TIME

The time interval when current increases or decreases continuously from the welding current to final taper current. See STANDARD WELDING TERMS. *See* Appendix 19.

TAP EXTRACTION

Removing a tap which has been broken off below the surface of the workpiece can be done using the following procedure:

If the hole provides clearance, a coated electrode can be used to build up the tap until it is above the surface. This is best accomplished by dipping it in and out of the puddle. The coating on the electrode helps to prevent damage to the threaded walls of the hole.

Once the tap has been built up above the surface, the end can be filed into a square, gripped by a wrench, and the tap backed out.

TAPS

Connections to a transformer winding that are used to vary the transformer turn ratio, thereby controlling welding voltage and current. See STANDARD WELDING TERMS.

TELLURIUM

(Chemical symbol: Te). A silver-gray, metallic element of the sulphur group. It is a poor conductor of heat and electricity. Tellurium forms well-defined compounds, known as *tellurides*, with other elements. It is used as an alloy in steel, lead, and ceramics, and is used in thermoelectric devices. It is used to some extent in the covering of welding cables to make them more resistant to abrasion. Atomic weight, 147.6; melting point, 461°C (862°F); specific gravity, 6.25.

TEMPER

The degree of hardness produced in an alloy by heat treatment and controlled cooling.

TEMPERATURE

The level of intensity of thermal energy that exists in a substance.

Temperature changes in welding are important variables. Heat is a fundamental factor in most of the welding processes and in thermal cutting. Cooling rates also have significant consequences that must be considered. Heat is a fundamental factor in most welding processes and in thermal cutting. *See* METALLURGY.

TEMPERATURE SCALES, Conversion

The two temperature scales commonly used in metal work are Fahrenheit (F) and Celsius (C). *See* Appendix 14.

On the Fahrenheit scale, the freezing point of water is 32°F and boiling point of water is 212°F.On the Celsius scale, 0°C is the point at which water freezes and 100°C is the boiling point. Thus, 100 divisions on the C scale equal 180 divisions on the F scale. This makes 1°C equivalent to 9/5 or 180/100 of 1°F.

To convert from °C to °F: °F = 9/5 °C + 32.

To convert from °F to °C: °C = 5/9 (°F – 32).

TEMPERATURES, Arc Welding

It has been estimated that the temperature of the metal arc is approximately 3300°C (6000°F). The temperature of the carbon arc varies considerably and is dependent on the arc length and the graphite content of the electrode. Its range is from 3790 to 5290°C (6850 to 9550°F). The atomic hydrogen flame has a theoretical temperature of 4000°C (7250°F). The heat absorption due to the formation of atomic hydrogen, however, reduces this temperature to about 2950°C (5340°F).

The temperature of the gas tungsten arc has been estimated to be 5500°C (10 000°F). The temperature produced by a plasma arc cutting torch is estimated to be 16 600°C (30 000°F).

TEMPERATURES, Fuel Gas

A number of fuel gases are used in welding and cutting operations, including acetylene, propane, methylacetylene-propadiene, propylene, natural gas and hydrogen. Table T-1 shows characteristics of the common fuel gases. *See also* FURNACE, Temperature.

Table T-1
Characteristics of the Common Fuel Gases

Fuel Gas	Formula	Specific Gravity[a]	Volume to Weight Radio[a]		Oxygen-to-Fuel Gas Combustion Ratio[b]	Flame Temperature for Oxygen[c]		Heat of Combustion					
								Primary		Secondary		Total	
		Air = 1	m^3/kg	ft^3/lb		°C	°F	MJ/m^3	Btu/ft^3	MJ/m^3	Btu/ft^3	MJ/m^3	Btu/ft^3
Acetylene	C_2H_2	0.906	0.91	14.6	2.5	3087	5589	19	507	36	963	55	1470
Propane	C_2H_3	1.52	0.54	8.7	5.0	2526	4579	10	255	94	2243	104	2498
Methylacetylene-propadiene (MPS)[d]	C_3H_4	1.48	0.55	8.9	4.0	2927	5301	21	571	70	1889	91	2460
Propylene	C_3H_6	1.48	0.55	8.9	4.5	2900	5250	16	438	73	1962	89	2400
Natural gas (methane)	CH_4	0.62	1.44	23.6	2.0	2538	4600	0.4	11	37	989	37	1000
Hydrogen	H_2	0.07	11.77	188.7	0.5	2660	4820					12	325

a. At 15.6°C (60°F).
b. *The volume units of oxygen required to completely burn a unit volume of fuel gas. A portion of the oxygen is obtained from the atmosphere.*
c. The temperature of the neutral flame.
d. May contain significant amounts of saturated hydrocarbons.

TEMPER CARBON

The microstructure of a casting of any type of malleable iron is derived by controlled annealing of white iron of suitable composition. During the annealing cycle, carbon that exists in combined form, either as massive carbides or as a micro constituent in pearlite, is converted to a form of free graphite known as temper carbon.

TEMPER COLORS

Temper colors on bare, clean, bright steel provide a useful visual method of estimating time and temperature of exposure of heat-affected areas in weldments, judging from surface appearance. When a weld is made by localized heating, temper colors ranging from shades of black, through blue, red, brown and tan will run in bands parallel to the long axis of the weld after the weld has cooled. These variations in color are the effect of various thicknesses of oxide films that form on the surface of iron and steel when heated in air. Sand blasting or pickling can be used to prepare a surface on which temper colors from welding can be observed. Temper colors can give a rough indication of the maximum temperature imposed on the base metal at varying distances from the weld. For example, if two different welds are compared for temper colors, and the brown-purple transition is found closer to the edge of the weld in the first plate, it can be concluded that the weld in the first plate was heated more rapidly and cooled faster than the weld in the second plate. The colors formed on iron and carbon steel by progressively higher temperatures are listed in Table T-2.

Table T-2
Temper Colors Formed on Iron and Carbon Steel

Color Formed on Surface	Approximate Temperature at Which Color Forms	
	°C	°F
Light Straw	200	400
Tan	230	450
Brown	275	525
Purple	300	575
Dark Blue	315	600
Black	425 and higher	800 and higher

TEMPERING

A process for increasing the degree of hardness or resiliency of a metal; the reheating of iron base alloys after hardening at a temperature below the critical range, followed by a specified rate of cooling.

TEMPER TIME, Resistance Welding

The time following quench time during which a current is passed through the weld for heat treating. See STANDARD WELDING TERMS. *See* Figure I-1.

TEMPLATE

A pattern or prototype of a part from which identical copies can be made. Templates also provide a permanent record of the size and shape of a part.

The most common template used in metalworking is the flat template made on heavy sheet metal. By laying the template on new stock and scribing around it, additional parts can be made at any time. Templates are frequently used for outlining parts in flame cutting operations. *See* PIPE WELDING, Accessories.

TEMPORARY WELD

A weld made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment. See STANDARD WELDING TERMS.

TENSILE STRENGTH

The resistance to breaking exhibited by a material when it is subjected to a pulling stress. The unit of tensile strength is the Pascal (lb/in.^{2}). *See* TENSILE TEST.

TENSILE TEST

A test to obtain an accurate assessment of the strength and ductility of a material or a weld, or in an all-weld-metal test, to determine mechanical properties such as tensile strength, yield strength, elongation, and reduction in area.

In a base metal tension test, the strength and ductility of metals are generally obtained from a uniaxial tensile test in which a machined specimen is subjected to an increasing load while simultaneous observations of extension are made. Longitudinal specimens are oriented parallel to the direction of rolling, and transverse specimens are oriented perpendicular to the rolling direction. The load can be plotted against the elongation, customarily as shown in Figure T-1. The stress (load divided by original area) is plotted against the strain (elongation divided by the original gauge length).

The yield strength shown by the engineering stress-strain curve is generally the strength at some arbitrary amount of extension under load or a permanent plastic strain (offset).

Details of specimen preparation and test procedures for tension tests for base metals are described in *ASTM A370, Standard Methods and Definitions for Mechanical Testing of Steel Products,* published by the American Society for Testing Materials, West Conshohocken, Pennsylvania.

Weld Tension Test. To obtain an accurate assessment of the strength and ductility of welds, several different specimens and orientations may be used. In some cases, the weld reinforcement is left intact on the test specimen.

All-Weld-Metal Test. The mechanical properties measured and reported in an all-weld-metal tension test are tensile strength, yield strength, elongation, and reduction in area. To determine the tensile properties of a weld metal, the test specimen orientation is parallel to the axis of the weld, and the entire specimen is machined from the weld metal. The chemical composition of the weld metal will be affected by the joint penetration.

If the purpose of the test is to qualify a filler metal, then melting of the base metal should be minimized when making the test weld. This procedure is described in AWS A5.1, *Specification for Covered Carbon Steel Arc Welding Electrodes*, published by American Welding Society, Miami, Florida.

TENSILE TESTING MACHINE

A device for accurately determining the tensile strength of metals, particularly welded specimens. Tensile testing machines are usually power driven when located in a test laboratory, however, some portable models available for field testing are operated by hydraulic pumps which apply the necessary pressure to a piston which draws the jaws apart.

The laboratory machines are usually large in scale, with means for gripping the specimen, applying tension and accurately recording the results. *See* Figure T-2. The machine applies tension to the specimen until it reaches the yield point, or the point at which permanent distortion begins. The yield point indicates the elasticity of the metal, and the final breaking strength, *or tensile strength,* is indicated on the machine when the specimen breaks.

In many tests, the specimen stretches, and the area at the break is reduced. The *percent reduction in area* is computed by comparing the reduced cross section with the original cross section of the specimen. The percent reduction in area is indicated on the machine, and the tension continues until the specimen breaks.

TENSION TEST

A test in which a specimen is loaded in tension until failure occurs. See STANDARD WELDING TERMS.

TERMS, WELDING

See STANDARD WELDING TERMS.

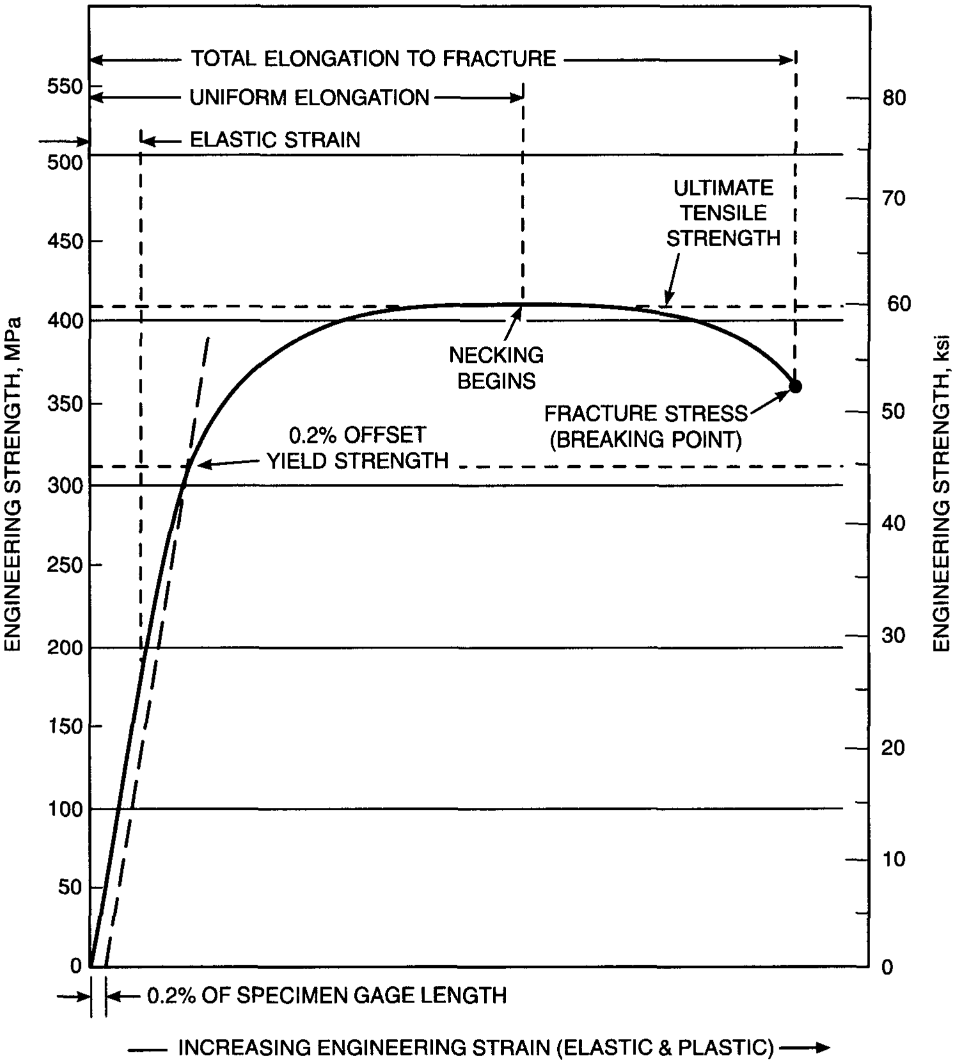


Figure T-1—Stress/Strain Diagram for Complete History of a Metal Tension Test Specimen from the Start of Loading and Carried to the Breaking Point

TESTING

Examination of welds to determine characteristics such as ductility, soundness, tensile properties, hardness, fracture toughness, fatigue properties of welded structural joints, corrosion factors, or behavior at elevated temperature.

The two main types of testing are destructive and nondestructive. Tensile testing, or loading in tension until failure occurs, is an example of destructive testing. Visual inspection is an example of nondestructive testing.

The ideal test would be to observe the structure in actual service, but this is rarely practical. Therefore, standardized tests and testing procedures are used that give results which can be related to metals and structures that have performed satisfactorily in service. Reference is frequently made to ANSI/AWS B4.0, *Standard Methods for Mechanical Testing of Welds.*

The problem of predicting the performance of structures from a laboratory-type test is a complex one, because the size, configuration, environment, and type of loading in service usually differ. In welded joints,

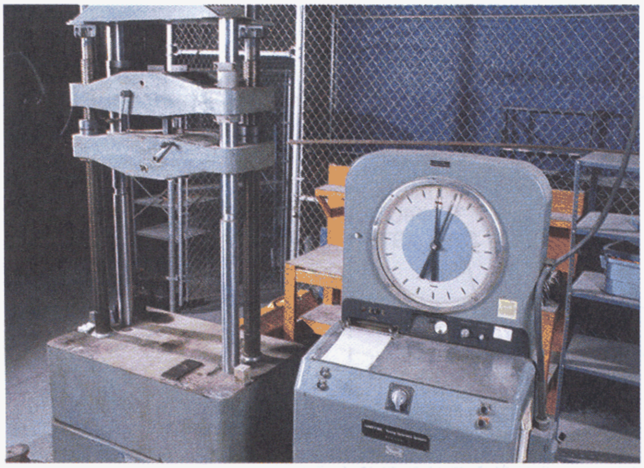


**Figure T-2—Tensile Testing Machine.
Load Capacity: 54 400 kg (120 000 lb)**

the complexity is further increased by the nature of the joint, which is both metallurgically and chemically heterogeneous. In addition to the unaffected base metal, the welded joint consists of weld metal and a heat-affected zone. Those regions are composed of a multitude of metallurgical structures as well as chemical heterogeneities, so a variety of properties can be expected throughout the welded joint.

Various testing methods are regularly used to evaluate the expected performance of welded joints. The property being tested, the test methods which may be used, and the application of results with special consideration of their relationship to welded joints are covered in the *Welding Handbook*, 8th Edition, Volume 1, Chapter 12; American Welding Society, Miami, Florida; 1987.

Among the various types of tests are pressure testing, bend test, compression testing, crushing, drift, fatigue, hydrostatic test, impact test, tensile, tube, visual testing, free bend test, magnetic testing, and x-ray testing.

TEST SPECIMEN

A prepared sample of the workpiece on which a mechanical test is to be made.

A base metal test specimen is a test specimen composed wholly of base metal; a filler metal test specimen is composed wholly of filler metal.

A weld metal test specimen is one with one or more welds with component base metal parts shaped in a way that compels failure to take place in the weld metal.

A welded joint test specimen has one or more welds and is primarily intended to compare the strength of the welded joint with that of the base metal.

A deposited metal test specimen is one substantially composed of deposited metal.

TEST WELD

A sample of welding which has been performed under known conditions and on which mechanical tests are to be made.

One of the ways a welder can test a weld is to make a specimen weld similar to the job being undertaken and break it to determine the strength of the weld metal.

THAWING, Pipelines

See PIPE, Thawing.

THEORETICAL ELECTRODE FORCE

The force, neglecting friction and inertia, in making spot, seam, or projection welds, available at the electrodes of a resistance welding machine by virtue of the initial force and theoretical mechanical advantage of the system. See STANDARD WELDING TERMS.

THEORETICAL THROAT

The distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross section of a fillet weld. This dimension is based on the assumption that the root opening is equal to zero. See STANDARD WELDING TERMS. *See* Appendix 11.

THERMAL CONDUCTIVITY

The property of a material to allow the passage of heat. The units of thermal conductivity are cal/cm^2/cm/ °C/s.

The three mechanisms of thermal conductivity by which heat can be transmitted from a heat source to a material that are significant to welding are conduction, convection and radiation. Conduction is most often the mechanism involved in a weldment.

The amount of heat being conducted through a body of matter is proportional to the cross-sectional area and the difference in temperature or gradient between the measuring points; and it is inversely proportional to the distance or length between the measuring points. These factors can be arranged in an equation with a proportionality constant for the thermal conductivity.

Thermal conductivity values for a number of metals and other materials used in welding are listed in Table T-3. As can be seen from the values in Table T-3, metals differ in thermal conductivity, but in the main, metals are much better heat conductors than nonmetals. Copper is an excellent conductor, which accounts for the difficulty in welding copper using a relatively low-temperature heat source, like an oxyacetylene flame. On the other hand, the good conductivity of copper explains its efficiency as a "heat sink" when employed as a hold-down fixture or as a backing bar. Iron is a relatively poor conductor compared to other metals, which partly accounts for the ease with which steel can be welded and thermally cut. Metals with high heat conductivity require more heat input during welding because the heat is conducted rapidly away from the puddle.

THERMAL CUTTER

One who performs manual or semiautomatic thermal cutting. Variations of this term are ARC CUTTER *and* OXYGEN CUTTER. *See* STANDARD WELDING TERMS.

THERMAL CUTTING (TC)

A group of cutting processes that severs or removes metal by localized melting, burning, or vaporizing of the workpieces. See STANDARD WELDING TERMS. *See also* ARC CUTTING, ELECTRON BEAM CUTTING, LASER BEAM CUTTING, *and* OXYGEN CUTTING.

THERMAL CUTTING OPERATOR

One who operates automatic, mechanized, or robotic thermal cutting equipment. Variations of this term are ARC CUTTING OPERATOR, ELECTRON BEAM CUTTING OPERATOR, LASER BEAM CUTTING OPERATOR, *and* OXYGEN CUTTING OPERATOR. *See* STANDARD WELDING TERMS.

THERMAL FLOW

Thermal flow will take place between substances in contact, or in close proximity, when the temperature levels differ. The transference of thermal energy always flows from the hotter substance to the cooler substance, regardless of the quantities of thermal energy held by each. The flow of thermal energy will continue in this direction, until a temperature difference no longer exists. The rate of thermal flow will be determined by the extent of the difference between the levels of temperature in the two substances. The rate of transfer of thermal energy is a characteristic physical property of each material termed *thermal conductivity*, a factor often requiring analysis when setting up welding parameters. Reference: George E. Linnert, *Welding Metallurgy*, Vol. 1, 4th Edition, Miami, Florida: American Welding Society, 1994.

Table T-3
Thermal Conductivity of Metals, Alloys, and Nonmetals

	Thermal Conductivity (Measured Near Room Temperature)	
Substance	**W/m/°K***	**cal/cm^2/cm/°C/s****
Aluminum	238.5	0.57
Copper	393.3	0.94
Iron	75.3	0.18
Magnesium	154.8	0.37
Mercury	8.43	0.02
Nickel	92.1	0.22
Silver	418.4	1.00
Titanium	221.8	0.53
Tungsten	167.4	0.40
Zirconium	225.9	0.54
Steel, low-carbon	71.1	0.17
Steel, high-carbon	66.9	0.16
Stainless Steel, 18-8	15.5	0.037
Carbon (graphite)	25.1	0.060
Glass	1.05	0.0025
Water	0.58	0.0014
Paper	0.12	0.0003
Argon	1.80×10^{-2}	0.043×10^{-3}
Carbon Dioxide	1.67×10^{-2}	0.040×10^{-3}
Helium	15.06×10^{-2}	0.360×10^{-3}
Nitrogen	2.59×10^{-2}	0.062×10^{-3}
Oxygen	2.64×10^{-2}	0.063×10^{-3}

*To convert values in W/m/°K to Btu/sq ft/ft/°F/hr, multiply by 0.577789.

**To convert values in cal/cm^2/cm/°C/s to Btu/sq ft/ft/°F/hr, multiply by 242.08.

THERMAL GOUGING

A thermal cutting process variation that removes metal by melting or burning the entire removed portion, to form a bevel or groove. See STANDARD WELDING TERMS. *See also* ARC GOUGING, BACKGOUGING, *and* OXYGEN GOUGING.

THERMAL GRADIENT

The difference in temperature between two points which are a stated unit distance apart. For example, if welding has been performed at a point in a steel plate and the weld is at a temperature of 1500°C (2732°F), and a point in the plate 25 mm (1 in.) away from the weld is at 100°C (212°F), then the temperature gradient is calculated as 1500 – 100 = 1400°C per 25 mm, which is a gradient of 56°C/mm (2732 –212 = 2520°F per in., which is a gradient of 2.52°F/0.001 in.). Reference: George E. Linnert, *Welding Metallurgy*, Vol. 1, 4th Edition. Miami, Florida: American Welding Society, 1994.

THERMAL SPRAY DEPOSIT

The coating or layer of surfacing material applied by a thermal spraying process. See STANDARD WELDING TERMS. *See* Figure T-3.

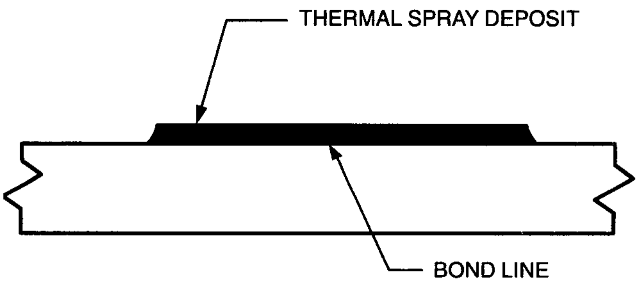


Figure T-3—Surfacing Material Applied by a Thermal Spraying Process

THERMAL SPRAY DEPOSIT DENSITY RATIO

The ratio of the density of the thermal spray deposit to the theoretical density of the surfacing material, usually expressed as percent of theoretical density. See STANDARD WELDING TERMS.

THERMAL SPRAY DEPOSIT INTERFACE

The interface between the thermal spray deposit and the substrate. See STANDARD WELDING TERMS.

THERMAL SPRAY DEPOSIT STRENGTH

The tensile strength of a thermal spray deposit. See STANDARD WELDING TERMS.

THERMAL SPRAY DEPOSIT STRESS

The residual stress in a thermal spray deposit resulting from rapid cooling of molten or semimolten particles as they impinge on the substrate. See STANDARD WELDING TERMS.

THERMAL SPRAYER

One who performs semiautomatic thermal spraying. Variations of this term are ARC SPRAYER, FLAME SPRAYER, and PLASMA SPRAYER.

THERMAL SPRAYING (THSP)

A group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a thermal spray deposit. The surfacing material may be in the form of powder, rod, cord, or wire. See STANDARD WELDING TERMS. *See also* ARC SPRAYING, FLAME SPRAYING, *and* PLASMA SPRAYING.

Thermal spraying can be used to form a coating on metals, ceramics, glass, most plastics, and wood. It is used extensively in the manufacture of original equipment components. For example, the aerospace industry has developed hundreds of applications, including air seals and wear-resistant surfaces to prevent fretting and galling at elevated temperatures. In addition, marine, mining, food, automotive, petroleum, electrical power generation, thermal processing, chemical processing and electronic applications use thermally sprayed coatings to achieve results that no substrate by itself can provide.

The surfacing is applied with a thermal spraying gun, which generates the necessary heat by using combustible gases or an electric arc. As the materials are heated, they change to a plastic or molten state, and are accelerated by a compressed gas. The particles, in a confined stream, are conveyed to a substrate. The particles strike the surface, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared surface and to each other. As the sprayed particles impinge on the substrate, they cool and build up, particle by particle, into a lamellar structure; thus a coating is formed.

Process Variations

The basic variations of the thermal spraying processes occur in the spray materials used, the method of heating, and the method of propelling the materials to the substrate.

Spray Materials. The spray materials used are in the form of wire, rod, cord (a continuous length of plastic tubing), or powder. Cord spraying is primarily used in Europe. Many metals, oxides, cermets, and intermetallic compounds, some organic plastics, and certain glasses can be deposited by one or more of the various processes.

Processes. Thermal spraying processes can be categorized under two basic groups, according to the methods of heat generation. *See* Table T- 4. Group 1 uses combustible gases as the heat source. Group 2 uses electric power as the heat source, such as plasma, electric arc, and induction plasma. Consumables used in Group 2 are in the powder or wire form.

Table T-4
Basic Groups of Thermal Spraying

Group I—Combustion	Group II—Electrical
1. Flame	1. Arc
a. Subsonic	2. Plasma arc
b. Hypersonic	3. Induction coupled plasma

Additional heat is generated at impact during hypersonic flame spraying, as the spray material gives up its kinetic energy.

Group I—Combustion

Subsonic Flame Spraying. In subsonic flame spraying, the spray material is fed into and melted by an oxyfuel gas flame. Whether the material is in the form of wire, rod or powder, molten particles are propelled onto the substrate by the force of the flame.

A wide variety of materials in these forms can be sprayed with the flame. Materials that cannot be melted with an oxyfuel gas flame, and those that burn or become severely oxidized in the oxyfuel flame, cannot be flame sprayed.

Flame spray accessories in the form of air jets and air shrouds are available to change the flame characteristics. These accessories can be used to adjust the shape of the flame and the velocity of the sprayed materials.

Materials are deposited in multiple layers, each of which can be as thin as 130 μm (0.0005 in.) per pass. The total thickness of material deposited will depend upon several factors including:

(1) Type of surfacing material and its properties

(2) Condition of the workpiece material, including geometry

(3) Service requirements of the coated product

(4) Post-spray treatment of the coated product

Hypersonic Flame Spraying. Detonation and continuous-flame guns are two types of hypersonic spray guns.

The detonation gun operates on principles significantly different from other flame spray methods. This method repeatedly heats and projects charges of powder onto a substrate by rapid successive detonations of an explosive mixture of oxygen and acetylene in the gun chamber.

The continuous-flame hypersonic guns used in the United States use a propylene-oxygen flame. The powder is brought to the torch using a nitrogen carrier. The torch is designed to confine the powder in the center of the flame. The particles leave the gun at velocities generally in excess of mach 4. This speed is far greater than achieved in most other spray methods. Particle impact velocities for various thermal spray processes are shown in Figure T-4. The kinetic energy released by impingement upon the substrate contributes additional heat that promotes bonding, high density, and appreciable hardness values.

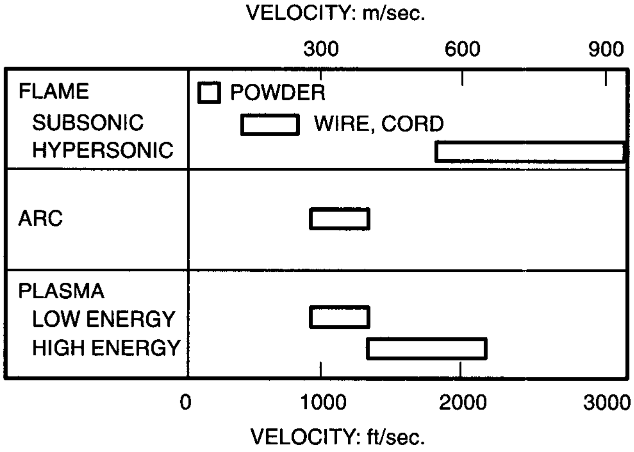


Figure T-4—Average Particle Impact Velocities for Various Thermal Spray Processes

Group II—Electric

Arc Spraying. The spray materials used with arc spraying, commonly called *electric arc spraying*, are metals and alloys in wire form, and powders contained in a metal sheath (cored wire). Two continuously fed wires are melted by an arc operating between them. The molten metal is atomized and propelled onto the substrate by a high-velocity gas jet, usually air. Recent work has been done using other gases. This method is restricted to spraying consumables that can be produced in continuous wire form.

Plasma Spraying. Plasma spraying is a thermal spraying process in which a nontransferred plasma arc gun is used to create an arc plasma that melts and propels the surfacing material to the substrate.

The term *nontransferred arc* means that the plasma arc is contained within the gun, and that the substrate is not part of the electric circuit. The arc is maintained between a tungsten cathode and a constricting nozzle which serves as the anode. An inert gas or a reducing gas, under pressure, enters the annular space between the anode and cathode, where it becomes ionized, producing temperatures up to 17 000°C (30 000°F). The hot plasma gas passes through the nozzle as a high-velocity jet. The surfacing material, in powder form, is injected into the hot gas stream, where it becomes molten and is propelled onto the substrate.

Plasma Transferred Arc (PTA). This process is a combination of welding and thermal spraying processes. Powder is introduced into the plasma arc stream from where it is melted and conveyed to the workpiece. The emitted spray forms a molten puddle on the substrate, which cools and solidifies as a parent metal dilution (weldment). As compared to a thermal spraying deposit, a PTA deposit is generally more localized, denser, and metallurgically bonded to the base. The selection of coating materials and suitable substrates is limited.

Vacuum Plasma Spraying. Vacuum spraying is a variation of plasma spraying which is performed in a vacuum chamber. The advantage of the process is the elimination of oxides from the deposit. This is especially advantageous in aircraft engine applications. The cost of this apparatus is about ten times that of standard plasma spray equipment. Operating costs are also higher.

Induction Coupled Plasma Spraying. Induction coupled plasma equipment is used to create an ultra high-temperature arc region 50 mm (2 in.) in diameter by 150 mm (6 in.) long, into which powders are injected. The powder is heated along a substantially longer path than that within a comparable plasma spray gun. The longer powder residence time makes possible the use of larger particles, assures the melting of the particles, and results in a more consistent sprayed coating.

Because of the size of the equipment, this system has limited torch movement and portability.

Procedures for Sprayed Coatings

Success in the use of thermally sprayed coatings relies on careful adherence to specific process procedures. This is a basic rule of thermal spraying, and deviation from the standards for a particular application, or inattention to detail, especially preparation, will produce an unreliable result.

Sprayed coating systems have four basic components: substrate type, bond coats as necessary, coating structure, and finish.

Substrates. Substrates on which the thermally sprayed coatings are applied include metals, oxides, ceramics, glass, most plastics, and wood. All spray materials cannot be applied to all substrates, since some require special techniques or are temperature sensitive.

Substrate preparation is required for every thermal spraying process, and is virtually the same for each process. Two important steps are:

(1) Cleaning the surface to eliminate contamination that will inhibit the bonding of the coating to the substrate.

(2) Roughening the substrate surface to create minute asperities or irregularities (anchor teeth), which provide a greater effective surface area to enhance coating adhesion and bond strength.

Bond Coats. Certain materials adhere to clean, smooth surfaces forming strong coating-to-substrate bonds, over a wide range of conditions. A thin layer of bonding material serves as an anchor for subsequent applied coating layers. Bond coatings are particularly applicable to substrates too thin or too hard to be prepared by abrasive roughening methods. Bond coatings are used extensively as a substrate for ceramic materials. Bond coatings of nickel, chromium, stainless steel, or the corrosion resistant alloys are applied in thicknesses of 0.05 to 0.33 mm (0.002 to 0.013 in.) or more. The bond coating provides a flexible and adherent substrate for ceramic deposits.

The bond between the coating and the substrate may be mechanical or metallurgical. Adhesion is influenced by a combination of: (1) coating material, (2) spray particle size, (3) substrate condition and geometry, (4) degree of surface roughness, (5) surface cleanliness, (6) surface temperature before, during, and after spraying, (7) particle impact velocity, (8) type of base material, and (9) spray angle.

Coating Structure. The deposited structure and chemistry of coatings sprayed in ambient air are different from those of the same material in the wrought or pre-sprayed form.

The differences in structure and chemistry are due to the incremental nature of the coating, and its reaction with the process gases and the atmosphere surrounding the coating material while in the molten state. For example, when air or oxygen is used as the process gas, oxides of the spray material are formed while the particles are in transit and become a part of the coating.

Metal coatings tend to be porous and brittle, and to differ in hardness from the original consumable material. The "as-sprayed" structures of coatings will be similar in their lamellar nature, but will exhibit varying characteristics, depending on the particular spraying process used, process variables, techniques employed, and the nature of the spray material applied.

The coating density will vary with the particle velocity, the heat source temperature of the spray process, and the amount of air used. A listing of heat source temperatures is shown in Table T-5. The density also varies with the type of powder, its mesh size, spray rate, standoff distance, and method of injection.

Table T-5
Heat Source Temperatures

	Temperature	
Source	**°C**	**°F**
Acetylene, oxygen	3100	5625
Arcs and plasmas	2200–8300	4000–15 000
Hydrogen, oxygen	2690	4875
MPS, oxygen	2870	5200
Natural gas, oxygen	2735	4955
Propane, oxygen	2640	4785

The nature of the bond in the "as-sprayed" condition can be modified by post spray thermal treatment. Modification is by diffusion, chemical reaction, or both, between the coating and the substrate.

The thermal spraying processes and related equipment in commercial use can be divided into two basic methods of deposition: combustion and electric heating.

Combustion

Thermal spraying which utilizes the heat from a chemical reaction is known as combustion, gas, or flame spraying. Any substance which does not sublime and which melts at temperatures less than 2760°C (5000°F) may be flame sprayed. The materials used are metals and alloys in the form of wire, cord, powder, and ceramics as powder, cord, or rod.

Wire and Rod. The equipment for flame spraying wire and rod is similar to that shown in Figure T-5. A cross section of a typical wire thermal spraying gun is shown in Figure T-6.

Figure T-5—Oxy-fuel Gas Wire Spray Equipment Capable of Spraying Wires Ranging from Low Melting Alloys (Babbitt) to Higher Melting Point Steels. Aluminum Wire Shown on Top Spool and Carbon Steel Wire on the Bottom Reel.

The feedstock material is drawn by drive rolls into the rear of the gun. The rolls are powered by an electric motor, or an air turbine. The feedstock proceeds through the nozzle where it is melted by a coaxial flame of burning gas.

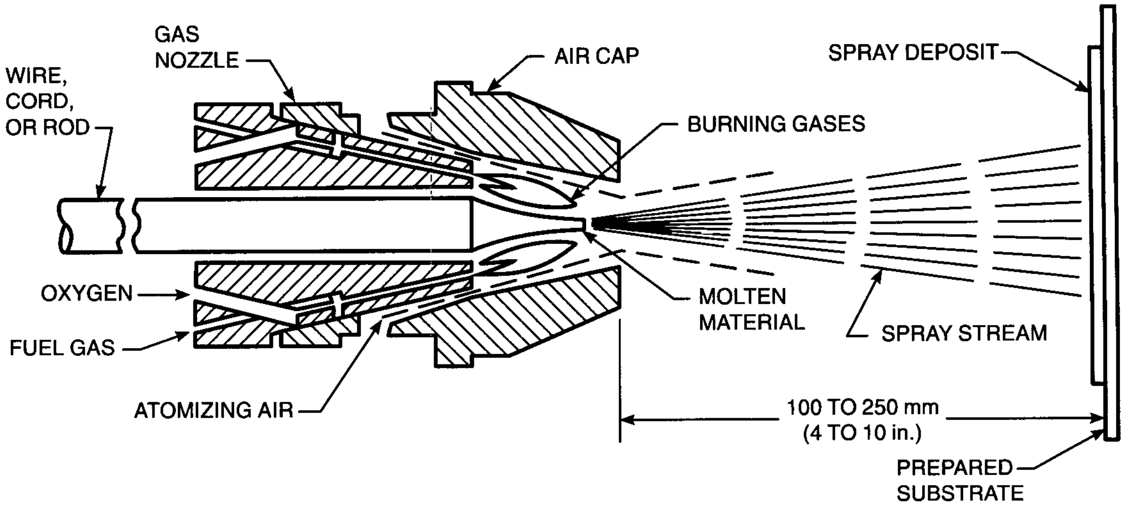


Figure T-6—Cross Section of a Typical Wire Thermal Spraying Gun

One of the following fuel gases may be combined with oxygen for use in flame spraying: acetylene, methylacetylene-propadiene stabilized (MPS), propane, hydrogen, or natural gas. Acetylene is widely used because higher flame temperatures are attainable. *See* Table T-5. In many cases lower temperature flames can be used to economic advantage. A fuel gas flame is used for melting only, and not for propelling or conveying the coating material. To accomplish spraying, the flame is surrounded with a stream of compressed gas, usually air, which atomizes the molten material and propels it onto the substrate. For special applications inert gas may be used.

Powder. Powder flame spraying guns are lighter and more compact than other types of thermal spraying equipment. Due to lower particle velocities and temperatures obtained, the coatings produced have lower adhesive strength, lower overall cohesive strength, and higher porosity than coatings produced by other spray processes.

The powder feedstock may be pure metal, an alloy, a composite, a carbide, a ceramic, or any combination of these. The process is used to apply "self fluxing" metallic alloy coatings. These materials contain boron and silicon, which serve as fluxing agents, and oxidation is minimized. Feedstock is stored in a hopper which may be integrated with the gun or connected to it. A small amount of gas is diverted to carry the powder from the hopper into the oxyfuel gas stream, where the powder is melted and carried by the flame onto the substrate. The typical powder feeding mechanism incorporates a container and metering device which regulates the feed rate of the material into the carrier gas stream. A hyper-velocity oxyfuel gas powder spray gun is shown in Figure T-7.

Fusion or metallurgical bonding to a metal substrate is accomplished by heating the deposit to its melting temperature range. The fusing temperature is usually in excess of 1040°C (1900°F), and is accomplished with any heating source such as a flame, induction coil, or a furnace.

Variations in the powder flame spraying process include compressed gas to feed powder to the flame, additional air jets to accelerate the molten particles, a remote powder feeder with an inert gas to convey powder through a pressurized tube into the gun, and devices for high-speed powder acceleration at atmospheric pressure. Such refinements tend to improve flow rate, and sometimes to increase particle velocity, which enhances bond strength and coating density.

Oxygen Detonation Gun. The detonation gun is different from other combustion spraying devices. It uses the energy of explosions of oxygen-acetylene mixtures, rather than a steady flame, to blast powdered particles onto the surface of the substrate. The resulting deposit is extremely hard, dense, and tightly bonded.

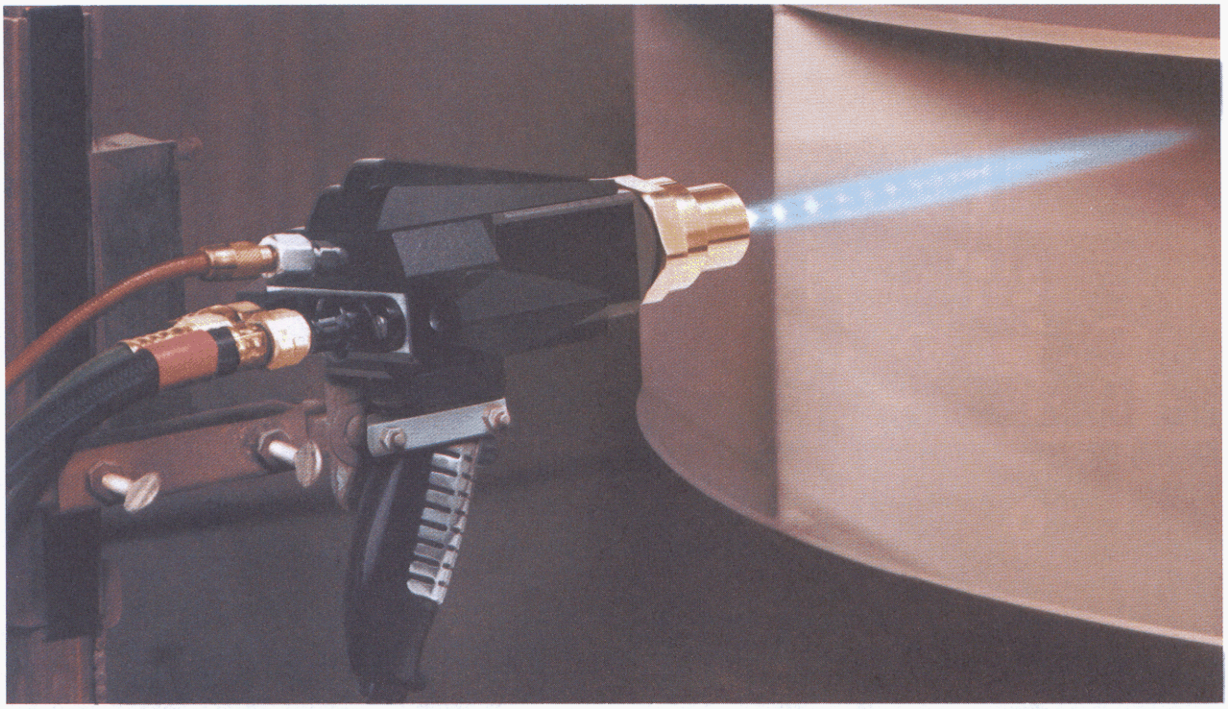


Figure T-7—Hyper Velocity Oxyfuel Gas Spray Gun. Note Diamond Pattern Resulting from Supersonic Outlet Velocity Shown Spraying Tungsten Carbide Powder.

The detonation gun, shown in Figure T-8, consists of a long barrel into which a mixture of oxygen, fuel gas, and powdered coating material, suspended in nitrogen, is introduced. The gas mixture is ignited by an electric spark several times per second, creating a series of controlled detonation waves (flame fronts) which accelerate and heat the powder particles as they move down the barrel. Exit particle velocities of approximately 760 m/sec (2500 ft/sec) are produced. After each ejection of powder, nitrogen purges the unit prior to successive detonations. Multiple detonations per second build up the coating to the specified thickness.

Temperatures above 3315°C (6000°F) are achieved within the detonation gun, while the substrate temperature is maintained below 150°C (300°F) by a carbon dioxide cooling system.

Coating thicknesses range between 0.05 and 0.50 mm (0.002 and 0.02 in.). The process produces a sound level in excess of 150 decibels, and is housed in a soundproof room. The actual coating operation is completely automatic and remotely controlled. The high particle impingement velocity results in a strong bond with the substrate. Excellent finishes are achievable, and the porosity content of the coating is low.

Electrical Heating

Wire Arc Process. The wire arc spray process uses an arc between two consumable wires (feedstock). They are kept insulated from each other and automatically advance to meet at a point within an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires initiates an arc as they converge, melting the tips of both wires. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets which form the atomized spray.

The velocity of the gas through the atomizing nozzle can be regulated over a range of 4.0 to 5.5 m/s (800 to 1100 ft/min) to control deposit characteristics. Molten metal particles are ejected from the arc at the rate of several thousand particles per second.

In comparison with wire flame spraying, the quantity of metal oxides is better controlled and spray rates

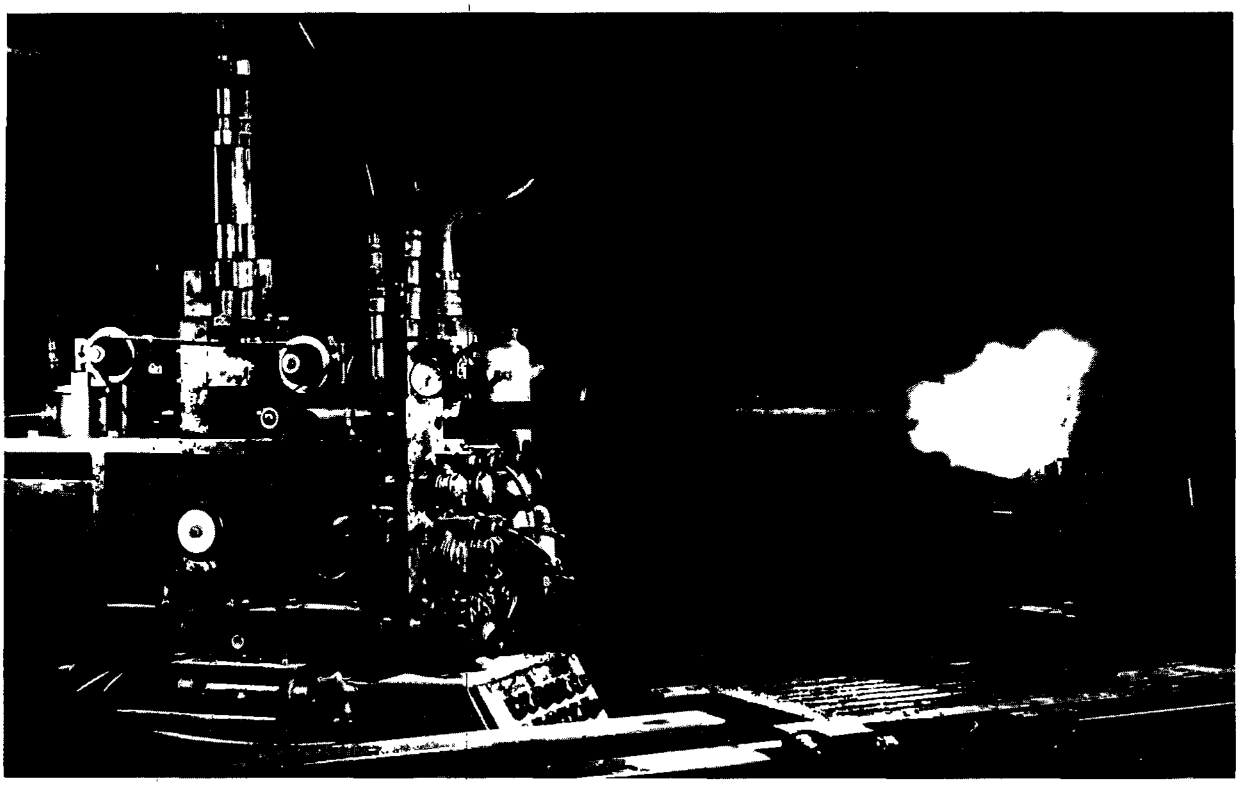


Figure T-8—Detonation Flame Spraying Equipment

are higher in wire arc spraying. Thus wire arc spraying is often more economical.

Wire Arc Spray Gun. A schematic view of a wire arc spray gun is shown in Figure T-9. A welding power supply is required to maintain the arc between the two wires.

The arc temperatures exceed the melting point of the spray material. During the melting cycle, the metal is superheated to the point where some volatilization may occur, especially with aluminum and zinc. The high particle temperatures produce metallurgical interactions or diffusion zones, or both, after impact with the substrate. These localized reactions form minute weld spots with good cohesive and adhesive strengths. Thus the coatings develop excellent bond strengths.

Power Source. Direct current constant potential power sources are normally used for wire arc spraying; one wire is positive (anode) and the other is negative (cathode). The tip of the cathode wire is heated to a higher temperature than the tip of the anode wire and melts at a faster rate. Consequently, the particles atomized from the cathode are much smaller than those from the anode wire when the two wires are of the same diameter.

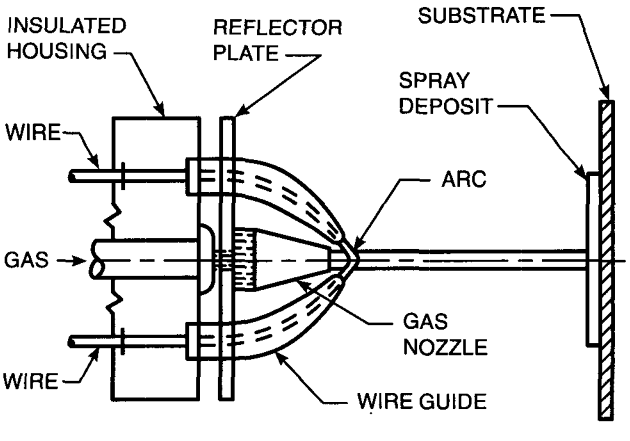


Figure T-9—Schematic View of a Wire Arc Spray Gun

The d-c power source, providing a voltage of 18 to 40 volts, permits operation over a wide range of metals and alloys. The arc gap and spray particle size increase with a rise in voltage. The voltage should be kept at the lowest possible level, consistent with good arc stability, to provide the smoothest coatings and maximum coating density.

Wire Control Unit. The wire control unit consists of two reel (or coil) holders, which are insulated from each other and connected to the spray gun with flexible insulated wire guide tubes. Wire sizes range from 1.6 to 3.2 mm (1/16 to 1/8 in.). Wires of larger diameters are usually in coil form, while smaller diameter wires are preferably level wound on reels or in barrels.

System Operations. Wire arc spray systems can be operated from a control console or from the gun. The control console will have the switches and regulators necessary for controlling and monitoring the operating circuits that power the gun and control the spray procedure, namely the following:

(1) A direct current power source, usually of the constant voltage type

(2) A dual wire feeding system

(3) A compressed gas supply with regulators and flow meters built into the control assembly

(4) Arc spray gun and related console switching

After the first pass has been applied over the entire surface of the workpiece, subsequent spraying is done using the lowest possible arc voltage consistent with good arc stability, and the normal spray gun-to-work distance. These conditions ensure the following:

(1) Fine particle size

(2) Minimum loss of alloy constituents

(3) A concentrated spray pattern

(4) High melting rate

Plasma Arc Spraying

Turbine and rocket engine components are exposed to extreme service conditions. Existing engineering materials will not stand up to these conditions without a protective thermally sprayed coating. In many cases, the spray coating consists of ceramic oxides and carbides which require temperatures higher than those possible with flame and arc processes. The plasma spray process evolved to meet these needs.

The plasma spray process also stimulated the evolution of a new family of materials and application techniques for a greatly expanded range of industrial applications. Plasma spraying supplements the older processes of flame and wire arc spraying.

In the plasma spray process, a gas or gas mixture is passed through an electric arc between a coaxially aligned tungsten alloy cathode and an orifice within a copper anode. The process is illustrated in Figure T-10. The gas passing through the orifice is ionized. The temperature of the ionized plasma is much higher than that obtained with a combustion flame.

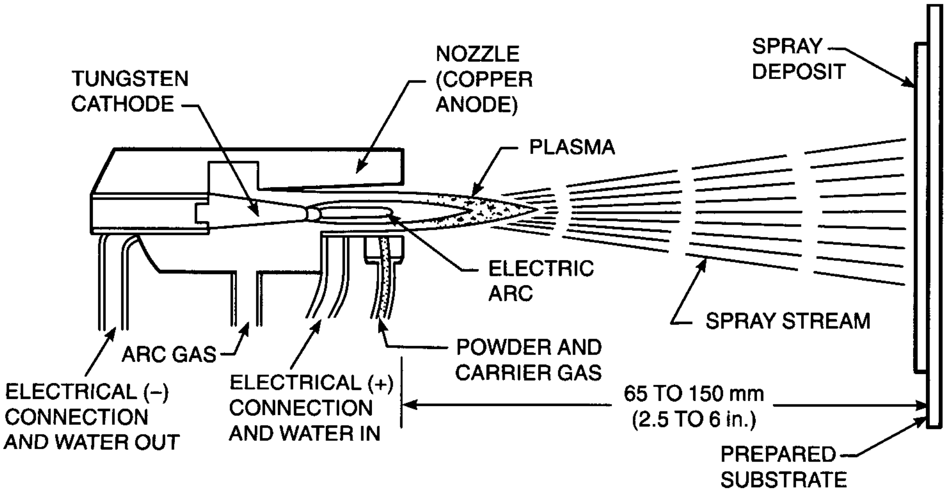


Figure T-10—Cross Section of a Plasma Arc Spraying Torch

As the plasma jet exits the gun, disassociated molecules of a diatomic gas recombine and liberate heat. The powder is introduced into the plasma, melted, and propelled onto the workpiece by a high-velocity gas stream. The heat content, temperature, and velocity of the plasma jet are controlled by the nozzle type, the arc current, the mixture ratio of gases and the gas flow rate.

The arc operates on direct current from a welding type power supply. The electric power to the arc is governed by a central control unit that regulates the flow of plasma gas and cooling water, and sequences these elements to allow the process to operate reliably and precisely. Either nitrogen or argon is used as the plasma forming gas. A secondary gas, either hydrogen or helium, may be added to increase the heat content and velocity of the plasma.

Controlled Atmosphere Plasma Spraying. Plasma arc spraying lends itself to controlled atmosphere applications. Temperature regulation of both the substrate and atmosphere are more precise in controlled atmospheres. This results in lower oxidation of the sprayed materials and less porosity in the sprayed deposit. It also produces closer control of the composition and morphology of the sprayed coating. This results in greater structural homogeneity, absence of oxide, increased hardness, and a thicker deposit capability. These benefits are produced at a higher deposition rate.

Fused Spray Deposits

A fused spray deposit is a self-fluxing alloy deposited by thermal spraying, which is subsequently heated to coalescence within itself and with the substrate. The materials wet the substrate without the addition of a fluxing agent, provided the substrate is properly cleaned and prepared to receive it. The materials are powdered nickel or cobalt alloys, and they may be applied by powder flame spraying or by plasma spraying.

The application of a fused deposit involves four operations:

(1) Surface preparation

(2) Spraying the self-fluxing alloy

(3) Fusing the coating to the substrate

(4) Finishing the coating to meet surface and dimensional requirements

Fused coatings are dense and nearly porosity free. The alloy compositions can result in hardness levels greater than 50 HRC. Coating thickness is limited to those ranges which can be heated to melting temperature without spalling. Self fluxing coatings are limited to applications where the effects of fusing temperatures and any distortion can be tolerated. Thick coatings of dissimilar metals can be applied in multiple passes. For optimum results, the surface to be coated should be cleaned of all oxide residues after each fusing stage or layer.

A properly sprayed and fused deposit will be nearly homogeneous, metallurgically bonded to the substrate, and have no open or visible porosity. It will have higher hardness than an equivalent mechanically bonded deposit, and will withstand pressures and environments better than non-fused deposits.

Self-Fluxing Alloys. Most self-fluxing alloys fall into two general groups: nickel-chromium-boron-silicon alloys and cobalt-chromium-boron-silicon alloys. In some cases tungsten carbide or chromium carbide particles are blended with an alloy from one of these groups.

The boron and silicon additions are crucial elements that act as fluxing agents and as melting point depressants. They permit fusing at temperatures compatible with steels, certain chromium-iron alloys, and some nickel base alloys.

The hardness of fused coatings will range from 20 to 60 HRC, depending upon alloy composition. Hardness is virtually unaffected by the thermal spraying procedures since there is almost no dilution with the base metal.

In addition to cleaning, blasting, thermal spraying, and work-handling equipment, some device or method is needed to fuse the sprayed deposit. Fusing may be done with an oxyfuel gas torch, in a furnace, or by induction heating.

Thermal sprayed deposits can be fused to a wide variety of substrates. Some base metals are easier to surface than others. Those which can be readily sprayed with one or more self-fluxing alloys and then fused are:

(1) Carbon and low-alloy steel with less than 0.25% carbon

(2) AISI 300 series stainless steels, except Types 303 and 321

(3) Certain grades of cast iron

(4) Nickel and nickel alloys that are free of titanium and aluminum

Metals that require special procedures to avoid undesirable metallurgical changes are carbon and low-alloy steels with more than 0.25% carbon, and AISI 400 series stainless steels, except Types 414 and 431.

Types 414, 431, and the precipitation hardening stainless steels are not recommended as base metals for self-fluxing alloys.

Cracking of some types of fused sprayed deposits on hardenable steels (above 25 HRC) can be avoided by isothermal annealing of the parts from the fusing temperature.

Post-Treatments

Sealing. Sealing of sprayed deposits is performed to lengthen the service life or prevent corrosion of the substrate, or both. Sprayed deposits of aluminum or zinc may be sealed with vinyl coatings, either clear or aluminum pigmented. The sealer may be applied to fill only subsurface pores in the deposit, or both subsurface pores and surface irregularities. The latter technique will provide a smooth coating to resist industrial atmospheres. The vinyl coatings may be applied with a brush or spray gun.

Epoxies, silicones, and other similar materials are used as sealants for certain corrosive conditions. Vacuum impregnations with plastic solutions are also possible.

Diffusing. A thin layer of aluminum may be diffused into a steel or silicon bronze substrate at 760°C (1400°F). The diffused layer can provide corrosion protection against hot gases up to 870°C (1600°F). After depositing the aluminum, the part can be coated with an aluminum pigmented bitumastic sealer or other suitable material, to prevent oxidation of the aluminum during the diffusion heat treatment. There are similar aircraft applications with diffusion temperatures dependent upon the base material to which the aluminum is applied.

Surface Finishing. Techniques for surface finishing of thermal spray deposits differ somewhat from those commonly used for metals. Most sprayed deposits are primarily mechanically bonded to the substrates, except for fused coatings. Excessive pressure or heat generated in the coating during the finishing operation can cause damage such as cracking, crazing, or separation from the substrate.

The selection of a finishing method depends on the type of deposit material, its hardness, the coating thickness, as well as dimensional and surface roughness requirements. Spray deposits of soft metals are usually finished by machining. Hardfaced substrates and ceramic sprayed coatings are usually finished by grinding.

Various other finishing methods are occasionally used. These include buffing, tumbling, burnishing, belt polishing, lapping, and honing.

Properties of Thermal Sprayed Deposits

The quality and the properties of thermal sprayed deposits are largely determined by the size, temperature, and velocity of the spray droplets as they impinge on the substrate, and the degree of oxidation of both the droplets and the substrate during spraying. These factors will vary with the method of spraying and the procedures employed.

The physical and mechanical properties of a spray deposit normally differ greatly from those of the original material. The deposit structure is lamellar and nonhomogeneous, and its cohesion is generally the result of mechanical interlocking. For these reasons, spray deposits should be considered as a separate and distinct form of fabricated material.

Oxide spray deposits tend to retain their physical properties with only modest losses. The chemical compositions of reactive type ceramics, such as carbides, silicides, and borides normally change when the materials are sprayed in air with the flame or plasma methods.

Microstructure. The microstructure of a transverse section through a flame sprayed metal deposit will show a heterogeneous mixture of layered metal particles (white), metal oxide inclusions (gray), and pores (black). A photomicrograph of a transverse section through a flame sprayed deposit of 0.80% carbon steel is shown in Figure T-11. The light layered particles are bonded to one another by chemical and mechanical interactions.

The microstructure of the polished and etched surface of the 0.80% carbon steel deposit is shown in Figure T-12. It has an emulsified appearance because the flattened steel particles (light) are separated by the oxide (gray).

As-sprayed, self-fluxing alloy deposits are oxidation resistant in nature. As shown in Figure T-13, the microstructure of a fused nickel-chromium self-fluxing alloy deposit has a cast structure with some porosity and inclusions. The roughness of the prepared substrate (bottom of figure) is also evident.

Hardness. The heterogeneous structures of spray deposits generally have a lower macrohardness than the original rod or wire supplied to the gun. However, the hardness of individual deposit particles (microhardness) may be much higher than that of the overall deposit. The type of hardness test should be selected to

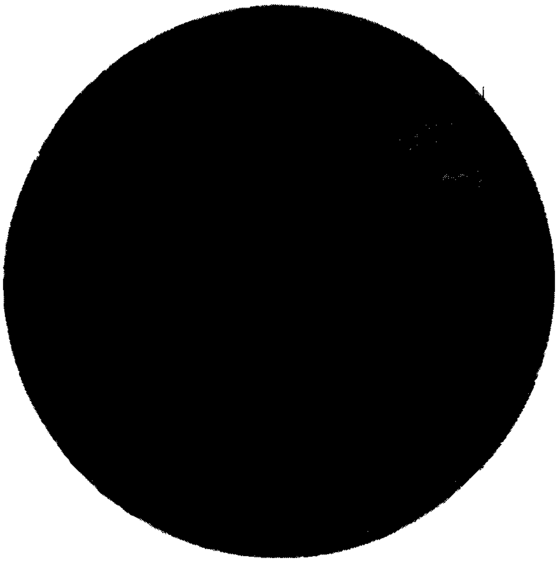


Figure T-11—Transverse Section Through a Flame Sprayed AISI 1080 Steel Deposit (X500 Reduced on Reproduction)

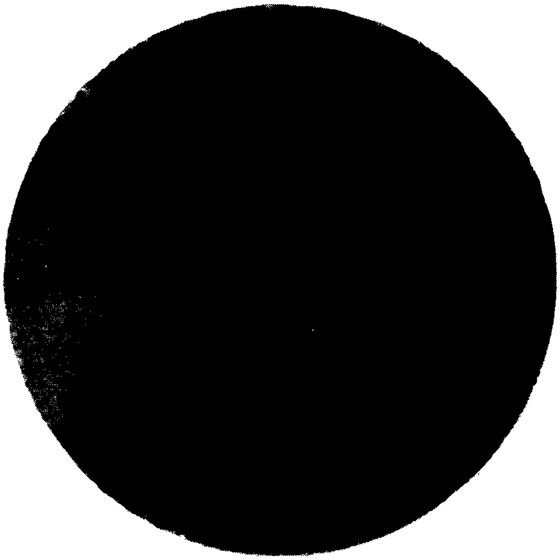


Figure T-12—Section Parallel to the Surface of a Flame Sprayed Deposit of AISI 1080 Steel (X500 Reduced on Reproduction)

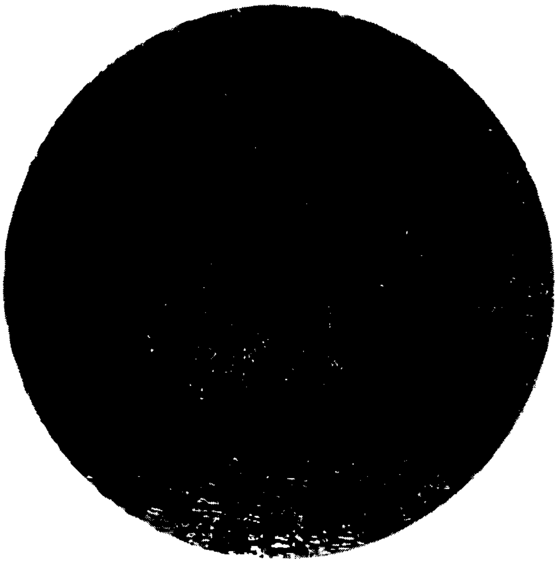


Figure T-13—Microstructure of a Fused Coating of a Self-Fluxing Nickel-Chromium Alloy (Top) on a Substrate (Bottom) (X250 Reduced on Reproduction)

give either the overall deposit hardness or the particle hardness. The thickness of the deposit must also be considered.

The Brinell and Rockwell hardness tests can be used to determine the hardness of fairly thick metallic deposits. Superficial Rockwell and Vickers hardness tests are suitable for thin metallic deposits.

Hardness tests with diamond indenters should be avoided. Microhardness tests can be used to determine the hardness of individual particles. The Knoop indentation hardness test is best suited for this.

Bond Strength. The strength of the bond between a spray deposit and the substrate depends upon many factors, including the following:

(1) Substrate material and its geometry

(2) Preparation of the substrate surface

(3) Spray angle to substrate

(4) Preheat

(5) Bond layer material and its application method and procedures

(6) Deposit material and its application method and procedures

(7) Thickness of deposit

(8) Post spraying thermal treatment

Density. Thermal sprayed deposits have densities less than 100% of the filler metals used because they are porous and contain some oxide. The densities of the flame sprayed deposits and the original wire for several metals are shown in Table T-6.

Table T-6
Comparison of the Densities of Flame Sprayed Metal Deposits and the Wire

Metal	Density, kg/m³ (lb/in.³) Flame Sprayed Deposit (Wire)	Density, kg/m³ (lb/in.³) Wire
1100 Aluminum	2408 (0.087)	2713 (0.098)
Copper	7501 (0.271)	8968 (0.324)
Molybdenum	9024 (0.326)	10214 (0.369)
AISI 1025 Steel	6754 (0.244)	7861 (0.284)
304 Stainless Steel	6892 (0.249)	8027 (0.290)
Zinc	6839 (0.229)	7141 (0.258)

Coating Selection and Applications

The selection of a proper coating material involves more than choosing the desired properties of the deposit. It should be approached as an engineering problem by considering such items as coating function and service environment, in addition to the physical and chemical properties of both the coating and the substrate. The properties of conventional materials are well understood, and their service performance predictable. This is not true of thermal spray coatings. The mechanical and corrosion resistant properties of sprayed materials differ from solid or powder metal parts of the same chemistry. Coating material selection should be based on properties related to end use and service environment, plus factors involving its compatibility with the substrate. It is not difficult to select the proper coating for a given function after all the pertinent factors are taken into consideration.

Wear Resistance. In the mechanical field, thermal spray hardfacing materials can be used to combat many types of wear. The ability of metal spray deposits to absorb and maintain a film of lubricant is a distinct advantage in many applications.

Electrical Characteristics. The electrical resistance of a metal spray deposit may be 50 to 100% higher than that of the same metal in cast or wrought form. This must be considered in the design of spray deposits for electrical conductors. Such applications include spraying of copper on electrical contacts, carbon brushes, and glass in automotive fuses, as well as silver or copper contacts.

In the field of electrical insulation, various ceramic deposits can be used for insulators. Magnetic shielding of electrical components may be provided with deposits of zinc or tin zinc applied to electronic cases and chassis. Condenser plates can be made by spraying aluminum on both sides of a cloth tape.

Foundry. Changes in contour of expensive patterns and match plates can be readily accomplished by the application of thermal spray deposits followed by appropriate finishing. Patterns and molds can be repaired with wear resistant deposits. Blow holes in castings that appear during machining can be filled to salvage the parts.

Brazing and Soldering. Thermal spraying is frequently used for the preplacement of solder or brazing filler metals. The usual practice is to apply the filler metal using thermal spraying techniques.

Aircraft and Missiles. Thermal spraying is used for air seals and wear-resistant surfaces to prevent fretting and galling at elevated temperatures. Deposits of alumina and zirconia are used for thermal insulation.

References: American Welding Society, *Thermal Spraying Practice, Theory and Application*, Miami, Florida: American Welding Society, 1985.

American Welding Society, *Welding Handbook*, Chapter 28, Thermal Spraying, Vol.2, 8th Ed. Miami, Florida: American Welding Society, 1991

THERMAL SPRAYING DEPOSITION EFFICIENCY

The ratio of the weight of thermal spray deposit to the weight of surfacing material sprayed, expressed in percent. See STANDARD WELDING TERMS.

THERMAL SPRAYING GUN

A device for heating, feeding, and directing the flow of surfacing material. See STANDARD WELDING TERMS.

THERMAL SPRAYING OPERATOR

One who operates automatic, mechanized, or robotic thermal spraying equipment. Variations of this term are ARC SPRAYING OPERATOR, FLAME SPRAYING OPERATOR, *and* PLASMA SPRAYING OPERATOR. *See* STANDARD WELDING TERMS.

THERMAL SPRAY PASS

A single progression of the thermal spraying gun across the substrate surface. See STANDARD WELDING TERMS.

THERMAL STRESS

Stress resulting from nonuniform temperature distribution. See STANDARD WELDING TERMS.

Thermal stress may refer to stresses in a welded joint, welded structure, or part and is produced by differences in temperature or coefficients of expansion during welding or cutting.

THERMITE, Cast Iron

A thermite mixture containing additions of ferrosilicon and mild steel.

THERMITE CRUCIBLE

The vessel in which the thermite reaction takes place. See STANDARD WELDING TERMS. *See also* THERMITE WELDING.

THERMITE FORGING

A thermite mixture with the addition of carbon, manganese, nickel and mild steel. *See* THERMITE WELDING.

THERMITE MIXTURE

A mixture of metal oxide and finely divided aluminum with the addition of alloying metals as required. See STANDARD WELDING TERMS.

THERMITE MOLD

A mold formed around the workpieces to receive molten metal. See STANDARD WELDING TERMS.

THERMITE REACTION

The chemical reaction between metal oxide and aluminum that produces superheated molten metal and a slag containing aluminum oxide. See STANDARD WELDING TERMS.

THERMITE WELDING (TW)

A welding process that produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal is obtained from the liquid metal. See STANDARD WELDING TERMS.

Historical Background

The thermite process was developed at the end of the 19th century when Hans Goldschmidt of Goldschmidt AG West Germany (Orgotheus Inc. USA) discovered that the exothermic reaction between a mixture of aluminum powder and a metal oxide can be initiated by an external heat source. The reaction is highly exothermic, and therefore, once started, it is self-sustaining.

The Thermite Reaction

The thermite mixture can be ignited and brought to a high temperature in one spot, and when started, the reaction will continue throughout the rest of the mass. This reaction occurs when the aluminum combines with the oxygen of the iron oxide to form aluminum oxide (slag) in a super-heated molten state while the iron is set free and is produced as liquid steel, also super-heated. The temperature created by this reaction is about 3150°C (5650°F), but because of heat loss through the crucible, the molten metal actually reaches about 2400°C (4350°F). When steel at this high temperature is poured around and between two iron or steel sections which have been previously heated to red heat, they will become dissolved and will amalgamate with the thermite steel. When the entire mass cools down it forms a single homogeneous section.

The thermite reaction is not explosive, and no danger is incurred in storing and handling the material, since it requires the temperature of liquid steel to ignite it.

Applications

This process is not often used in production welding because other processes are more efficient, but thermite welding continues to be used for making butt welds between lengths of railroad rails, for joining very thick sections of cast iron and steel castings, and for joining very large size steel reinforcing bars embedded in concrete structures. Circumstances can arise where thermite welding is the best process to fill special needs. Repair of massive sections that have cracked in large machines is an application where thermite welding can be used to advantage.

The most common application of the process is the welding of rail sections into continuous lengths to minimize the number of bolted joints in the track structure. In coal mines, the main hauling track is often welded to minimize maintenance and to reduce coal spillage caused by uneven track. Crane rails are usually welded to minimize joint maintenance and vibration of the building as heavily loaded wheels pass over the joint.

Thermite welding is also used in the marine field for repair of heavy sections of ferrous metal, such as broken stern frames, rudder parts, shafts, and struts.

Worn wabblers on the ends of steel mill rolls may also be replaced with tough thermite metal deposit that is machinable. Thermite welding is particularly applicable for repairs involving large volumes of metal, where the heat of fusion cannot be raised satisfactorily or efficiently by other means, or where fractures or voids in large sections require a large quantity of weld metal.

Thermite welding can be used to repair ingot molds at significant savings over replacement. The blades of large dredge cutters may be thermite welded to a center ring. Quantities up to several thousand pounds are poured at one time. In this case, thermite welding is a production tool rather than a repair method.

Safety

The presence of moisture in the thermite mix, in the crucible, or on the workpieces can lead to rapid formation of steam when the thermite reaction takes place. Steam pressure may cause violent ejection of molten metal from the crucible. Therefore, the thermite mix should be stored in a dry place; the crucible should be dry, and moisture should not be allowed to enter the system before or during welding.

THERMOCOMPRESSION BONDING

A nonstandard term for HOT PRESSURE WELDING.

THERMO-ELECTRICITY

Electricity produced by heating metals.

THERMOCOUPLE

Two different metals welded together and used for the purpose of producing thermo-electricity.

THERMOMETER

An instrument for measuring relative temperatures. *See* Appendix 14. *See also* PYROMETER.

THERMOSTAT

A device that opens and closes a circuit when the temperature changes.

THREADING AND KNURLING, Thermal Spraying

A method of surface roughening in which spiral threads are prepared, followed by upsetting with a knurling tool. See STANDARD WELDING TERMS. *See* Figure T-14.

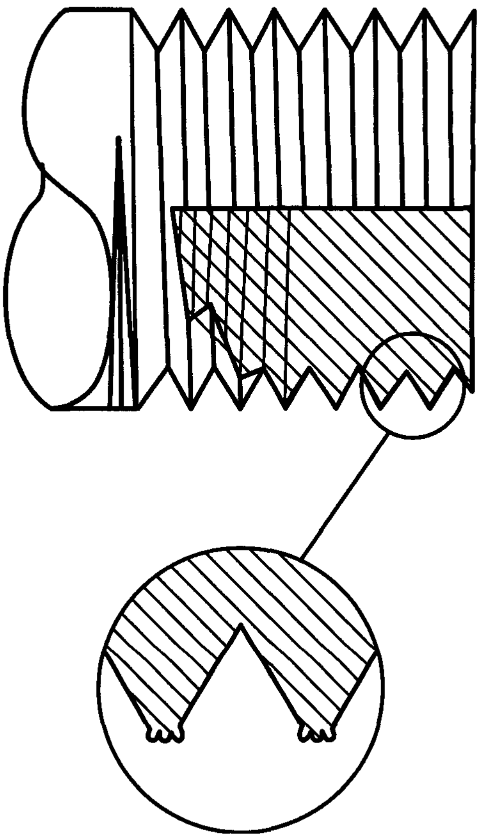


Figure T-14—Threading and Knurling as a Preparation for Thermal Spraying

3F

A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the vertical welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

3G

A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the vertical welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

THREE PHASE

A generator or circuit delivering three voltages that are 1/3 of a cycle apart in reaching their maximum value. Three-phase current is generally used for circuits of 220 volts or more.

THREE-PHASE WELDING

See RESISTANCE WELDING.

THROAT AREA

The area bounded by the physical parts of the secondary circuit in a resistance spot, seam, or projection welding machine. Used to determine the dimensions of a part that can be welded and determine, in part, the secondary impedance of the equipment. See STANDARD WELDING TERMS.

THROAT CRACK

See STANDARD WELDING TERMS. *See* Appendix 9.

THROAT DEPTH

In a resistance spot, seam, or projection welding machine, the distance from the centerline of the electrodes or platens to the nearest point of interference for flat sheets. See STANDARD WELDING TERMS.

THROAT HEIGHT

The unobstructed dimension between the arms and throughout the throat depth in a resistance welding machine. See STANDARD WELDING TERMS.

THROAT LENGTH

A nonstandard term when used for CONSTRICTING ORIFICE LENGTH.

THROAT OF A FILLET WELD

See STANDARD WELDING TERMS. *See* ACTUAL THROAT, EFFECTIVE THROAT, *and* THEORETICAL THROAT.

THROAT OF A GROOVE WELD

A nonstandard term for GROOVE WELD SIZE.

THROAT OPENING

A nonstandard term for THROAT HEIGHT.

TIG WELDING

A nonstandard term for GAS TUNGSTEN ARC WELDING. *See* GAS TUNGSTEN ARC WELDING.

***TIG* as a Nonstandard Term.** Although the terms *TIG* and *MIG* are popularly used, they do not accurately reflect the technology of the processes. In the document ANSI/AWS A3.0, *Standard Welding Terms and Definitions*, the American Welding Society (AWS) Definitions and Symbols Committee has stated a preference for *GTAW* (gas tungsten arc welding) because it is a more definitive term than *TIG*.

The gas tungsten arc process was originally used with an inert gas as the arc- shielding atmosphere. The term *tungsten inert gas (TIG)* became popular. The later application of non-inert, i.e., active, gases for arc shielding rendered the term TIG inaccurate. To remove that discrepancy, the term *tungsten active gas* (TAG) was proposed by some. With that terminology, the welding of stainless steel with argon is referred to as a *TIG* welding process, and if hydrogen is added to the argon shielding gas, the welding process becomes *TAG*. If the latter gas mixture is used for welding a noble metal, the welding process would then revert to *TIG*. Thus the name of the welding process depends not only on the composition of the shielding gas but also on the base metal composition. Logically, such terminology would be comparable to making the name of the shielded metal arc welding process dependent on the type of electrode covering and the composition of the base metal.

The proponents of *TIG* correctly cite its simplicity, brevity, and ease of pronunciation. However, "tungsten inert gas," by itself is incomplete. Only when the word *welding* is added is the term complete and may be logically compared with gas tungsten arc welding. The term would be *TIGW*, and it would lose some of the cited advantages.

Arguments similar to those made in support of GTAW also apply to gas metal arc welding (GMAW) versus metal inert gas (MIG) welding. Both GTAW and GMAW are part of a coherent letter designation system that has been developed by the Definitions Subcommittee of AWS for all of the welding and allied processes. Haphazard changes cannot be made without damage to the letter system as a whole. The Definitions Subcommittee prefers the terms gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW), with modifiers to denote the variations of the processes. The terminology in the document, ANSI/AWS A3.0, *Standard Welding Terms and Definitions*, has been widely accepted by such organizations as the American Society for Metals, the American Society of Mechanical Engineers, and the Department of Defense, as well as the American Welding Society. *See* STANDARD WELDING TERMS.

TIN

(Chemical symbol: Sn). A silvery-white, malleable and somewhat ductile metal with a low melting point. It is a crystalline structure. It takes a high polish and is used to coat other metals to prevent corrosion, since it does not corrode easily in air. Tin, when added to steel, slightly increases hardness but reduces impact strength. Atomic weight, 118.7; melting point, 231°C (448°F); specific gravity, 5.85.

TINNING

A nonstandard term when used for PRECOATING. *See* PRECOATING.

TIP

See STANDARD WELDING TERMS. *See also* CUTTING TIP *and* WELDING TIP.

A tip, sometimes called a nozzle, is the part of a gas torch from which the gas is discharged; also, the portion of a resistance spot welding electrode which comes in contact with the workpiece.

TIP SKID

A nonstandard term for ELECTRODE SKID.

TITANIUM

(Chemical Symbol: Ti). A lustrous white metal of the tin group occurring naturally as titanium oxide or in other oxide forms. The free element is precipitated by heating the oxide with aluminum or by the electrolysis of the solution in calcium chloride. Atomic weight, 48.1; melting point, 1668°C (3034°F); boiling point, 3260°C (5900°F); specific gravity, 4.5; density 4.51g/cm^3.

Titanium is highly resistant to corrosion, has high-temperature stability, and is used in alloys to achieve excellent strength-to-weight ratios. These properties have led to its widespread use in the chemical, aerospace, marine, and medical fields. Among recent applications for titanium alloys are in the petro-chemical industry and in sports equipment manufacturing.

Titanium is used as a stabilizer in stainless steel to prevent precipitation of carbon during welding. It has been used for rimmed steels, performing a valuable function in distributing sulphur in high-sulphur steels.

Titanium has a strong chemical affinity for oxygen, and forms a tight microscopic oxide film on freshly prepared surfaces at room temperature (similar to magnesium and aluminum). The oxide film makes titanium passive to further reactivity. This passivity accounts, in part, for its excellent corrosion resistance to aqueous salt or oxidizing acid solutions, and acceptable corrosion resistance to mineral acids.

TITANIUM DIOXIDE

(Chemical symbol: TiO_2). Titanium dioxide (TiO_2) is an important compound extensively used in electrode coatings. *See* RUTILE *and* ELECTRODE MANUFACTURE.

TITANIUM WELDING

When heated in air above 650°C (1200°F), titanium tends to oxidize rapidly. At elevated temperatures it has the propensity for dissolving discreet amounts of its own oxide into solution. For these reasons, the welding of titanium requires protective shielding, such as an inert gas atmosphere, to prevent contamination and embrittlement from oxygen and nitrogen. The relatively low coefficients of thermal expansion and conductivity minimize the possibility of distortion due to welding.

Pure titanium is quite ductile (15 to 25% elongation) and has a relatively low ultimate tensile strength, approximately 207 MPa (30 ksi). Some limited amounts of oxygen and nitrogen in solid solution markedly strengthen titanium, but embrittle it if present in sufficient quantity. Carbon exerts a similar but less intensive effect. Hydrogen also promotes embrittlement when present above specified limits. These elements are usually unintentionally added by contamination when the metal is processed. Intentional additions of various alloying elements may result in tensile strengths exceeding 1380 MPa (200 ksi), but there is a resultant sacrifice of ductility. The combination of high strength, low density, and excellent corrosion resistance results in a very desirable strength-to-weight ratio, up to temperatures as high as 650°C (1200°F).

The weld metal tensile, impact and hardness properties for titanium and titanium alloy welding electrodes and rods are shown in Table T-7. These data were from multi-pass gas tungsten arc welded plate of 12.7 mm (0.5 in.) thickness, or greater, with plate and filler metal of identical composition.

Weldability

Titanium alloys may be classified according to their ability to produce tough, ductile welds. One such rating is shown in Table T-8. All alloys rated A or B in Table T-8 are considered usable in the as-welded condition for most applications. Many alloys of limited weldability can be subjected to postweld annealing to improve ductility. All of the weldable titanium alloy grades in the annealed condition will produce joint efficiencies close to 100%.

Filler Metals

When welding titanium and titanium alloys, the filler metal should have the same nominal composition as the base metal. Filler metal is usually used in the form of bare rod or wire, depending on the welding process and the type of operation (manual, semiauto-

Table T-7
Mechanical Properties of Titanium and Titanium Alloy Weld Metal

		All-Weld Metal Tensile Test						Impact Strength, Charpy V-notch						Rockwell Hardness			Impurity Content[a]		
		UTS		0.2% YS		El in 1 in. (25.4 mm)	RA	J			ft·lb								
No.	AWS Filler Metal Classification[b]	MPa	ksi	MPa	ksi	%	%	20°C	0°C	−62°C	68°F	32°F	−80°F	BM	HAZ	Weld	H, ppm	O, %	Fe, %
														(Rockwell B)					
1	ERTi-1c	414	60	324	47	41	77	220	216	224	162	159	165	46	47	46	20	0.09	<0.06
2	ERTi-2c	400	58	296	43	42	76	54	57	48	40	42	35	43	45	44	30	0.07	<0.06
3	ERTi-3	565	82	441	64	24	48	21	19	17	16	14	13	53	55	56	50	0.16	0.13
4	ERTi-4	607	88	476	69	22	46	37	30	33	27	22	25	55	57	57	40	0.20	0.28
5	ERTi-0.2Pd	496	73	476	58	28	59	56	52	45	41	38	33	52	53	53	45	0.13	0.16
6	ERTi-3Al-2.5V	689	100	545	79	20	59	62	57	48	46	42	35	60	60	60	75	0.08	0.08
7	ERTi-3Al-2.5V-1	703	101	572	83	18	56	58	59	50	43	44	37	58	60	60	15	0.08	0.08
														(Rockwell C)					
8	ERTi-5Al-2.5Sn	951	138	855	124	12	26	34	28	20	25	21	15	33	34	35	50	0.18	0.44
9	ERTi-5Al-2.5Sn-1	862	125	779	113	15	28	57	56	42	42	41	31	29	31	31	25	0.10	0.19
10	ERTi-6Al-2Cb-1Ta-1Mo	910	132	800	116	11	27	52	52	37	39	38	28	30	31	32	40	0.09	0.06
11	ERTi-6Al-4V	1007	146	841	122	12	39	23	24	15	17	18	11	32	36	36	35	0.13	0.18
12	ERTi-6Al-4V-1	958	139	827	120	10	25	24	21	18	18	16	13	30	34	34	45	0.10	<0.06
13	ERTi-8Al-1Mo-1V	965	140	841	122	7	15	36	30	22	27	22	17	33	36	36	70	0.08	0.08
14	ERTi-13V-11Cr-3Al	800	116	765	111	22	39	5	5	5	4	4	4	29	30	30	>75	0.10	0.13
15[b]	Ti-5Al-6Sn-2Zr-0.8Mo-0.25Si	1010	147	858	125	12	20	29	27	19	21	20	14	37	38	39	75	0.14	0.05
16[b]	Ti-3Al-8V-6Cr-4Zr-4Mo	817	119	748	109	10	28	7	8	5	5	6	4	29	29	28	35	0.09	0.17

a. The composition for all the weld metals included carbon in the range of 0.02 to 0.04% and nitrogen in the range of 0.005 to 0.012%. The nominal alloy contents in percent are shown in the AWS Classification designation.

b. Alloy Nos. 15 and 16 are not included in the AWS filler metal specification.

c. Difference in toughness between ERTi-1 and ERTi-2 due to hydrogen content. Other titanium alloys are not sensitive to hydrogen within nominal specification limits.

Table T-8
Weldability of Titanium Alloys

Nominal Composition % (balance Ti)[1]	Rating[2]
Commercially pure (all)	A
0.15 Pd	A
5Al-2.5Sn (standard interstitial)	B
5Al-2.5Sn (low interstitial)	A
O—5Al-5Sn-5Zr	A
O—7Al-12Zr	B
O—7Al-2Cb-1Ta	A
8Al-1Mo-1V	A
8Mn	C
O—2Fe-2Cr-2Mo	D
O—2.5Al-16V	C
O—4Al-4Mn	D
4Al-3Mo-1V	C
5Al-1.25Fe-2.75Cr	C
5Al-1.5Fe-1.4Cr-1.2Mo	D
6Al-4V (standard interstitial)	B
6Al-1V (low interstitial)	A
6Al-6V-2Sn-1 (Fe, Cu)	C
7Al-1Mo	C
O—1Al-8V-5Fe	D
3Al-13V-11Cr	B
6Al-2Cb-1Ta-1Mo	A

1. O—Obsolete alloys, no longer produced commercially.
2. A—Excellent, B—fair to good, C—limited, for special applications or welded with special treatment, D—welding not recommended.

matic, or automatic). Refer to ANSI/AWS A5.16, *Specification for Titanium and Titanium Alloy Welding Electrodes and Rods.* The compositions of standard titanium welding electrodes and rods are shown in Table T-9.

When welding commercially pure titanium, an unalloyed filler metal can tolerate some contamination from the welding atmosphere without significant loss in ductility. The ERTi-1,-2, -3, and -4 filler metal classifications are designed for this purpose, as are those in AMS Specification 4951 (available from the Society of Automotive Engineers [*see* Appendix 2]). Unalloyed filler metal may be used to weld titanium alloys when weld metal ductility is more important than joint strength. Joint efficiencies of less that 100% can be expected.

For cryogenic applications where base metals with extra-low interstitial impurities are specified, the filler metals should also be low in those impurities. To be effective, the welding must be done with equipment and procedures that prevent contamination of the weld metal with carbon, oxygen, nitrogen, or hydrogen. The quality and cleanliness of the filler metal are important considerations in the welding of titanium. Filler metal can be a source of serious contamination of the weld metal from inclusions, dirt, oil, and drawing compounds on the filler metal surfaces. The relatively large surface area-to-volume ratios of wire or rod used make cleanliness very important. Physical defects in wire, such as cracks, seams, or laps, can entrap surface contaminants, and make their removal difficult or impossible. The filler rod or wire should be carefully inspected for mechanical defects, thoroughly cleaned, suitably handled, packaged, and stored to prevent contamination.

Weld Stress Relief

Residual stresses in weldments are relieved during annealing or solution heat treatment. A stress-relieving heat treatment might be applicable when it is not necessary to heat-treat the weld to obtain the required mechanical properties. Weld stress relief can be beneficial in maintaining dimensions, reducing cracking tendencies, or avoiding stress-corrosion cracking in certain alloys. However, stress relieving treatments of heat-treatable titanium alloys may be detrimental. Thermal stress-relieving could alter the mechanical properties of the weld by an aging reaction with heat-treatable alloys. This response might reduce the beneficial effects expected from stress relieving because of reduced weld ductility resulting from aging.

Cleaning

Prior to welding, brazing or heat treating, titanium components must be washed clean of surface contaminants and dried. Oil, fingerprints, grease, paint, and other foreign matter should be removed using a suitable solvent cleaning method. Ordinary tap water should not be used to rinse titanium parts. Chlorides and other cleaning residues left on titanium can lead to stress-corrosion cracking when the components are heated above about 290°C (550°F) during welding, brazing and heat-treating. Hydrocarbon residues can result in contamination and embrittlement of the titanium. Parts to be welded or brazed usually have a light oxide coating in the vicinity of the joint. The coating can be removed by pickling in an aqueous solution of 2 to 4% hydrofluoric acid (used with proper precautions) and 30 to 40% nitric acid, followed by appropriate water rinsing and drying. Hydrogen absorption by titanium alloys is generally not a problem at tempera-

Table T-9
Titanium and Titanium Alloy Bare Welding Electrodes and Rods

	Chemical Composition, Percent[a]													
AWS Classification	C	O_2	H_2	N_2	Al	V	Sn	Cr	Fe	Mo	Nb	Ta	Pd	Ti
ERTi-1[b]	0.03	0.10	0.005	0.012	—	—	—	—	0.10	—	—	—	—	Bal.
ERTi-2	0.05	0.10	0.008	0.020	—	—	—	—	0.20	—	—	—	—	Bal.
ERTi-3	0.05	0.10–0.15	0.008	0.020	—	—	—	—	0.20	—	—	—	—	Bal.
ERTi-4	0.05	0.15–0.25	0.008	0.020	—	—	—	—	0.30	—	—	—	—	Bal.
ERTi-0.2Pd	0.05	0.15	0.008	0.020	—	—	—	—	0.25	—	—	—	0.15–0.25	Bal.
ERTi-3Al-2.5V	0.05	0.12	0.008	0.020	2.5–3.5	2.0–3.0	—	—	0.25	—	—	—	—	Bal.
ERTi-3Al-2.5V-1[b]	0.04	0.10	0.005	0.012	2.5–3.5	2.0–3.0	—	—	0.25	—	—	—	—	Bal.
ERTi-5Al-2.5Sn	0.05	0.12	0.008	0.030	4.7–5.6	—	2.0–3.0	—	0.40	—	—	—	—	Bal.
ERTi-5Al-2.5Sn1[b]	0.04	0.10	0.005	0.012	4.7–5.6	—	2.0–3.0	—	0.25	—	—	—	—	Bal.
ERTi-6Al-2Cb-1Ta-1Mo	0.04	0.10	0.005	0.012	5.5–6.5	—	—	—	0.15	0.5–1.5	1.5–2.5	1.5–2.5	—	Bal.
ERTi-6Al-4V	0.05	0.15	0.008	0.020	5.5–6.75	3.5–4.5	—	—	0.25	—	—	—	—	Bal.
ERTi-6Al-4V-1[b]	0.04	0.10	0.005	0.012	5.5–6.75	3.5–4.5	—	—	0.15	—	—	—	—	Bal.
ERTi-8Al-1Mo-1V	0.05	0.12	0.008	0.03	7.35–8.35	.75–1.25	—	—	0.25	.75–1.25	—	—	—	Bal.
ERTi-13V-11Cr-3Al	0.05	0.12	0.008	0.03	2.5–3.5	12.5–14.5	—	10.0–12.0	0.25	—	—	—	—	Bal.

a. Single values are maximum.
b. Extra-low interstitials for welding similar base metals.

tures up to 60°C (140°F). The part should be handled, after pickling and rinsing, with lint-free gloves during assembly in the welding or brazing fixture. The fixturing itself should be thoroughly cleaned and degreased prior to loading the workpieces.

Oxide scale formed at temperatures above 595°C (1100°F) is difficult to remove chemically. Mechanical methods, such as vapor blasting and grit blasting, should be used for scale removal. Mechanical operations are usually followed by a pickling operation to ensure complete removal of surface contamination.

To control porosity in welding operations, the surfaces to be joined are often given special treatments, including draw filing, wire brushing, or abrading the joint and adjacent surfaces prior to fitup and final cleaning. Sheared joint edges frequently require special treatments to remove entrapped dirt, metal slivers, and small cracks because these edge discontinuities promote weld porosity.

Preweld cleaning operations should be accomplished immediately prior to welding. If this is not practical, the parts should be stored with a desiccant in sealed bags or in a humidity-controlled storage room. Alternatively, thorough degreasing and light pickling of parts just prior to welding or brazing is strongly recommended. Mechanical abrasion of the faying surfaces followed by washing with a suitable solvent, may be used in lieu of pickling treatment.

Protection During Joining. Because of the sensitivity of titanium to embrittlement by oxygen, nitrogen, and hydrogen, the entire component or that portion to be heated above about 260°C (500°F) must be protected from atmospheric contamination. Protection or shielding is commonly provided by a high-purity inert gas cover in the open or in a chamber, or by a vacuum of 0.013 Pa (10^{-4} torr) or lower.

During arc welding, titanium must be protected from the atmosphere until it has cooled below about 425°C (800°F). Adequate protection can be provided by an auxiliary inert gas shielding device when welding in the open. For critical applications, welding should be done in a gas-tight chamber that is thoroughly purged of air prior to filling with high-purity argon, helium, or mixtures of the two.

The purity of the shielding gas influences the mechanical properties of the welded joint. Both air and water vapor are particularly detrimental. The purity of commercial inert gases used for welding is normally satisfactory, but care must be taken to ensure that moisture and air are not entrained into the gas delivery system. The dew point of the gas should be measured at the welding location or as it is purged from a welding chamber. A dew point of –40°C (–40°F) at the point of weld is the approximate maximum moisture limit. Shielding gases have a dew point of –51°C (–60°F) or lower.

The inert gas at the cylinder or other source must be sufficiently dry to allow a margin for some moisture pickup in the delivery system. One method of checking gas purity is to weld a sample piece of titanium, prior to welding the workpiece itself, then to bend it. The surface appearance and the degree of bending are a good indication of the gas purity. A second sample should be welded and bent after the workpiece is completed to assure that the shielding was satisfactory during welding.

The color of a weld bead on titanium is often used as a measure of the level of contamination or the shielding gas purity. A light bronze color indicates a small amount of surface contamination; a shiny blue color indicates a greater amount of surface contamination. Neither of these levels of surface contamination is desirable, but may be acceptable on a single or final weld pass, provided the surface layer is removed before the weldment is placed in service. A white, flaky layer on the weld bead indicates excessive contamination, which is not an acceptable condition. In multipass groove welds, no surface contamination is acceptable and must be removed before depositing additional passes. If a white or gray flaky oxide is present, the gas shielding system should be inspected, and the cause of contamination corrected. The contaminated weld metal should be removed because it is likely to be brittle.

When brazing or diffusion welding titanium parts, they must be protected by high-purity inert gas or processed in a vacuum. The time at temperature should be as short as practical because hot titanium (a "getter") absorbs oxygen, nitrogen, and hydrogen by diffusion when available in even minute amounts.

Gas Shielded Arc Welding

The three processes normally used for joining titanium are gas tungsten arc, gas metal arc, and plasma arc welding.

Welding with all three processes can be done with manual, semiautomatic, or automatic equipment. Manual and automatic welding can be done in the open or in a chamber filled with inert gas. Semiautomatic welding is usually done in the open, but could conceivably be performed in a chamber.

The main concern with welding in the open is adequate inert gas shielding of (1) the molten weld pool and adjacent base metal (primary shielding), (2) the hot, solidified weld metal and heat-affected zone (secondary shielding, and (3) the back side of the weld joint (backing).

Primary Gas Shielding. Primary gas shielding is provided by the arc welding torch or arc welding gun nozzle. The nozzle size usually ranges from 12.7 to 19 mm (0.5 to 0.75 in.). In general, the largest nozzle consistent with accessibility and visibility should be used. Nozzles that provide laminar flow of the shielding gas are desirable because they lessen the possibility of turbulent gas flow where air mixes into the gas stream at its periphery. Proper shielding of the molten weld pool is critical.

Secondary Gas Shielding. The primary gas shielding advances with the arc welding gun and a secondary inert shielding gas is necessary to protect the solidified, cooling weld bead and the heat-affected zone. The hot weld zone must be shielded from the atmosphere until it has cooled to a temperature where oxidation is not a problem. The low thermal conductivity, and consequent slow cooling, of titanium requires that a considerable length of the hot weld be shielded; more than is usually provided by gas flow from an arc welding gun.

The common form of secondary shielding is a trailing shield; a typical design is shown in Figure T-15. It consists of a metal chamber fitted to the torch nozzle and held by a clamp. The inert gas flows through a porous metal diffuser screen over the weld area. The shield must be wide enough to cover the heat-affected zone on each side of the weld bead.

A trailing shield is used for machine or automatic welding where travel speeds are higher. In one important application, the trailing shield, used in welding pipe in the horizontal-rolled position, is curved to conform to the pipe surface.

For manual welding, a large gas nozzle or an auxiliary annular gas nozzle can be used with slow welding speeds. Trailing gas shielding can interfere with the visibility of the weld pool and manipulation of the manual arc welding torch.

Secondary shielding can be incorporated into the fixturing, as shown in Figure T-16. Inert gas passages are provided in the hold-down bars on both sides of the weld seam. Shielding gas flows from the arc welding torch and hold-down bars into the channel formed by the bars, displacing the air from above the weld.

Backing Gas Shielding. Inert gas shielding is required to protect the weld root and adjacent base

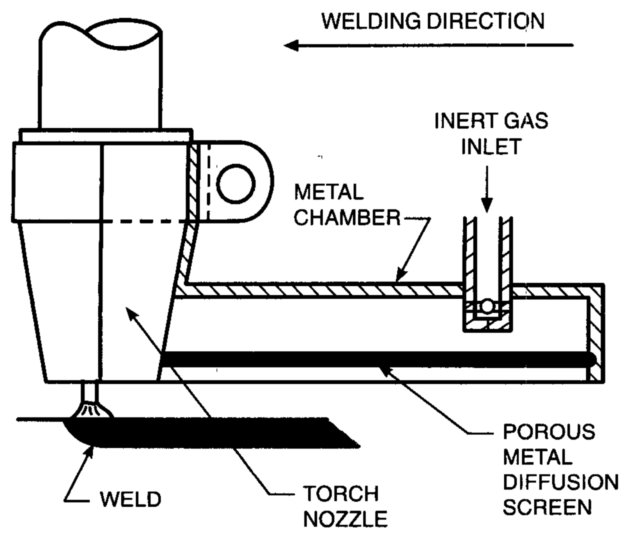


Figure T-15—Torch Trailing Shield for Gas Shielded Arc Welding of Titanium and Other Reactive Metals

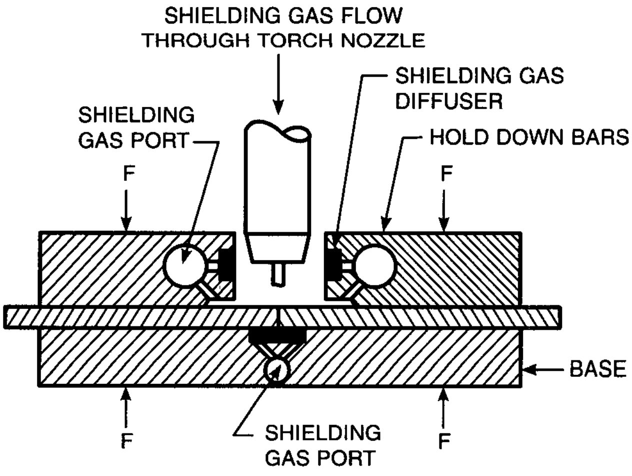


Figure T-16—Secondary Inert Gas Shielding Incorporated in the Welding Fixture

metal from atmospheric contamination during welding. This is accomplished using gas passages in a backing (bar or ring) as shown in Figure T-17. The backing is incorporated into the fixturing (*see* Figure T-16), and contains a clearance groove under the joint that is filled with inert gas prior to welding. The inert gas pressure in the groove must be kept low to avoid forming a concave root surface. The backing should be tightly fitted along the entire length to ensure uniform weld quality.

The backing, which is often made of water-cooled copper, can serve to remove heat from the weld and accelerate cooling. Stainless steel backing may be used when lower cooling rates are acceptable. The root opening of the joint must be near zero to prevent the arc from impinging on and fusing the titanium weld to the backing bar. Contamination of the titanium weld metal may embrittle it, resulting in a cracked weld.

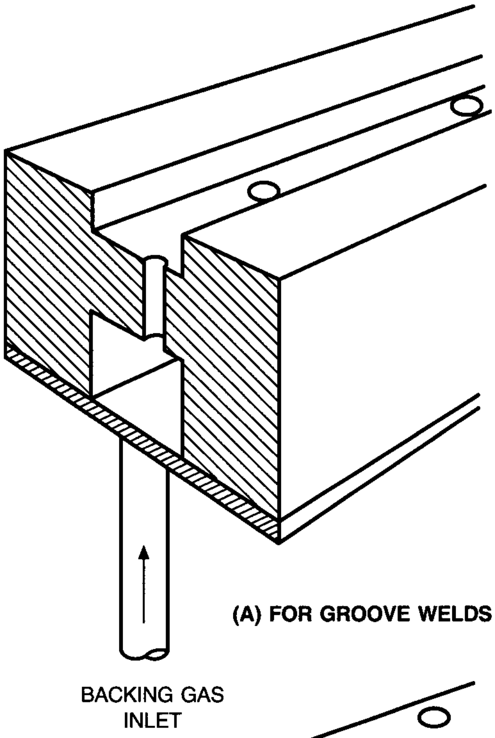
When welding pipe or tubing, the interior of the pipe must be purged of air with inert gas. Usually a volume of inert gas that is at least six times the volume of the pipe is required to displace the air. In large systems, internal dams can be placed on both sides of the joint to confine the backing gas to the vicinity of the weld joint. Internal dams must have an inlet for the inert gas, an outlet for the displaced air and inert gas to escape, and internal gas pressure must be low, 50.8 or 76.2 mm (2 or 3 in.) of mercury. Suitable dams are available commercially.

Welding in a Chamber. Many titanium weldment designs are not adaptable to welding in the open air; adequate inert gas shielding of weld joints would be difficult to achieve. An acceptable procedure is to weld such an assembly in an enclosed chamber filled with inert gas.

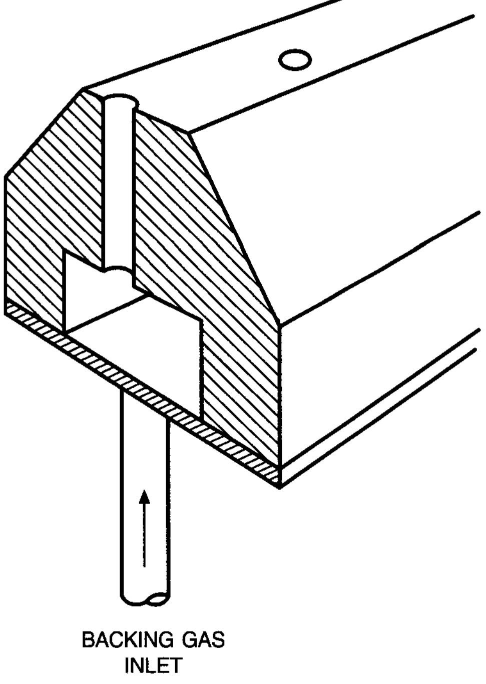
Two types of welding chambers are used: flow-purged and vacuum-purged. The welding atmosphere in a flow-purged chamber is obtained by flowing inert gas through the chamber to flush out the air. The volume of inert gas needed to obtain a welding atmosphere of sufficient purity in the chamber is about six times the chamber volume.

The appropriate inert gas flow rate and air displacement time for a specific chamber should be established by welding tests. During welding, inert gas flows through the arc welding torch to ensure adequate shielding of the molten weld pool. A low, positive gas pressure is always maintained in the chamber to prevent air from entering. The welding atmosphere should be monitored during actual welding operations by running weld beads on test coupons prior to, during, and after welding the actual assemblies. The test coupons should be evaluated visually and mechanically to verify that the chamber atmosphere was satisfactory during the welding operation.

When contamination of the titanium during welding must be absolutely avoided, welding is performed in a vacuum-purged chamber. Air is removed from the



(A) FOR GROOVE WELDS



(B) FOR CORNER OR FILLET WELDS

Figure T-17—Weld Backing Bars that Provide Inert Gas Shielding

chamber by a vacuum pumping system to a pressure of usually 0.013 Pa (10^{-4} torr) or lower. The chamber is then back-filled with inert gas having a dew point of –60°C (–76°F) or lower.

Accessibility to the work is through glove ports in the chamber. The gloves, welding torch or gun, fixturing, and other material installed or placed in the chamber must be impervious to air and water, and void of volatiles that can contaminate the titanium.

Joint Design. The weld joint designs used for welding titanium are similar to those used for steels. Actual joint design depends on several factors, including the welding process, type of operation (manual or machine), joint accessibility, and inspection requirements.

Edge preparation should be done by a machining process that does not contaminate the titanium or leave embedded particles on the surface. As mentioned previously, root opening is important when welding with temporary backing. Fixturing or tack welds should be used to maintain uniform root opening during welding.

The design of a weldment, the types of joints, and joint locations can be limited by shielding requirements. When welding in a chamber, positioning for welding each joint must be considered during the design phase.

Preheat and Interpass Temperature. Preheat and interpass temperatures must be kept low for welding in open air to avoid surface oxidation. Surface oxides dissolved in the molten weld metal can cause problems when the weld solidifies. A low preheat is generally employed to drive off adsorbed surface moisture prior to welding. Preheat and interpass temperatures should not exceed 120°C (250°F). Prolonged exposure to air at temperatures above 120°C (250°F) can cause an oxide film to form on the faying surfaces. This oxide film must be removed with a stainless steel wire brush or rotary carbide burrs prior to welding.

Gas Tungsten Arc Welding

Gas tungsten arc welding (GTAW) is commonly used to weld titanium and its alloys, particularly for sheet thicknesses up to 3 mm (0.125 in.). Welding in open air is best done in the flat position to maintain adequate inert gas shielding with the welding torch and secondary shielding devices. Specially designed secondary shielding devices may be required when welding in positions other than flat. Welding in positions other than flat may contribute to the amount of porosity in the weld metal.

Direct current electrode negative (DCEN) is normally used with Type EWTh-2 tungsten electrodes of proper size. Contamination of the weld with tungsten should be avoided because it embrittles the titanium. Electrode extension from the gas nozzle should be limited to the amount required for good visibility of the weld pool. Excessive extension is likely to result in weld metal contamination.

When welding in open air, welding should be terminated on a runoff tab or the welding torch should dwell over the weld with a postflow of shielding gas after shutting off the welding current. When a filler metal is added, the heated end of the welding rod must be held under the gas nozzle at all times to avoid contamination. If the tip of the rod becomes contaminated, it must be cut off before continuing the weld.

Welding conditions for a specific application depend on joint thickness, joint design, the weld tooling design, and method of welding (manual or machine). For any given section thickness and joint design, various combinations of amperage, voltage, welding speed, and filler wire feed rate can be used to produce satisfactory welds.

Typical welding conditions that can be used for machine gas tungsten arc welding of titanium are shown in Table T-10. The welding conditions generally do not have to be adjusted radically to accommodate the various titanium alloys, however, certain adjustments are often made to control weld porosity.

Gas Metal Arc Welding

Gas metal arc welding (GMAW) can be used for joining titanium. It is more economical than gas tungsten arc welding because of the deposition rates, particularly with thick sections. Selecting the correct welding conditions should produce a smoothly contoured weld that blends with the base metal.

With GMAW, the droplets of filler metal being transferred across the arc are exposed to much higher temperatures than the filler metal fed into a GTAW molten weld pool. The combination of high temperature and fine particle size makes the filler metal highly susceptible to contamination by impurities in the arc atmosphere. Consequently, the welding gun and auxiliary gas shielding must be carefully designed to prevent contamination of the inert gas welding atmosphere.

Equipment. Conventional GMAW power sources and control systems are satisfactory for welding titanium. Conventional GMAW guns are modified to provide the necessary auxiliary gas shielding needed for titanium.

Filler Metal Transfer. Titanium filler metal can be transferred by all three types of metal transfer: short-circuiting, globular, and spray. Globular transfer is not recommended for welding titanium because of excessive spatter and incomplete fusion in the weld. Short-circuiting transfer can be used for welding thin sections in all positions. When welding thick sections, in positions other than flat, incomplete fusion can be a problem because of the inherent low heat input.

When welding thick sections in the flat and horizontal positions, spray transfer is preferred to take advantage of high heat input and high deposition rates. Pulsed spray welding provides spray transfer with

Table T-10
Typical Conditions for GTAW Machine Welding of Titanium

Sheet Thickness		Filler Wire Diameter		Filler Wire Feed		Shielding Gas	Arc Voltage, V	Welding Current, A	Travel Speed	
mm	in.	mm	in.	mm/s	in./min				mm/s	in./min
0.203	0.008	—	—	—	—	He	14	10	6.77	16
0.762	0.030	—	—	—	—	Ar	10	25–30	4.23	10
1.524	0.060	—	—	—	—	Ar	10	90–100	4.23	10
1.524	0.060	1.587	0.062	9.31	22	Ar	10	120–130	5.08	12
2.286	0.090	—	—	—	—	Ar	12	190–200	4.23	10
2.286	0.090	1.587	0.062	9.31	22	Ar	12	200–210	5.08	12
3.175	0.125	1.587	0.062	8.46	20	Ar	12	220–230	4.23	10

lower heat inputs that is advantageous for welding thinner sections and in positions other than flat.

Plasma Arc Welding

Plasma arc welding (PAW) is an extension of gas tungsten arc welding in that the arc plasma is forced through a constricting nozzle. Inert gas shielding of the weld is provided by a shielding gas nozzle and an auxiliary trailing shield similar to that used with GTAW and GMAW. Welding is accomplished with a transferred arc using direct current, electrode negative supplied by a constant current power source.

Argon, with a dew point of –60°C (–76°F) or lower, is generally used as the orifice gas and shielding gas, but helium-argon mixtures are sometimes used for shielding. Hydrogen must not be added to the inert gas because of its embrittling effects on titanium.

Plasma arc welding can be done using two techniques: melt-in and keyhole. The melt-in technique is similar to GTAW. The keyhole technique provides deep joint penetration for welding square-groove joints in one pass. The two techniques can be combined for welding groove joints in thick sections.

Square-groove joints in titanium alloys from about 1.6 to 12.7 mm (0.062 to 0.50 in) thick can be welded with one pass with the keyhole technique. Plasma arc welds tend to be undercut along the top edges and have convex faces unless filler metal is added during welding, or when a second pass is made as a cosmetic pass.

Electron Beam Welding

Electron beam welding (EBW) in high vacuum is well suited for joining titanium; oxygen and nitrogen contamination of the weld is held within acceptable levels. When electron beam welds are made in a vacuum or nonvacuum, inert-gas shielding requirements are the same as for arc welding.

The process variables are accelerating voltage, beam current, beam diameter, and travel speed. Beam dispersion increases with atmospheric density, pressure, or both. Deep joint penetration in square-groove welds is obtained with high beam power density and a keyhole in the weld metal.

Laser Beam Welding

Laser beam welds can be produced in titanium by the conventional melt-in technique or by the keyhole technique. With the keyhole technique, as much as 90% of the laser beam energy can be absorbed, depending on the metal. Absorption efficiency is significantly lower with the melt-in technique. At an energy level of 15 kW, the maximum thickness of Ti-6Al-4V alloy that can be welded in a single pass is about 15 mm (0.60 in.).

When welding with a high power density, ionization of metal vapor above the molten weld pool diffuses the laser beam and interferes with welding. This can be prevented by blowing the metal ions away from the weld pool with inert gas, preferably helium. Helium-argon mixtures can also be used. At the same time, a titanium weld must be shielded from the atmosphere to prevent contamination and embrittlement, as described previously for arc welding.

Other Processes

Titanium can also be welded using the diffusion, friction, resistance, and flash welding processes. Refer to American Welding Society *Welding Handbook*, Vol. 2, 8th Edition. American Welding Society, Miami, Florida. 1991.

Thermal Cutting

Titanium can be severed by oxyfuel gas cutting (OFC) at speeds approximately three times faster than an equivalent thickness of steel, however, the cuts result in a contaminated and hardened surface requiring some type of edge preparation before welding. The depth of hardening in titanium after OFC is less than 0.3 mm (0.010 in.), but the overall hardened zone can extend up to 1.6 mm (0.06 in.) deep.

Titanium can also be cut using the plasma arc cutting (PAC) process. The cut face will be contaminated to some degree because of the exposure of the hot titanium to the atmosphere.

Safe Practices

The possibility of spontaneous ignition of titanium and titanium alloys is extremely remote. As in the case of magnesium and aluminum, the occurrence of fires is usually encountered where an accumulation of grinding dust or machining chips exists. Even in extremely high surface-to-volume ratios, accumulations of clean titanium particles do not ignite at any temperature below incipient fusion temperature of the air.

However, spontaneous ignition of fine grinding dust or lathe chips saturated with oil under hot, humid conditions has been reported. Water or water-based coolants should be used for all machining operations. Carbon dioxide is also a satisfactory coolant. Large accumulations of chips, turnings, or other metal powders, should be removed and stored in closed metal containers. Dry grinding should be done in a manner that will allow proper heat dissipation.

Dry compound extinguishing agents or dry sand are effective for titanium fires. Ordinary extinguishing agents such as water, carbon tetrachloride, and carbon dioxide foam are ineffective and should not be used.

Violent oxidation reaction (explosion) occurs between titanium and liquid oxygen or red-fuming nitric acid. Reference: American Welding Society, *Welding Handbook*, Volume 3, 8th Edition; American Welding Society, Miami, Florida.

T-JOINT

A joint between two members located approximately at right angles to each other in the form of a T. *See* STANDARD WELDING TERMS. *See* Appendix 5.

TOBIN BRONZE

A copper alloy with exceptionally good welding properties. It is approximately 60% copper, 39% zinc and 1% tin. The melting point of Tobin bronze is 885°C (1625°F). *See* COPPER ALLOY WELDING.

TOE

See WELD TOE.

TOE CRACK

See STANDARD WELDING TERMS. *See* Appendixes 8 and 9.

TOE OF WELD

See STANDARD WELDING TERMS. *See also* WELD TOE.

TOOL AND DIE WELDING

Virtually all types of tool steel can be welded by the shielded metal arc, gas tungsten arc, plasma arc, or electron beam processes. Die units used for blanking, forming, forging, drawing, embossing, coining, or hot and cold trimming can be salvaged or reclaimed using one of these processes.

Tool and die welding applications can be separated into four categories:

(1) Repairing of dies
(2) Composite fabrication of dies
(3) Correction of designs
(4) Improvement of properties by hardfacing

Die Welding and Repair. Welding professionals, along with tool engineers, have developed tool and die welding and repair methods which can be economically significant. Research, development and testing by welding equipment and electrode manufacturers have resulted in varied lines of tool and die welding electrodes, with recommended procedures for their use. This combined effort has served to minimize down-time in manufacturing facilities that use tools and dies.

Tool and Die Welding Electrodes

Tool and die welding electrodes can be divided into two categories: basic tool steel welding electrodes, and alloy welding electrodes. A combination of these two types is used for some applications.

Basic Tool Steel Welding Electrodes. This group of coated electrodes includes water-hardening, air-hardening, hot-working and high-speed steel. These electrodes are in an annealed state, and the weld metal is hardened by air quenching from the high heat of the arc. The weld deposits are "hard-as-welded," whether they are applied to hardened or annealed tool steel, mild, medium, or high-carbon steel, or to other alloy steels. The weld deposits can be annealed to facilitate machining, then heat treated and tempered. As a general rule, weld deposits will respond to the heat treatment recommended for the average tool steel in its classification.

Alloy Welding Electrodes. Included in this group are low-alloy electrodes for plastic or zinc casting molds and flame-hardened dies. Also in this group are the more highly alloyed electrodes used to weld dies for forging, drawing and forming. These electrodes produce machinable weld deposits which are not affected by heat treatment. They are available in several types, providing a range of hardness in the weld deposits. Additional hardness is obtained by work hardening.

Combination. Other alloy electrodes are sometimes used in conjunction with tool and die welding electrodes, especially for applications on cast dies for drawing or forming. Nickel-iron electrodes, nickel electrodes, and copper-nickel electrodes can be used as foundation on cast units, then other tool and die electrodes are used to finish the castings.

Current, Coatings, and Deposits. Generally, tool and die welding electrodes should be used on direct current electrode positive (DCEP). The percentage of alloying elements lost in the weld deposits during welding can be regained by selecting an electrode which incorporates the required alloys in the coating. Mineral-alloyed coatings are preferred.

The introduction of a mineral-alloyed coating on the electrodes also helps produce a desirable spray action of the arc and forms a protective slag, which is easily removed.

Tool and die welding electrodes will produce sound homogeneous weld deposits free from porosity. In many cases, laboratory tests have revealed weld deposit structures that are superior to parent steel of the same class.

Gas metal arc and flux-cored arc welding can be used to weld tools and dies, generally using small diameter (less than 1.5 mm [0.060 in.]) wires. The plasma arc, electron beam and laser beam processes, with or without filler metal, can also be used for tool and die welding.

Factors Influencing Hardness

The hardness developed in weld deposits "as-welded" and "heat-treated" will vary according to the following principal factors:

(1) Preheat treatment (i.e., the preheating temperature)
(2) Technique during the welding sequence
(3) Admixture of the base metal with the deposit
(4) Rate of cooling and mass of the workpiece
(5) Tempering temperature after welding.

Preheating. As a crack-preventive measure, it is very important to preheat the workpieces to which tool and die electrodes are to be applied. The degree of preheat is a primary factor affecting the hardness developed in weld deposits because preheating tends to delay the rate of air quenching. For a given set of welding conditions, such as current and welding speed, the cooling rate will be faster for a weld made without preheat than with preheat. Preheating also helps to reduce or prevent shrinkage stresses and deformation.

Welding Technique. Welding technique affects the hardness of the weld deposit. Direct current electrode positive (DCEP) is recommended because it minimizes arc penetration, resulting in less admixture with the base metal.

The smallest electrode adequate for the job should be selected because it requires less heat, and this influences the ultimate hardness of the deposit.

Work positioning, travel speed, welding current, and manipulation of the arc all exert an influence on weld hardness.

Ultimate hardness and characteristics of the weld deposits can be enhanced by thorough peening while at forging temperatures. Extended deposits should not be made before peening because the metal will cool; hot metal is more ductile.

Admixture and Cooling. The admixture (dilution) of the deposits with the base metal produces weld metal that is alloyed in direct proportion to the alloys contained in the electrodes and in the parent metal. When elements such as carbon and chromium are added to steels to enhance hardenability, the percentage of these elements will be directly reflected in the "as-welded" or "as-heat treated" hardness of the deposits.

Rate of Cooling. The rate of cooling after welding, which is governed by the preheating temperature and the size of the workpiece, affects the ultimate hardness. The larger the workpiece, the slower the air quench.

Tempering. In welding tool steel, changes take place in the steel that require tempering. Hardening a tool steel with heat treatment requires tempering afterward. To gain the same results, weld deposits should also be tempered. Tempering yields toughness with very little reduction of hardness. It refines the grain structure and relieves stresses and strains set up in the welding process. Tempering or drawing must suit requirements. Size governs the length of time of the draw, which should never be less than one hour. Deposits of the alloy type should not be tempered, but the units on which they are applied should be stress relieved. Partial repairs should be tempered according to the draw-range temperatures of the base metal; full repairs should be tempered according to the recommended draw-range temperatures for the electrode.

Fundamentals of Welding Tool Steel

Tool steels are carbon steels to which alloys have been added in varying quantities. Such elements as carbon, manganese, silicon, chromium, nickel, tungsten, vanadium, molybdenum and cobalt are added to steel to bring about such characteristics as greater wear resistance and hardness, greater toughness or strength, stabilized size and shape during changes caused by heat and cold, and "red hardness," a condition in which the steel will remain hard while red hot.

Because of the diversified composition of tool steels, heat treating is a complex subject. However, knowledge of the fundamentals of tool steels will be of help in setting up specifications for heat treating. In practical tool and die welding, it is not necessary that the electrode match the analysis of the tool steel being welded, but in most cases, the welding electrode should match as closely as possible the heat treatment recommended for that tool steel classification. Such terms as *annealing, normalizing, hardening,* and *tempering* should be thoroughly understood.

The four general classifications of tool steels are (1) water-hardening, (2) oil-hardening, (3) air-hardening and (4) hot working. It is necessary to study the analysis of the composition of tool steels in order to become familiar with their properties and characteristics. Although hundreds of different tool steels are available, four general classes of electrodes (including high-speed steel electrodes) will generally suffice to weld them. It would be impractical to have a welding electrode to match each and every analysis, or exact specifications for heat treatment of this great variety of tool steels. In welding, however, it is not a question of matching the analysis of the steel, but of matching as closely as possible the heat treatment in its classification.

Recommended Welding Sequence. Tool and die welding is not complicated if instructions and recommendations are followed explicitly. The following basic principles should help to meet almost any tool and die welding specifications.

(1) Identify the type of tool steel to be welded. This will determine the heat treatment involved and will govern the handling of the unit in the welding sequence.

(2) Select the correct electrode. In making partial repairs of cutting edges or working surfaces, select the electrode that will match, as closely as possible, the heat treatment of the metal to be welded.

To make full repairs to cutting edges or working surfaces, choose the electrode with characteristics best suited for the type of work to which the unit will be subjected. Take into consideration any factors involving heat, abrasion, shock, and thickness of metal to be cut or formed.

For forging die repair, or facing cast or carbon-steel dies for drawing or forming, select alloy electrodes recommended by the manufacturer for these purposes.

The size of the electrode to be used for a repair will depend on the width and depth of the damaged area. In general, a 2.4 mm (3/32 in.) diameter electrode will repair a damaged area 2.4 mm (3/32 in.) wide and 2.4 mm (3/32 in.) deep. The same relation applies to other electrode diameters. Always select the smallest electrode, especially for sharp cutting edges, because less heat is required for welding. There is also less chance of creating shear marks, and less grinding will be necessary after welding.

(3) Prepare the surface to be welded. In making partial repairs of cutting edges or working surfaces, rough-grind damaged areas to allow for a uniform depth of at least 3 mm (1/8 in.) of finished deposits.

In making repairs to entire cutting edges of tool or dies, rough-grind edges to be welded to an approximate 45° angle to allow deposits of 6 mm (1/4 in.) of finished metal.

On die units that require repairs over large areas, prepare surfaces so that finished deposits will be at least 3 mm (1/8 in.) deep.

For repairs to drawing and forming dies of cast structure, the edges or areas to be faced should be prepared uniformly so that finished deposits are at least 3 mm (1/8 in.) deep. To prepare for extremely long deposits, for forming edges or over large areas on cast-iron base metal, studding may be required. The studs should be staggered, spaced 40 mm (1-1/2 in.) apart.

When preparing damaged forging die blocks for welding, areas to be repaired should be chipped, ground or machined as uniformly as possible to a finished depth of about 5 mm (3/16 in.) for the inlay deposit, or, where necessary, to below the heat-checked depth.

(4) Preheat. Identification of the type of steel to be welded will determine the draw range temperatures involved. It is very important not to exceed maximum preheat temperature or exceed the maximum temperature of the draw range for the type of steel to be welded. Hardness will be lost if the unit is preheated to a temperature above the draw range, because the original structure of the steel will be disturbed. Maintain temperature under the minimum of the draw range in preheating, and never above the maximum for the interpass temperature while welding. This will retain the original hardness of the steel.

(5) Welding. Generally, direct current electrode positive (DCEP) is used to apply tool-steel and alloy electrodes. However, they may also be applied with ac.

Keep the temperature of the parent metal as uniform as possible during welding to assure uniform hardness of deposits.

In welding cutting edges, position the work, if possible, so that the deposit will flow or roll over the cutting edges.

Always try to work slightly upward, as gravity causes the deposit to roll back and build up evenly. Gravity also causes slag to roll out of the crater and keep it clean. There is no need to weave the electrode in an intricate pattern.

In depositing beads, a slow travel speed is used to secure an even deposit and to assure more uniform fusion of the electrode with the base metal. Keep the area clean by frequent brushing.

Thoroughly peen all deposits to offset shrinkage and stress. Ball peen hammers are generally used, but small pneumatic hammers are efficient for large areas.

It is important not to deposit excess metal in one pass. On final passes, retain beads as close as possible to finished size. This will eliminate excessive grinding.

When welding cutting edges, the arc should not be broken by rapidly pulling away the electrode. Lowering the electrode gradually as you stop welding will prevent deep craters and the searing of sharp edges adjacent to the weld area.

When repairing parts of cutting edges, the weld bead should first progress in one direction to within a short distance of the other end; then it should progress in the opposite direction and overlap the first bead. This will prevent craters and sear marks at the extreme end of the deposited metal.

When welding deeply damaged cutting edges (or drawing and forming surfaces), start at the bottom and gradually fill up the damaged areas. Use a slightly higher amperage on the first and second beads than on finishing beads. Peening while the weld metal is in the forging state also eliminates sear marks at the edges of the deposits.

If two or three dissimilar types of tool-steel electrodes are to be welded on one die unit, care must be exercised in applying the electrodes in sequence to their draw ranges; the first electrode applied must have the highest draw range, then the electrodes are applied in decreasing order to the electrode with the lowest draw range. This will prevent the annealing of previously applied deposits.

To make repairs to entire cutting or forming edges of draw rings, extrusion dies or similar circular parts, the skip-weld method should be used to ensure even distribution of heat.

Warping or distortion is offset by preheating to expand the units, and by peening to stretch welded deposits and to offset stresses. These are mechanical problems. Shims and clamps can be used to advantage. Peening will relieve the stresses set up in the welding operation by stretching the deposited metal. Do not weld more than 75 mm (3 in.) before peening.

(6) Post-heat or Temper Deposits or Sections. After welding, the unit is allowed to cool to approximately room temperature and is then tempered by reheating to the recommended temperature. This is important, as post-heating serves as a tempering medium for the deposited metal. Postheating refines the grain structure and relieves stresses set up by welding.

In tempering deposits made to effect a partial repair, the general rule is to temper according to the draw-range temperature of the base metal. If a unit has been repaired over the entire edge or working area, temper the deposits according to the draw range temperatures recommended for the electrode used. All welded units should be tempered or drawn to meet requirements of the base metal and the electrode.

The welder should seek advice from the manufacturer of the unit or the electrode manufacturer on heat-treating specifications as to the length of time welded units should be drawn or tempered.

Preheating equipment can also be used for post-heating, tempering or drawing. A temperature-controlled furnace should be used if available.

Composite Fabrication

Sometimes die units can be fabricated as composites. Water-hardening, oil-hardening, air-hardening or hot-work tool steel electrodes can be applied to a base of a mild, medium or high-carbon steel (or SAE graded steel). The weld deposits are confined to cutting edges or working areas. The result is a fabricated composite die constructed mostly of inexpensive steel.

The same basic principles can be followed on drawing and forming dies that are used on cast structures: deposit the tool steel alloy along sharp contours, belt lines and radii. This prolongs the life of the forming surfaces, helping to withstand abrasion, scoring or fouling.

Flame-hardening dies can be fabricated by using low-alloy electrodes.

Existing tool steel units can be converted into composite units to meet unusual conditions by welding a better grade of tool steel along the cutting edges or working areas.

Because deposits made with tool-steel electrodes are hard as welded, it is not necessary to post-heat treat fabricated composite units except for tempering as recommended. To facilitate machining, however, the deposit can be annealed and subsequently heat treated with the recommended heat treatment.

The recommended welding sequence for composite fabrication is similar to that used for welding tool steel. On units with composite construction, tempering should always favor the deposited metal. The base metal acts only as a retaining medium for the cutting or working edge of the desired tool steel. For the recommended tempering temperatures of deposits in composite fabrication, refer to manufacturer's information on each electrode.

TOOL BRAZING

Although brazing as applied to tools is generally for repairs, there are many applications in which brazing is used to make composite tools by joining hard, tough metal to a softer steel. Whether the application is repairing or building a tool, the same general brazing processes are used. Brazing with a silver-base filler metal is probably the most widely used of the processes; this is particularly true for high-speed steel cutting tool reclamation, and for applying cemented carbide tips. *See* BRAZING, Carbide Tools.

Repair Technique

Brazing with a silver-base filler metal has been successfully used to reclaim tools that had broken and appeared ready for the scrap heap. An example is a gear cutter which had broken into three pieces.

The equipment needed to restore this cutter consisted of an oxyacetylene torch, a small length of 0.8 mm (0.031 in.) diameter silver alloy brazing wire, a jar of flux, a few ounces of solvent, and a small length of nichrome wire for holding the parts while brazing.

Cleanliness is the first law of good brazing practice. In making this repair, the first step was to carefully clean the pieces individually with a solvent to make certain that each piece was scrupulously clean and bright. All surfaces of the pieces were then fluxed. It is important to use a silver brazing flux which is entirely liquid and active in dissolving oxides at the exact temperature required for silver alloy brazing.

Precoating

Joint surfaces of each broken piece were precoated (pretinned) with a silver brazing alloy in the following process:

(1) An oxyacetylene torch was used to bring the surfaces to be joined to brazing temperature, or approximately 635°C (1175°F). The flame was kept moving to assure uniform heating and to avoid hot spots. Enough silver brazing alloy was applied to cover the surface completely.

(2) While the heat was maintained, the molten brazing alloy was puddled, rubbed into the surface with a metal rod until the surface was completely covered with a thin, even coat. After pretinning, all joint surfaces were again liberally covered with flux to get rid of oxides which tend to form during final heating. Pieces were then assembled upright so that the weight of the upper piece would cause the parts to settle into intimate contact during brazing. The parts were carefully aligned. With irregular breaks this is seldom a problem as the parts tend to align themselves naturally.

Heating. Heat was applied to the cutter with an oxyacetylene torch; the torch was chosen primarily because of its speed in heating the tool steel to 635°C (1175°F), the brazing alloy melting point, or flow point.

When the metal glowed a dull red and the flux was completely liquid and clear, the joints had to be only touched with silver alloy wire, and the alloy was pulled by capillary action throughout all joint areas. The alloy was fed into the joints until it became visibly evident that all breaks had been completely filled. While every step is important, this dual heating is the payoff. Heat must be uniformly distributed and the torch kept moving to avoid affecting tool temper and setting up strains. After brazing, the cutter was covered with several layers of insulating blanket and left in position to cool slowly. *See* American Welding Society *Welding Handbook*, Volume 4, 8th Edition, Miami, Florida: American Welding Society.

TORCH

See STANDARD WELDING TERMS. *See also* AIR CARBON ARC CUTTING TORCH, GAS TUNGSTEN ARC CUTTING TORCH, GAS TUNGSTEN ARC WELDING TORCH, HEATING TORCH, OXYFUEL GAS CUTTING TORCH, OXYFUEL GAS WELDING TORCH, PLASMA ARC CUTTING TORCH, *and* PLASMA ARC WELDING TORCH.

TORCH BRAZING (TB)

A brazing process that uses heat from a fuel gas flame. See STANDARD WELDING TERMS.

TORCH CLASSIFICATION

Injector Torch. These low-pressure torches operate on an acetylene pressure of less than 7 Pa (1 psi). They were originally designed for use with low-pressure acetylene generators where higher acetylene pressures were not available. The acetylene, passing through relatively large openings, is drawn into the mixer by the action of the high pressure of the oxygen as it passes through a very small orifice in the injector.

Balanced Pressure Torch. These torches utilize acetylene under pressures from 7 to 103 Pa (1 to 15 psi), depending upon the size of the tip. The torch utilizes both oxygen and the fuel gas under equal pressures. In this case, the ports at the entrance to the mixer are equal in area, and under equal pressures deliver equal volumes of oxygen and the fuel gas to the mixer. The flow of gases is not influenced by the mixer, as it is in the injector torch.

TORCH SOLDERING (TS)

A soldering process that uses heat from a fuel gas flame. See STANDARD WELDING TERMS.

TORCH TIP

See STANDARD WELDING TERMS. *See* WELDING TIP *and* CUTTING TIP.

TORSION TEST

A test to determine the amount of stress caused in a metal or material when twisted; for example, the torsion strength of wire is tested to see how much twisting can be applied before it will split or break.

TOUGHNESS

The resistance of a material to fracture after permanent deformation has begun.

Materials with the property of toughness are those that will withstand heavy shocks or absorb a large amount of energy.

TRACER

A radioisotope mixed with a stable material used to trace another material as it undergoes chemical and physical changes. *See* ISOTOPES.

TRACK WELDING

The welding of railroad track prior to installation and for repair of damage (e.g., wear). *See* RAIL JOINT WELDING.

TRAINING

Training is essential to the production of quality welds and weldments in all processes. The American Welding Society offers materials for use in training courses for welding personnel.

AWS document EG2.0, *Guide for the Training and Qualification of Welding Personnel: Entry Level Welder*, provides a complete curriculum for training welders to Entry Level (Level I) requirements. The curriculum is based on a needs analysis from 800 responses to a survey conducted in the United States.

AWS/ANSI EG3.0 and EG4.0 cover qualifications for Level II (Advanced) welders and Level III (Expert) welders, respectively. These documents are available from the American Welding Society. Interested persons should contact the American Welding Society, 550 N.W. LeJeune Rd. Miami, Florida 33126. (800) 443-9353. Fax (305) 443-6445.

TRAINING QUALIFICATIONS FOR CODE WORK

Welder, welding operator, and tack welder qualification tests determine the ability of the persons tested to produce acceptably sound welds with the process, materials, and procedure required in the tests. Various codes, specifications, and governing rules generally prescribe similar methods for qualifying welders, welding operators, and tack welders. The applicable code or specification should be consulted for precise details and requirements.

Welding operators frequently take qualifying tests to comply with the requirements of a code or specification governing a particular type of work on which the operator is to be employed. Table T-11 lists some of the principal codes and specifications containing rules for qualifying welding operators. Each of these codes contains specific provisions governing the procedure to be followed in qualifying welding operators for work under that code. The codes usually provide for the following requirements:

(1) The manner of supervising the tests
(2) The number and types of tests required
(3) The method of welding the specimens
(4) The method of testing the specimens
(5) The test results required
(6) Provision for retests in the event of initial failure
(7) The period of time qualification is effective
(8) The method of requalification.

In some cases, the codes prescribe a specific method of recording the results of the qualification tests. Usually the method requires completing a form covering qualifications, issuing a certificate, and filing these records with the employer.

No two codes are exactly alike with respect to the provisions for qualifying welding operators, so it necessary, when seeking detailed information as to the types of tests required and the method of test supervision, to consult the specific code or specification governing the particular type of work to be done.

TRANSFERRED ARC

A plasma arc established between the electrode of the plasma arc torch and the workpiece. See STANDARD WELDING TERMS.

TRANSFER OF WELD METAL

Molten metal produced at the tip or end of a consumable arc welding electrode transfers to the work-

Table T-11
Typical Codes and Specifications for Welded or Brazed Products that Require Performance or Procedure Qualification

Designation	Title
AWS D1.1	Structural Welding Code—Steel
AWS D1.2	Structural Welding Code—Aluminum
AWS D1.3	Structural Welding Code—Sheet Metal
AWS D1.4	Structural Welding Code—Reinforcing Steel
AWS D3.6	Specification for Underwater Welding
AWS D9.1	Specification for Welding Sheet Metal
AWS D14.1	Specification for Welding Industrial and Mill Cranes
AWS D14.2	Specification for Metal Cutting Tool Weldments
AWS D14.3	Specification for Earthmoving and Construction Equipment
AWS D14.4	Classification and Application of Welded Joints for Machinery and Equipment
AWS D14.5	Specification for Welding of Presses and Press Components
AWS D14.6	Specification for Rotating Elements of Equipment
AWS D15.1	Railroad Welding Specification
ASME	Boiler and Pressure Vessel Code
ASME B31	Code for Pressure Piping
	National Board Inspection Code
API STD 1104	Standard for Welding Pipelines and Related Facilities

piece and weld pool by one of three major modes: (1) globular, (2) spray, (3) and short-circuiting.Transfer under pulsed current operation is often considered to constitute a fourth mode called "pulsed transfer," but there is actually no difference in mode, but only in the current at which the globular mode makes transitions to the spray mode.

The various metal transfer modes are important because they change the amount of heat carried to the workpiece and weld pool, and thus the deposition rate, and greatly affect control of the molten weld pool in out-of-position welding. For example, welding overhead is facilitated by short-circuiting transfer, where capillary attraction helps overcome the effects of gravity on the molten metal. The physics underlying each mode are covered in the *Welding Handbook*, 8th Edition, Volume 1: Miami, Florida: American Welding Society, 1989.

See also GLOBULAR METAL TRANSFER, SPRAY TRANSFER, Arc Welding, *and* SHORT CIRCUITING TRANSFER.

TRANSFORMER

A device used to change alternating current from one voltage to another. It consists of two electrical circuits joined together by a magnetic circuit formed in an iron core.

TRANSFORMER EFFICIENCY

The power delivered by a transformer (output) divided by the power input to it.

TRANSFORMER WELDING MACHINE

An alternating-current arc welding machine.

TRANSVERSE BEND SPECIMEN

See STANDARD WELDING TERMS. *See also* TRANSVERSE WELD TEST SPECIMEN.

TRANSVERSE CRACK

A crack with its major axis oriented approximately perpendicular to the weld axis. See STANDARD WELDING TERMS. *See* Appendix 9.

TRANSVERSE SEAM WELDING

A seam weld made in a direction essentially at a right angle to the throat depth of a seam welding machine.

TRANSVERSE TENSION SPECIMEN

See STANDARD WELDING TERMS. *See also* TRANSVERSE WELD TEST SPECIMEN.

TRANSVERSE WELD TEST SPECIMEN

A weld test specimen with its major axis perpendicular to the weld axis. See STANDARD WELDING TERMS. *See also* LONGITUDINAL WELD TEST SPECIMEN.

TRAVEL ANGLE

The angle less than 90 degrees between the electrode axis and a line perpendicular to the weld axis, in a plane determined by the electrode axis and the weld axis. This angle can also be used to partially define the position of guns, torches, rods, and beams. See STANDARD WELDING TERMS. *See* Figure T-18. *See also* DRAG ANGLE, PUSH ANGLE, *and* WORK ANGLE.

TRAVEL ANGLE, Pipe

The angle less than 90 degrees between the electrode axis and a line perpendicular to the weld axis at its point of intersection with the extension of the electrode axis, in a plane determined by the electrode axis and a line tangent to the pipe surface at the same point. This angle can also be used to partially define the position of guns, torches, rods, and beams. See STANDARD WELDING TERMS. *See* Figure T-19. *See also* DRAG ANGLE, PUSH ANGLE, *and* WORK ANGLE.

TRAVEL SPEED

Rate of weld progression.

TRAVEL START DELAY TIME

The time interval from arc initiation to the start of the torch, gun, or workpiece travel. See STANDARD WELDING TERMS. *See* Appendix 19.

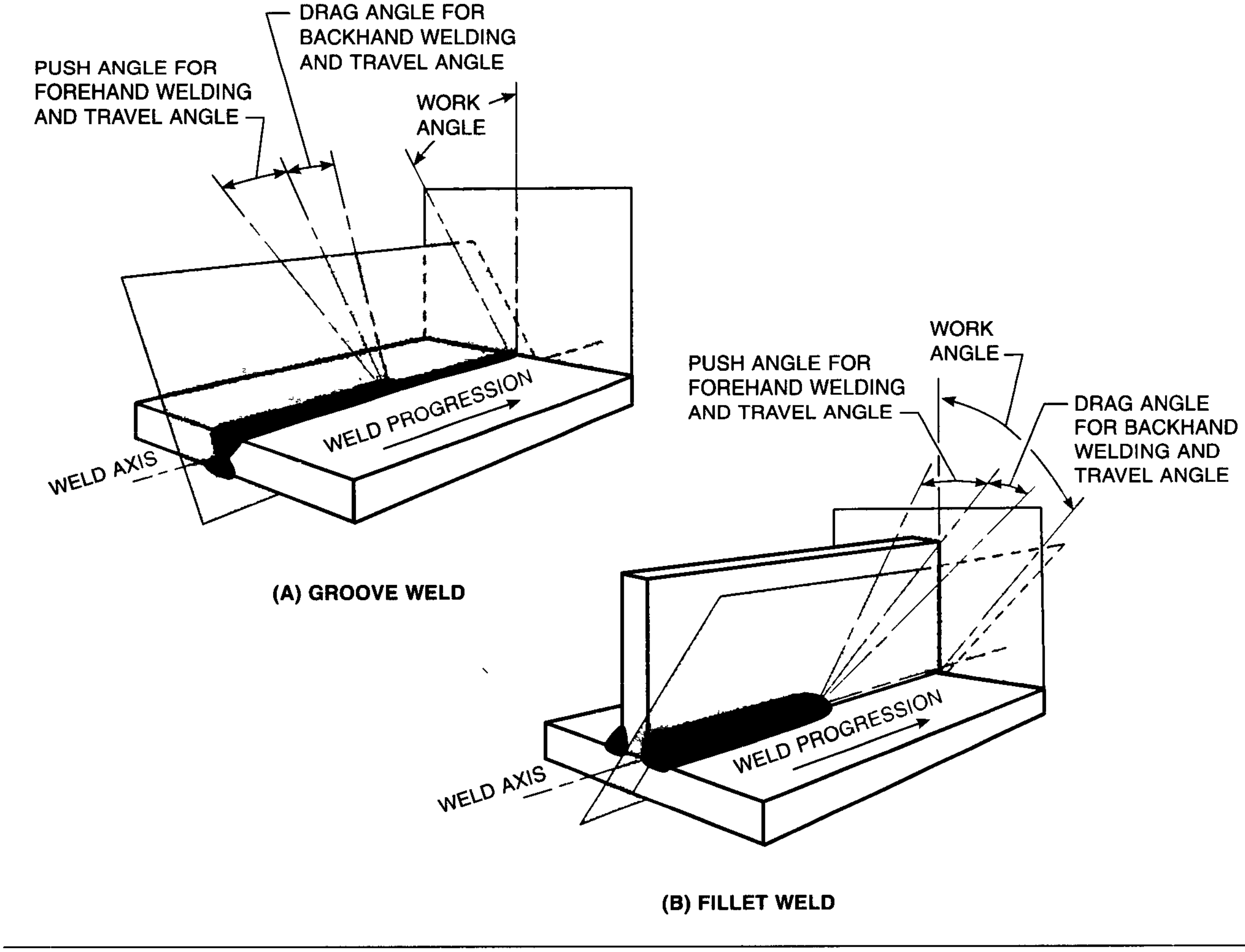
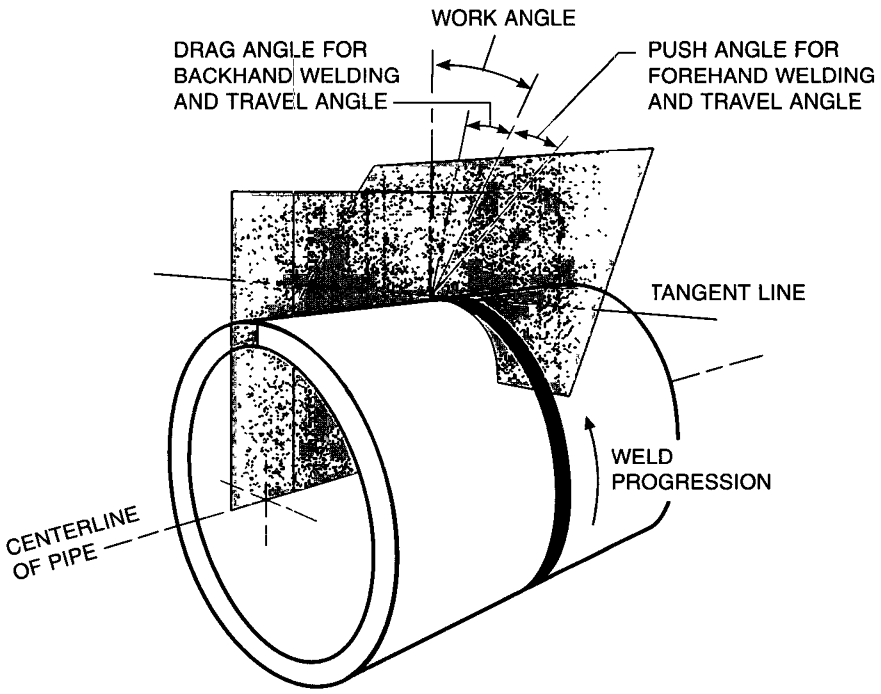


Figure T-18—Travel Angle and Torch Positions



PIPE WELD

Figure T-19—Position of Electrode, Gun, Torch, Rod, or Beam for Pipe Welding

TRAVEL STOP DELAY TIME

The time interval from beginning of downslope time or crater fill time to shut-off of torch, gun, or workpiece travel. See STANDARD WELDING TERMS. *See* Appendix 19.

TREPANNING

A mechanical process for removing a specimen from a welded seam so that the weld metal may be examined. The specimen, or plug, should include the entire width of the weld seam and enough of the adjacent parent metal to allow observation of the degree of fusion. The plug is cut with a circular saw which has a pilot (drill) in the center. An electric drill, pneumatic motor, or drill press may be used to drive the trepan.

The trepanned plug is usually polished to a bright, smooth finish and then etched. A satisfactory etching reagent for steel specimens is a 50% solution of hydrochloric acid used at a temperature of 70°C (160°F). At this temperature, the solution is active but there is negligible change in concentration because of evaporation.

The principal defects which may appear in the etched specimen (as noted in both the API and ASME codes) are lack of fusion, slag inclusions, gas pockets, cracks and undercutting.

TROOSITE

A micro constituent of hardened or hardened-and-tempered steel, which etches rapidly and therefore usually appears as a dark substance. It consists of a very fine aggregate of ferrite cementite and is not visible with the unaided eye. It can be viewed using a high-powered microscope. Troosite usually occurs in rounded or nodular form. *See* METALLURGY.

TRUE RESISTANCE

Actual resistance measured in ohms as compared to counter-electromotive force.

TUBE MANUFACTURE

The manufacturing process for welded steel tubing requires elaborate precision production equipment. Flat steel strip is fed continuously from coils through forming rolls, which gradually shape it into a circular form. At the beginning of the operation, the top and bottom forming rolls are opposite in contour, but the final forming rolls are of the same contour top and bottom. From the forming rolls the butted tube is passed through the welding section of the machine. When the resistance process is used, the welding unit consists of a high-amperage current supply connected to a pair of copper alloy discs which serve as electrodes and make contact with the two edges of the formed strip. When the tubing passes under the electrodes, the current is automatically applied and travels from one electrode to another across the seam cleft, creating heat through the resistance offered to the flow of the current by the edge surfaces.

The moment the current is applied, the side rolls exert sufficient pressure to bring the edges together to form a welded joint. The material at the extreme edges of the butted joints, having been heated somewhat beyond the plastic state, is squeezed outward, and the union is made with unexposed metal which is in the plastic condition. No extra metal is added, since the weld is a complete union of the butted edges. The manufacturing process results in a weld free from inclusions, oxides, overheated structures and similar defects, and one which has the same composition as the base metal.

Historical Background

The first electric welded tubing is said to have been produced in 1896 in Cleveland, Ohio. The first commercial oxyacetylene-welded tubing in this country was believed to have been in 1912. The Johnson Process, which uses resistance welding for producing welded steel tubing, was patented in the early 1920s.

In 1929, the National Bureau of Standards completed an investigation of the properties of electric resistance welded steel tubing which clearly established the integrity of the product. The results of these tests were reported in Research Paper No. 161, Bureau of Standards, April, 1930.

Progress in this field is evidenced by the fact that welded tubing meets the rigid requirements and specifications of the automotive industry, those required for boilers, condensers and heat exchangers; and the requirements of the United States Army, Navy and other government departments.

TUBE TESTING

Tubing is tested by one of several destructive or nondestructive methods. These tests are shown in Figure T-20.

Drift and Compression Tests

The drift test consists of placing a hardened steel pin in a tube or vessel made of thin sheet metal, and applying pressure with a manual or power-driven hammer until the tube or vessel is split, either in the weld or elsewhere. The compression test is a crushing test used with tubing, which forces the tubing into folds, thus indicating both strength and ductility of the weld metal. Both of these tests are confined to tubing and to small sheet metal parts.

Hydraulic Tests

These tests are common for testing welded tanks, barrels, or cylinders when they can be filled with water. The pressure is applied with a small hydraulic pump, as indicated in Figure T-21. This test can be applied to the destruction of the tank if so required. It may also be applied at a pressure which will not destroy the tank or strain the metal or welds beyond the elastic limit. It is a relatively simple test to make; the only apparatus required is a pump, a gauge, and a valve. Sometimes the test pressure used is three times the working pressure, but as a rule, weld defects in tanks will be indicated when tested and hammered at 1-1/2 times the working pressure.

Air Pressure Tests

Air pressure should not be used for testing tanks, because air compresses into a smaller space than water. For example, if a tank were filled to a pressure of 550 or 690 kPa (80 or 100 psi), and the weld should break, the air will expand with such violence that injury to persons in the vicinity could occur. Water under pressure, on the other hand, does not expand, and when a tank breaks, the break occurs with a harmless spurt of water.

Tensile Test

A portable tensile testing apparatus is a valuable piece of equipment, particularly useful in the field to test the strength of specimens cut out of pipe or tank welds. It consists of a hydraulic cylinder with jaws to clamp the specimen and a pump to increase the pressure within the cylinder. The jaws of the clamp are pulled apart by hydraulic pressure until the specimen breaks. *See* TENSILE TEST.

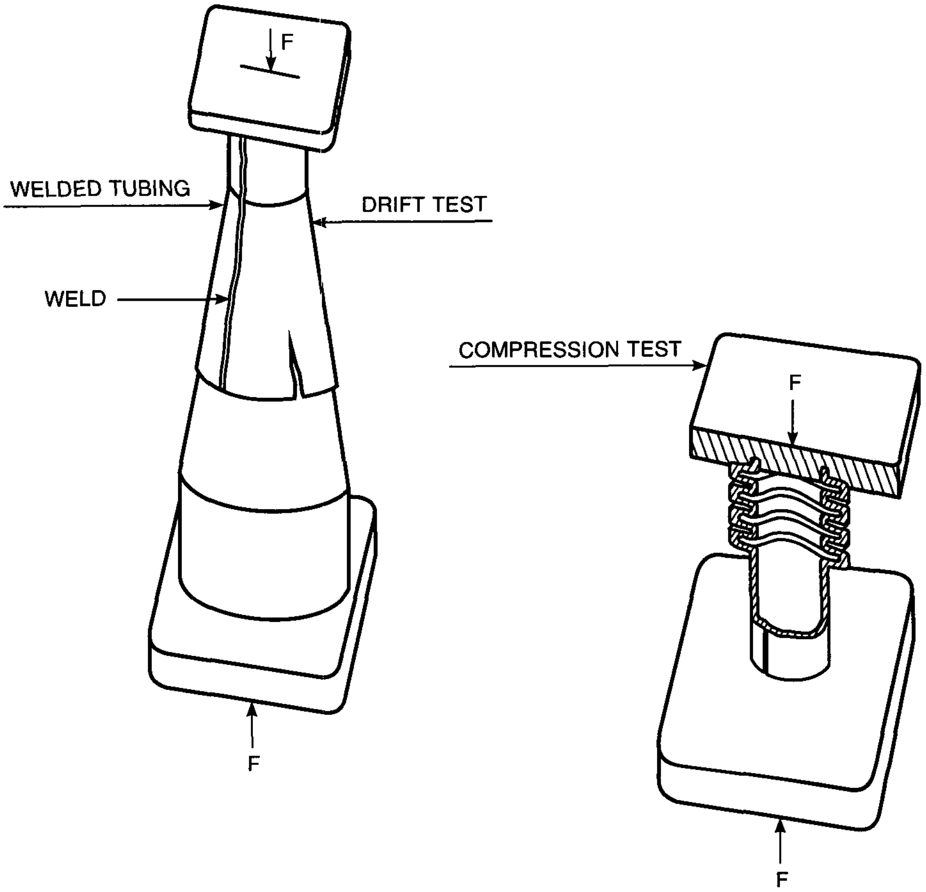


Figure T-20—Drift and Compression Tests Used on Thin Wall Tubing

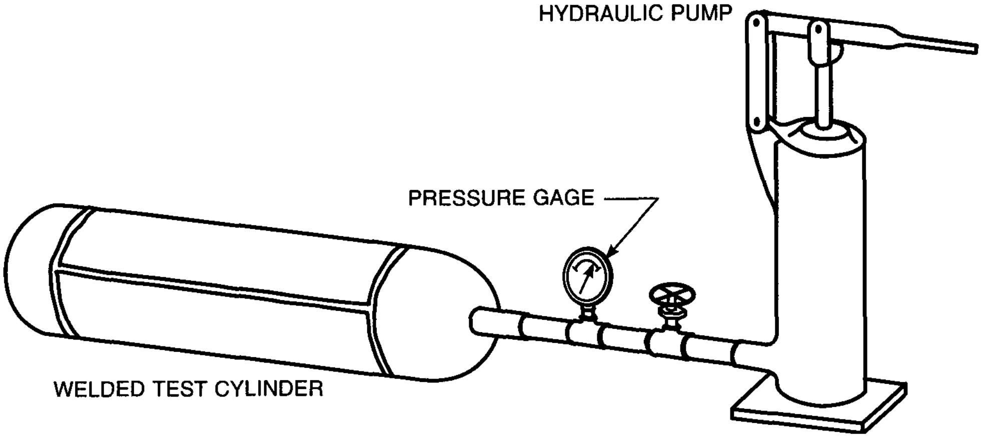


Figure T-21—Hydraulic Pump Used for Testing Welded Tubing or Small Cylinders

TUBULAR JOINT

A joint between two or more members, at least one of which is tubular. See STANDARD WELDING TERMS.

TUNGSTEN

(Chemical symbol: W). A very hard steel-gray metal which melts at a temperature of approximately 3400°C (6150°F), the highest melting point of all metals. Tungsten is used in the pure state and also in alloys for electrodes for resistance welding and arc welding. Its tensile strength when drawn into wire is approximately 3448 MPa (500 000 psi). As an alloying element in tool steel, tungsten tends to produce a fine, dense grain when used in relatively small quantities. When used in larger quantities, from 17 to 20%, and in combination with other alloys, it produces a steel that retains its hardness at high temperatures. Tungsten is also used in certain heat resistant steels in which the retention of strength at high temperatures is important. This element is usually used in combination with chromium or other alloying agents.

Tungsten has a density of 19.3 g/cm^3 (0.697 lb/in.^{3}). It is hard even after being heated to a red heat. Atomic weight 184.0: melting point, 3400°C (6150°F); specific gravity, 18.7.

TUNGSTEN CARBIDE

An alloy produced by exposing tungsten, heated to high temperatures, to carbon monoxide or other hydrocarbon gases. Tungsten carbide is almost as hard as the diamond, registering between 9 and 10 on the Mohs Scale. It is crushed and graded into various sizes; it is furnished in irregular fragments for hardfacing, and is also molded into shapes to be used in place of black diamonds in cutting tools.

A number of welding rods and electrodes are made to deposit small particles of this very hard alloy on the cutting faces of tools, bits, and other parts on which it is embedded in a matrix of softer welded deposit. There are several methods for accomplishing this purpose by using various types of rods. *See* HARDFACING.

TUNGSTEN ELECTRODE

A nonfiller metal electrode used in arc welding, arc cutting, and plasma spraying, made principally of tungsten. See STANDARD WELDING TERMS.

Pure tungsten or tungsten alloy electrodes for gas tungsten arc welding are manufactured in a variety of sizes and lengths. Table T-12 shows specifications and color coding of tungsten electrodes in accordance with the various AWS/ASTM classifications.

As drawn, the tungsten electrodes have a dense, black oxide coating. Before marketing, however, the surface is cleaned, either by chemical cleaning and etching, or by grinding the surface. The chemically cleaned electrodes are usually a bright gray color and have had all surface contaminants or oxides removed. Ground electrodes have been cleaned of all surface impurities by centerless grinding, which gives them the advantage of a bright surface as well as concentricity. The ground finish allows a tighter fit in the torch collet and will reduce electrical resistance losses to a minimum.

Electrodes are manufactured according to ANSI/AWS A5.12, *Specifications for Tungsten Arc Welding Electrodes*, in which the standard diameters of electrodes are 0.25, 0.5, 1.0, 1.6, 2.4, 3.2, 4.0, 4.8 and 6.4 mm (0.010, 0.020, 0.040, 1/16, 3/32, 1/8, 5/32, 3/16, and 1/4 in.). The tolerance for the 0.25 mm

Table T-12
Color Code and Alloying Elements for Various Tungsten Electrode Alloys

AWS Classification	Color[a]	Alloying Element	Alloying Oxide	Nominal Weight or Alloying Oxide Percent
EWP	Green	—	—	—
EWCe-2	Orange	Cerium	CeO_2	2
EWLa-1	Black	Lanthanum	La_2O_3	1
EWTh-1	Yellow	Thorium	ThO_2	1
EWTh-2	Red	Thorium	ThO_2	2
EWZr-1	Brown	Zirconium	ZrO_2	.25
EWG	Gray	Not Specified[b]	—	—

a. Color may be applied in the form of bands, dots, etc., at any point on the surface of the electrode.
b. Manufacturer must identify the type and nominal content of the rare earth oxide addition.

(0.010 in.) diameter electrode is ±0.025 mm (±0.001 in.); for the 0.5 mm (0.020 in.) electrode it is ±0.05 mm (±0.002 in.). All of the other sizes have a diameter tolerance of ±0.08 mm (±0.003 in.).

Electrodes are available in 75, 150, 180, 300, 450, and 600 mm (3, 6, 7, 12, 18, and 24 in.) lengths, with the three shorter lengths having a ±1.6 mm (±1/16 in.) tolerance, while the three longer electrodes must be within ±3.2 mm (±1/8 in.) of the specified length. The 0.25 mm (0.010 in.) diameter electrode is also available in coil form.

Tungsten Electrode Selection

There are many factors to be considered when selecting proper tungsten electrodes for gas tungsten arc welding. Probably the most influential factor, however, is the type and thickness of base metal. The capability of a tungsten electrode to carry welding current depends on the tungsten alloy used, the electrode diameter, the type and polarity of the current, and the extension of the electrode beyond the collet (the sleeve or tube which holds the electrode).

An electrode of a given size will have its greatest current-carrying capacity with direct current, straight polarity (DCEN); less with alternating current, and still less with direct current, reverse polarity (DCEP). Table T-13 lists some of the typical current values which may be used with argon gas shielding. There are, however, other factors which should be carefully considered before selecting an electrode for a specific application.

All tungsten electrodes will do a welding job and may be used in a similar manner. However, each electrode classification contributes distinct advantages to operating characteristics and usability. For this reason, electrode selection must take into account the advantages of one classification of electrodes over another.

Pure tungsten electrodes (EWP) are generally used with alternating current, either balanced wave or continuous high-frequency stabilized. The current-carrying capacity of pure tungsten is lower than that of alloy tungsten electrodes.

Pure tungsten electrodes have reasonably good resistance to contamination and maintain a balled end, which is preferred for aluminum and magnesium welding with ac.

Tungsten electrodes alloyed with thoria (thorium oxide), ceria (cerium oxide), lanthana (lanthanum oxide), or zirconia (zirconium oxide) are available commercially. The addition of these oxides makes arc starting easier and produces a more stable arc. Alloyed tungsten electrodes also have about a 50% greater current-carrying capacity for the same diameter pure tungsten electrode. The alloyed electrodes (except zirconiated) are designed basically for direct current (DCEN) welding applications. They can be used on alternating current welding, but considerable difficulty is experienced in maintaining a satisfactory "balled" end.

Table T-13
Recommended Tungsten Electrodes[a] and Gas Cups for Various Welding Currents

Electrode Diameter		Use Gas Cup I.D.,	Direct Current, A		Alternating Current, A	
mm	in.	in.	Straight Polarity[b], DCEN	Reverse Polarity[b], DCEP	Unbalanced Wave[c]	Balanced Wave[c]
0.25	0.010	1/4	up to 15		up to 15	up to 15
0.50	0.020	1/4	5–20		5–15	10–20
1.00	0.040	3/8	15–80		10–60	20–30
1.6	1/16	3/8	70–150	10–20	50–100	30–80
2.4	3/32	1/2	150–250	15–30	100–160	60–130
3.2	1/8	1/2	250–400	25–40	150–210	100–180
4.0	5/32	1/2	400–500	40–55	200–275	160–240
4.8	3/16	5/8	500–750	55–80	250–350	190–300
6.4	1/4	3/4	750–1100	80–125	325–450	325–450

a. All values are based on the use of argon as the shielding gas.
b. Use EWCe-2, EWLa-1, or EWTh-2 electrodes.
c. Use EWP electrodes.

Zirconium alloyed tungsten (EWZr) is ideal for a-c welding applications because of its high resistance to contamination, as well as good arc starting characteristics. These electrodes are highly recommended for those welding conditions where minute quantities of any type of foreign matter in the weld are intolerable. Zirconium electrodes are used for the welding of aluminum and magnesium. Pure tungsten or zirconium-tungsten electrodes form a hemispherical or "balled" end as used. If welding conditions are right, the balled end should be clean, shiny, and as reflective as a mirrored surface.

The primary advantage of the tungsten electrode is a high melting point to prevent contamination of the weld. Melting occurs when the electrode is overheated by excessive welding currents. For the most satisfactory welding operations, electrode temperatures should approach the melting point but not exceed it. After the classification of electrode is selected, the size of the electrode is selected. Usually, the electrode size selected is near the maximum current range for the particular electrode and type of job. If this is the case, the following must be considered: too small an electrode may result in the molten tip falling off to contaminate the weld, and too large an electrode will produce an arc that will become difficult to control. If the current is correct for the welding operation, the electrode will have a hemispherical end. If the current is too high, a "ball" will form on the end of the electrode. If the diameter of this "ball" exceeds the diameter of the electrode by 1-1/2 times, there is a likelihood that it will drop off to contaminate the weld. For this reason, the welding current should be reduced when these conditions become apparent. *See* GAS TUNGSTEN ARC WELDING.

T-WELD

A weld in which one plate is welded vertically to another, as in the case of the edge of a transverse bulkhead being welded against the shell plating or deck. This is a weld which in all cases requires exceptional care, and can only be used where it is possible to work from both sides of the vertical plate. A T-weld is also used for welding a rod in a vertical position to a flat surface, such as the rung of a ladder, or a plate welded vertically to a pipe stanchion, as in the case of water closet stalls.

TWIN CARBON ARC BRAZING (TCAB)

A brazing process that uses heat from an arc between two carbon electrodes. This is an obsolete or seldom-used process. See STANDARD WELDING TERMS.

TWIN CARBON ARC WELDING (CAW-T)

A carbon arc welding process variation that uses an arc between two carbon electrodes and no shielding. See STANDARD WELDING TERMS.

TWIN-POINT WELDING

A spot welding process employing two electrodes and a shunt bar so that two welds may be made at one time. This setup is used in "push-pull" welding, and is sometimes referred to as *series spot welding.*

2F, Pipe

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately vertical, in which the weld is made in the horizontal welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

2F, Plate

A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the horizontal welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

2FR

A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately horizontal, in which the weld is made in the horizontal welding position by rotating the pipe about its axis. See STANDARD WELDING TERMS. *See* Appendix 4.

2G, Pipe

A welding test position designation for a circumferential groove weld applied to a joint in a pipe, with its axis approximately vertical, in which the weld is made in the horizontal welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

2G, Plate

A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the horizontal welding position. See STANDARD WELDING TERMS. *See* Appendix 4.

TWO-PHASE CIRCUIT

A circuit in which there are two voltages, differing by one-quarter cycle.

TWO-POLE

A switch that opens or closes both sides of a circuit at one time.

TWO-STAGE REGULATOR

See OXYACETYLENE WELDING *and* REGULATOR.

TYPE OF JOINT

See STANDARD WELDING TERMS. *See also* JOINT TYPE.

TYPES OF WELDS

See BEAD WELD, BUTT WELD, FILLET WELD, GROOVE WELD, PLUG WELD, *and* SLOT WELD.

The titanium wing boxes on these F-14 fighter planes were welded with the electron beam process at the Grumman plant in Bethpage, New York

U

U-BEND

See BEND TEST.

U-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

ULTRASONIC COUPLER, Ultrasonic Soldering and Ultrasonic Welding

Elements through which ultrasonic vibration is transmitted from the transducer to the tip. See STANDARD WELDING TERMS.

ULTRASONIC SOLDERING (USS)

A soldering process variation in which high-frequency vibratory energy is transmitted through molten solder to remove undesirable surface films and thereby promote wetting of the base metal. This operation is usually accomplished without flux. See STANDARD WELDING TERMS.

ULTRASONIC TESTING (UT)

A nondestructive test (NDT) method in which beams of high-frequency sound waves are introduced into a test object to detect and locate internal discontinuities. A sound beam is directed into the test object on a predictable path, and is reflected at interfaces or other interruptions in material continuity. The reflected beam is detected and analyzed to define the presence and location of discontinuities.

The detection, location and evaluation of discontinuities is possible because (1) the velocity of sound through a given material is nearly constant, making distance measurements possible, and (2) the amplitude of the reflected sound pulse is nearly proportional to the size of the reflected discontinuity.

Ultrasound wave is electronically collected and presented on a cathode ray tube (CRT) screen for evaluation by a qualified and certified ultrasound technician.

Ultrasonic testing can be used to detect cracks, laminations, shrinkage cavities, pores, slag inclusions, incomplete fusion or bonding, incomplete joint penetration, and other discontinuities in weldments and brazements. With proper techniques, the approximate position and depth of the discontinuity can be determined, and in some cases, the approximate size of the discontinuity can be determined.

Advantages

The principal advantages of UT compared to other NDT methods are the following:

(1) Discontinuities in thick sections can be detected.

(2) Relatively high sensitivity to small discontinuities is exhibited.

(3) Depth of internal discontinuities can be determined; size and shape of discontinuities can be estimated.

(4) Adequate inspections can be made from one surface.

(5) Equipment can be moved to the job site.

(6) Process is nonhazardous to personnel or other equipment.

Limitations

The following limitations apply to ultrasonic testing:

(1) Set-up and operation require trained and experienced technicians, especially for manual examinations.

(2) Weldments that are rough, irregular in shape, very small, or thin are difficult or impossible to inspect; this includes fillet welds.

(3) Discontinuities at the surface are difficult to detect.

(4) A coupler is needed between the sound transducers and the weldment to transmit the ultrasonic wave energy.

(5) Reference standards are required to calibrate the equipment and to evaluate the size of discontinuities.

(6) Reference standards should describe the item to be examined with respect to design, material specifications, and heat treatment condition.

Equipment

A block diagram of a pulse-echo flaw detector is shown in Figure U-1. Most ultrasonic testing systems use the following basic components:

(1) An electronic signal generator (pulser) that produces bursts of alternating voltage.

(2) A sending transducer that emits a beam of ultrasonic waves when alternating voltage is applied.

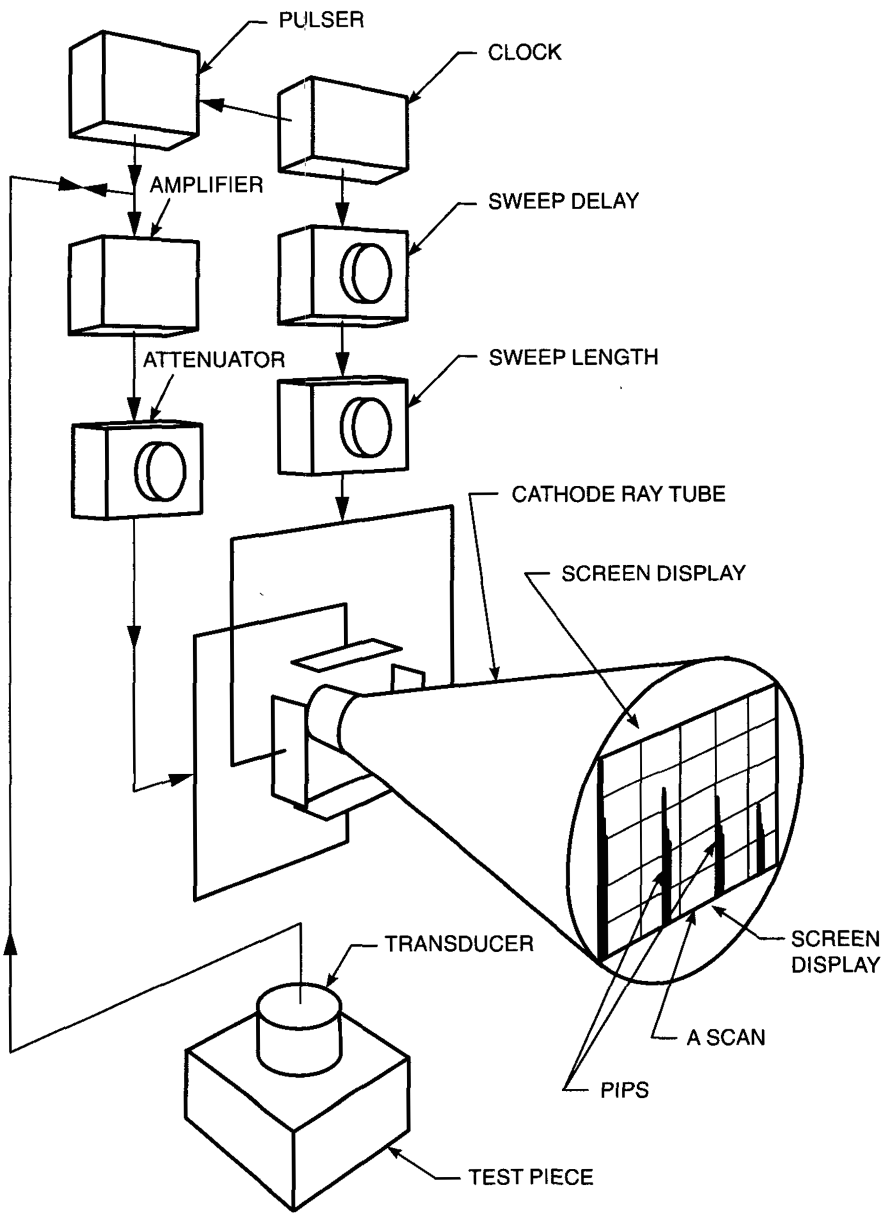


Figure U-1—Block Diagram of a Pulse-Echo Flaw Detector

The sound wave frequencies used are between 1 and 6 MHz, which are beyond the audible range. Most weld testing is performed at 2.25 MHz. Higher frequencies, i.e., 5 MHz, will produce small, sharp sound beams useful in locating and evaluating discontinuities in thin wall weldments.

(3) A coupler to transmit the ultrasonic energy from the transducer to the test piece and vice versa.

(4) A receiving transducer to convert the sound waves to alternating voltage. This transducer may be combined with the sending transducer.

(5) An electronic device to amplify and demodulate or otherwise change the signal from the receiving transducer.

(6) A display or indicating device to characterize or record the output from the test piece.

(7) An electronic timer to control the operation.

There are three basic modes of propagating sound through metals: longitudinal, (sometimes called straight or compressional), transverse (also called shear wave), and surface waves (sometimes referred to as Rayleigh waves). In the longitudinal and transverse modes, waves are propagated by the displacement of successive atoms or molecules in the metal.

Longitudinal wave ultrasound is generally limited in use to detecting inclusions and lamellar-type discontinuities in base metal. Transverse wave ultrasound is most valuable in the detection of weld discontinuities because of its ability to furnish three-dimensional coordinates for discontinuity locations, orientations, and characteristics. The sensitivity of shear waves is also about double that of longitudinal waves for the same frequency and search unit size.

The zones in the base metal adjacent to a weld should be tested with longitudinal waves first, to ensure that the base metal does not contain discontinuities that would interfere with shear wave evaluation of the weld.

In the third mode, surface waves are propagated along the metal surface, similar to waves on the surface of water. These surface waves have little movement below the surface of a metal, therefore they are not used for examination of welded and brazed joints.

Coupling. A liquid material is used for transmission of ultrasonic waves into the test object. Some of the more common coupling agents are water, light oil, glycerine, and cellulose gum powder mixed with water.

A weldment must be smooth and flat to allow intimate coupling. Weld spatter, slag, and other irregularities should be removed. Depending on the testing technique, it may be necessary to remove the weld reinforcement.

Calibration. Ultrasonic testing is basically a comparative evaluation. The horizontal (time) and the vertical (amplitude) dimensions on the CRT screen of the test unit are related to distance and size, respectively. It is necessary to establish a zero starting point for these variables, and to calibrate an ultrasonic unit to a basic standard before use.

Various test blocks are used to assist in calibration of the equipment. Known reflecting areas can simulate typical discontinuities. Notches substitute for surface cracks, side-drilled holes for slag inclusions or internal cracks, and angulated flat-bottomed holes for small areas of incomplete fusion. The test block material must be similar in acoustic qualities to the metal being tested.

The International Institute of Welding (IIW) test block is widely used as a calibration block for ultrasonic testing of steel welds. This block and other test blocks are used to calibrate an instrument for sensitivity, resolution, linearity, angle of sound propagation, and distance and gain calibrations.

Standard test blocks are shown in ASTM E164, *Standard Practice for Ultrasonic Contact Examination of Weldments,* latest edition, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

Test Procedures. Most ultrasonic testing of welds is done following a specific code or procedure. An example of such a procedure is that contained in AWS D1.1, *Structural Welding Code—Steel* for testing groove welds in structures.

ASTM E164, *Standard Practice for Ultrasonic Contact Examination of Weldments* covers examination of specific weld configurations in wrought ferrous and aluminum alloys to detect weld discontinuities. Procedures for calibrating the equipment and appropriate calibration blocks are included. Other ASTM standards cover testing procedures with various ultrasonic inspection methods for inspection of pipe and tubing.

Procedures for UT of boiler and pressure vessel components are given in ASME *Boiler and Pressure Vessel Code, Section V, Nondestructive Examination.*

Section XI, *Inservice Inspection Requirements for Nuclear Power Plants*, gives methods for locating, sizing, and evaluating discontinuities for continuing service life and fracture mechanics analysis.

Operator Qualifications. The reliability of ultrasonic examination depends greatly on the interpretive ability of the ultrasonic testing technician. In general, UT requires more training and experience than the other nondestructive testing methods, with the possible exception of radiographic testing. Many critical variables are controlled by the operators. For this reason, most standards require ultrasonic technicians to meet the requirements of ASNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing.*

Reporting. Careful tabulation of information in a report form is necessary for a meaningful test. Reporting requirements are included in ANSI/AWS D1.1, *Structural Welding Code—Steel.* The welding inspector should be familiar with the kinds of data that must be recorded and evaluated so that a satisfactory determination of weld quality can be obtained. Standards for testing have been published by the American Society for Nondestructive Testing, the American Society of Mechanical Engineers, and the American Welding Society. *See* Appendix 2.

Reference: American Welding Society, *Welding Handbook*, Vol. 1, 8th Edition. American Welding Society: Miami, Florida, 1987.

ULTRASONIC WELDING (USW)

A solid-state welding process that produces a weld by the local application of high-frequency vibratory energy as the workpieces are held together under pressure. See STANDARD WELDING TERMS.

Ultrasonic welding produces a sound metallurgical bond without melting the base metal. The basic force in ultrasonic welding is high-intensity vibrational energy. High- frequency electrical energy is converted to mechanical vibration, and a coupler (sonotrode) transmits the vibration to the work. An anvil counters the clamping force.

This process involves complex relationships between the static clamping force, the oscillating shear forces, and a moderate temperature rise in the weld zone. The magnitudes of these factors required to produce a weld are functions of the thickness, surface condition, and the mechanical properties of the workpieces.

Typical components of an ultrasonic welding system are illustrated in Figure U-2. The ultrasonic vibration is generated in the transducer. This vibration is transmitted through a coupling system or sonotrode, which is represented by the wedge and reed members in Figure U-2. The sonotrode tip is the component that directly contacts one of the workpieces and transmits the vibratory energy into it. (The sonotrode is the acoustical equivalent of the electrode and its holder used in resistance spot or seam welding). The clamping force is applied through at least part of the sonotrode, which in this case is the reed member. The anvil supports the weldment and opposes the clamping force.

Applications

Ultrasonic welding is used to join both monometallic and bimetallic joints. The process is used to produce lap joints between metal sheets or foils, between wires or ribbons and flat surfaces, between crossed or parallel wires, and for joining other types of assemblies that can be supported on the anvil.

This process is being used as a production tool in the semiconductor, microcircuit, and electrical contact industries, for fabricating small motor armatures, in the manufacture of aluminum foil, and in the assembly of aluminum components. It is receiving acceptance as a structural joining method by the automotive and aerospace industries. The process is uniquely useful for encapsulating materials such as explosives, pyrotechnics, and reactive chemicals that require hermetic sealing but cannot be processed by high-temperature joining methods.

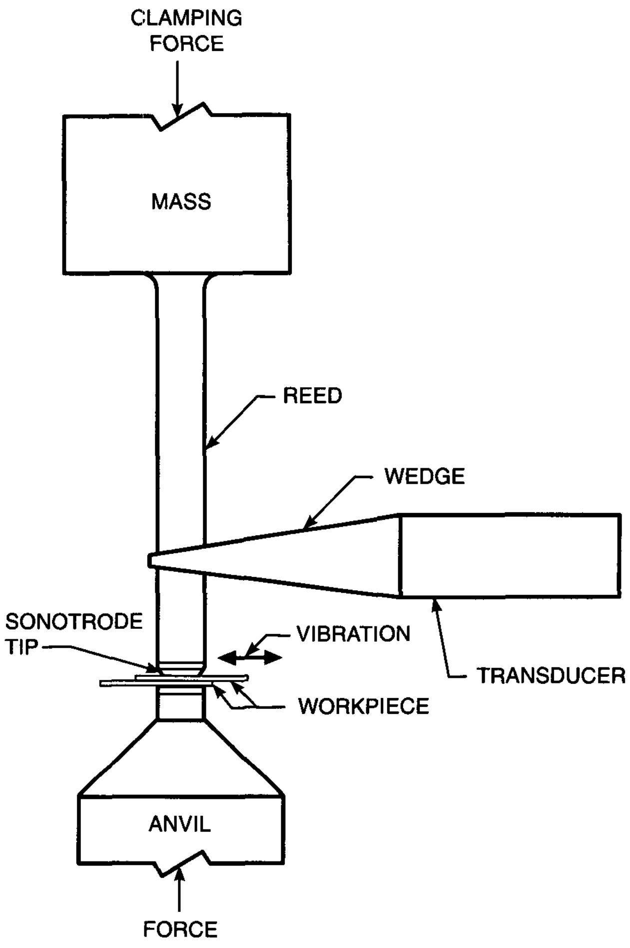


Figure U-2—Wedge-Reed Ultrasonic Spot Welding System

The most important application of the USW process is the assembly of miniaturized electronics components. Fine aluminum and gold lead wires are attached to transistors, diodes, and other semiconductor devices. Wires and ribbons are bonded to thin films and microminiaturized circuits. Diode and transistor chips are mounted directly on substrates. Reliable joints with low electrical resistance are produced without contamination or thermal distortion of the components.

Electrical connections, both single and stranded wires, can be joined to other wires and to terminals. The joints are frequently made through anodized coatings on aluminum, or through certain types of electrical insulation. Other current carrying devices, such as electric motors, field coils, harnesses, transformers and capacitors may be assembled with ultrasonically welded connections.

Broken and random lengths of aluminum foil are welded in continuous seams by foil rolling mills, with almost undetectable splices after subsequent working operations. Aluminum and copper sheet up to about 0.5 mm (0.020 in.) can be spliced together using special processing and equipment.

In structural applications, USW produces joints of high integrity within the limitations of weldable sheet thickness. An example is the assembly of a helicopter access door, in which inner and outer skins of aluminum alloy are joined by multiple ultrasonic spot welds.

Ultrasonic welding has reduced fabrication costs for some solar energy conversion and collection systems. An ultrasonic seam welding machine, operating at speeds up to 9 m/min (30 ft/min), joins all connectors in a single row in a fraction of the time require for hand soldering or individual spot welding. Solar collectors for hot water heating systems consisting of copper or aluminum tubing can be welded at significantly lower energy cost than soldering, resistance spot welding, or roll welding.

Other applications include continuous seam welding to assemble components of corrugated heat exchangers, and welding strainer screens without clogging the holes. Beryllium foil windows for space radiation counters have been ring welded to stainless steel frames to provide a helium leak-tight bond. Pinch-off weld closures in copper and aluminum tubing used in refrigeration and air conditioning are produced with special serrated bar tips and anvils.

Process Variations

There are four variations of the process, based on the type of weld produced. These are spot, ring, line and continuous seam welding. In addition, two variants of ultrasonic spot welding are used in microelectronics.

Spot Welding. In spot welding, individual weld spots are produced by the momentary introduction of vibratory energy into the workpieces as they are held together under pressure between the sonotrode tip and the anvil face. The tip vibrates in a plane essentially parallel to the plane of the weld interface, perpendicular to the axis of static force application. Spot welds between sheets are roughly elliptical in shape at the interface. They can be overlapped to produce an essentially continuous weld joint. This type of seam may contain as few as 2 to 4 welds/cm (5 to 10 welds/in.). Closer weld spacing may be necessary if a leak-tight joint is required.

Ring Welding. Ring welding produces a closed loop weld which is usually circular in form but may also be square, rectangular or oval. In this variation, the sonotrode tip is hollow, and the tip face is contoured to the shape of the desired weld. The tip is vibrated torsionally in a plane parallel to the weld interface. The weld is completed in a single, brief weld cycle.

Line Welding. Line welding is a variation of spot welding in which the workpieces are clamped between an anvil and a linear sonotrode tip. The tip is oscillated parallel to the plane of the weld interface and perpendicular to both the weld line and the direction of applied static force. The result is a narrow linear weld, which can be up to 150 mm (6 in.) long, produced in a single weld cycle.

Continuous Seam Welding. In this variation, joints are produced between workpieces that are passed between a rotating, disk-shaped sonotrode tip and a roller type or flat anvil. The tip may traverse the work while it is supported on a fixed anvil, or the work may be moved between the tip and a counter-rotating or traversing anvil. Area bonds may be produced by overlapping seam welds.

The flow of energy through an ultrasonic welding system begins with the introduction of 60 Hz electrical power into a frequency converter. This device converts the applied frequency to that required for the welding system, which is usually in the range of 10 to 75 kHz. The high-frequency electrical energy is conducted to one or more transducers in the welding system, where it is converted to mechanical vibratory energy of the same frequency. The vibratory energy is transmitted through the sonotrode and sonotrode tip into the workpiece. Some of the energy passes through the weld zone and dissipates in the anvil support structure.

For practical usage, the power required for welding is usually measured in terms of the high-frequency electrical power delivered to the transducer. This power can be monitored continuously and provides a reliable average value to associate with equipment performance as well as with weld quality. The product of the power in watts and welding time in seconds is the energy, in watt-seconds or joules, used in welding. The energy required to make an ultrasonic weld can be related to the hardness of the workpieces and the thickness of the part in contact with the sonotrode tip.

Process Advantages and Limitations

Ultrasonic welding has advantages over resistance spot welding in that little heat is applied during joining and no melting of the metal occurs. This process permits welding thin to thick sections, as well as joining a wide variety of dissimilar metals. Welds can be made through certain types of surface coatings and platings. Ultrasonic welding of aluminum, copper and other high-conductivity metals requires substantially less energy than resistance welding. As compared to cold welding, the pressures used in USW are much lower, welding times are shorter, and thickness deformation is significantly lower.

A major disadvantage is that the thickness of the component adjacent to the sonotrode tip must not exceed relatively thin gauges because of the power limitations of present ultrasonic welding equipment. The range of thicknesses of a particular metal that can be welded depends on the properties of that metal. Ultrasonic welding is limited to lap joints. Butt welds cannot be made in metals because there is no effective means of supporting the workpieces and applying clamping force. However, ultrasonic butt welds are made in some polymer systems.

Safety

The welding machine operator should be provided with eye and ear protection.

Most ultrasonic welding equipment is designed with interlocks and other safety devices to prevent personnel from contacting high voltages in the equipment. Nevertheless, consideration must be given to operating personnel and all personnel in the area of the welding operations. There must be strict conformance to the manufacturers' operating instructions and safety recommendations as well as requirements in ANSI/ ASC Z-49.1 (latest edition), *Safety in Welding and Cutting* and applicable requirements of the Occupational Safety and Health Administration (OSHA).

ULTRA-SPEED WELDING

A nonstandard term for COMMUTATOR-CONTROLLED WELDING.

ULTRAVIOLET RAYS

Light rays which are outside of the visual spectrum at the violet end. These rays are comparatively intense in arc welding; eye protection must be worn during welding operations. *See* EYE PROTECTION.

UNAFFECTED ZONE

The area of the base metal outside of the zone of a weld in which no changes in grain size have occurred due to the effects of welding.

UNBALANCED FLAME

An oxyacetylene flame with an excess of either oxygen or acetylene; a flame that is oxidizing or carburizing.

UNDERBEAD CRACK

A crack in the heat-affected zone generally not extending to the surface of the base metal. See STANDARD WELDING TERMS. *See* Appendixes 8 and 9.

UNDERCUT

A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal. See STANDARD WELDING TERMS. *See* Appendix 8.

Causes: Excessive welding current; improper electrode technique; mismatch between electrode design and weld position.

Corrections: use a moderate welding current and proper welding speed; use an electrode that produces a puddle of the proper size; proper weaving technique; proper positioning of the electrode relative to a horizontal fillet weld.

The term *undercut* is used to describe either of two situations. One is the melting away of the sidewall of a weld groove at the edge of the bead, thus forming a sharp recess in the sidewall in the area in which the next bead is to be deposited. The other is the reduction in thickness of the base metal at the line where the beads in the final layer of weld metal tie into the surface of the base metal (e.g., at the toe of the weld).

Both types of undercut are usually due to the specific welding technique used by the welder. High amperage and a long arc increase the tendency to undercut. Incorrect electrode position and travel speed are also causes, as is improper dwell time in a weave bead. Even the type of electrode used has an influence. The various classifications of electrodes show widely different characteristics in this respect. With some electrodes, even the most skilled welder may be unable to avoid undercutting completely in certain welding positions, particularly on joints with restricted access.

Undercut of the sidewalls of a weld groove will in no way affect the completed weld if the undercut is removed before the next bead is deposited at that location. A well-rounded chipping tool or grinding wheel will be required to remove the undercut. If the undercut is slight, however, an experienced welder who knows just how deep the arc will penetrate may not need to remove the undercut.

The amount of undercut permitted in a completed weld is usually dictated by the fabrication code being used, and the requirements specified should be followed because excessive undercut can materially reduce the strength of the joint. This is particularly true in applications subject to fatigue. Fortunately, this type of undercut can be detected by visual examination of the completed weld, and it can be corrected by blend grinding or depositing an additional bead.

UNDERFILL

A condition in which the weld face or root surface extends below the adjacent surface of the base metal. See STANDARD WELDING TERMS. *See* Appendix 8.

UNDERWATER CUTTING

Underwater cutting is used for salvage work and for cutting below the water surface on piers, dry docks, and ships. The two methods most widely used are oxyfuel gas cutting (OFC) and oxygen arc cutting (AOC).

Technique. The technique for underwater cutting with OFC is not materially different from that used in cutting steel in open air. An underwater OFC torch embodies the same features as a standard OFC torch with the additional feature of supplying its own ambient atmosphere. In the underwater cutting torch, fuel and oxygen are mixed together and burned to produce the preheat flame. Cutting oxygen is provided through the tip to sever the steel. In addition, the torch provides an air bubble around the cutting tip. The air bubble is maintained by a flow of compressed air around the tip. The air shield stabilizes the preheat flame and at the same time displaces the water from the cutting area.

Special Equipment. The underwater cutting torch has connections for three hoses to supply compressed air, fuel gas, and oxygen. A combination shield and spacer device is attached at the cutting end of the torch. The adjustable shield controls the formation of the air bubble. The shield is adjusted so that the preheat flame is positioned at the correct distance from the work. This feature is essential for underwater work because of poor visibility and reduced operator mobility caused by cumbersome diving suits. Slots in the shield allow the burned gases to escape. A short torch is used to reduce the reaction force produced by the compressed air and cutting oxygen pushing against the surrounding water.

Gases. As the depth of water at which the cutting is being done increases, the gas pressures must be increased to overcome both the added water pressure and the frictional losses in the longer hoses. Approximately 3.5 kPa (1/2 psi) for each 300 mm (12 in.) of depth must be added to the basic gas pressure requirements used in air for the thickness being cut.

Methylacetylene-propadiene (MPS), propylene, and hydrogen are the best all-purpose preheat gases, because they can be used at any depths to which divers can descend and perform satisfactorily. Acetylene must not be used at depths greater than approximately 6 m (20 ft), because its maximum safe operating pressure is 100 kPa (15 psi).

No great difficulty is experienced in underwater severing of steel plate in thicknesses from 13 mm (1/2 in.) to approximately 101 mm (4 in.) with the oxyfuel gas cutting torch. Under 13 mm (1/2 in.) thickness, the constant quenching effect of the surrounding water lowers the efficiency of preheating. This requires much larger preheating flames and preheat gas flows. Cutting oxygen orifice size is considerably larger for underwater cutting than for cutting in air. A special apparatus for lighting the preheat flames under water is also needed.

Oxygen Lance Cutting (LOC)

The LOC process can also be used underwater. The lance must be lighted before it is placed underwater; then piercing proceeds essentially the same as in air. The process produces a violent bubbling action which can restrict visibility.

Oxygen Arc Cutting (AOC)

This is another underwater cutting process used to cut ferrous and nonferrous metals in any position. Underwater electrodes for AOC are steel tubes with a waterproof coating. A fully insulated electrode holder equipped with a suitable flash-back arrester is required. *See* OXYFUEL GAS CUTTING, OXYGEN LANCE CUTTING, *and* OXYGEN ARC CUTTING.

UNDERWATER WELDING

Underwater welding (wet welding) is described as welding at ambient pressure with the welder/diver in the water with no physical barrier between the water and the welding arc. Although it is a complex metallurgical process, wet welding closely resembles welding in air in that the welding arc and molten metal are shielded from the environment (water or air) by gas and slag produced by decomposition of flux coated electrodes or flux cored wire. Underwater dry welding is done at ambient pressure in a chamber from which water has been displaced. Depending on the size and configuration of the chamber, the welder/diver may be completely in the chamber, or only partially in the chamber, and may work in conventional welder's attire, dive gear, or a combination of both.

Underwater welding has been used during the installation of new offshore drilling structures, sub-sea pipelines and hot taps, docks and harbor facilities, and for modifications and additions to underwater structures. However, underwater welding is most often required for repairs to existing structures. Maintenance and repair applications include:

(1) Replacement of damaged sub-sea pipeline sections and pipeline manifolds

(2) Replacement of structural members damaged by corrosion and fatigue

(3) Damage occurring during installation, boat collisions, or other accidental damage.

Specifications for underwater welding are published by American Welding Society, Miami, Florida; in ANSI/AWS D3.6-93, *Specification for Underwater Welding*.

UNDERWRITERS LABORATORIES, INC.

A not-for-profit organization chartered to maintain and operate product and safety certification programs. *See* Appendix 2.

Underwriters Laboratories carries out safety examination and testing of devices, systems, and materials against reasonably foreseeable risks. Success in the testing results in a UL label. Founded in 1894, UL representatives make unannounced visits to factories which make products bearing the UL label to check correct maintenance of product integrity.

UNDERWRITERS LABORATORIES STANDARDS

Rules formulated by the Underwriters' Laboratories to assure the safe construction of industrial equipment, including welding apparatus.

UNFIRED PRESSURE VESSELS

Unfired pressure vessels are containers for the containment of pressure either internal or external. Section VIII of the ASME Boiler and Pressure Vessel Code (BPVC) covers unfired pressure vessels. These include towers, reactors and other oil and chemical refining vessels, heat exchangers for refineries, paper mills, and other process industries, as well as storage tanks for large and small air and gas compressors. *See* BOILER CONSTRUCTION CODE.

UNIDIRECTIONAL CURRENT

An electrical current that flows in one direction only.

UNIFIED NUMBERING SYSTEM (UNS)

A method for cross referencing the different numbering systems used to identify metals, alloys, and welding filler metals. With UNS, it is possible to correlate over 4400 metals and alloys used in a variety of specifications, regardless of the identifying number used by a society, trade association, producer, or user.

UNS is produced jointly by the Society of Automotive Engineers (SAE) and the American Society for Testing and Materials (ASTM). It cross references the numbered metal and alloy designations of the major organizations and systems, including Federal and military. Over 500 of the listed numbers are for welding and brazing filler metals that are classified by deposited metal composition. *See* Table U-1.

UNIONMELT WELDING

See SUBMERGED ARC WELDING.

UNIPHASE

A single-phase alternating current.

UNMIXED ZONE

A thin boundary layer of weld metal, adjacent to the weld interface, that solidified without mixing with the remaining weld metal. See STANDARD WELDING TERMS. *See also* MIXED ZONE.

UPHILL, *adv.*

Welding with an upward progression. See STANDARD WELDING TERMS.

UPSET

Bulk deformation resulting from the application of pressure in welding. The upset may be measured as a percent increase in interface area, a reduction in length, a percent reduction in lap joint thickness, or a reduction in cross wire weld stack height.

Table U-1
SAE-ASTM Unified Numbering System*

UNS Number**	Metals and/or Alloys in Each Series
AXXXXX	Aluminum and Aluminum Alloys
CXXXXX	Copper and Copper Alloys
EXXXXX	Rare Earth and Similar Metals and Alloys
FXXXXX	Cast Irons
GXXXXX	AISI and SAE Carbon and Alloy Steels
HXXXXX	AISI and SAE H-Steels
JXXXXX	Cast Steels (except Tool Steels)
KXXXXX	Miscellaneous Steels and Ferrous Alloys
LXXXXX	Low Melting Metals and Alloys
MXXXXX	Miscellaneous Nonferrous Metals and Alloys
NXXXXX	Nickel and Nickel Alloys
PXXXXX	Precious Metals and Alloys
RXXXXX	Reactive and Refractory Metals and Alloys
SXXXXX	Heat and Corrosion Resistant Steels (including Stainless, Valve Steels, and Iron-Base "Superalloys")
TXXXXX	Tool Steels, Wrought and Cast
WXXXXX	Welding Filler Metals
ZXXXXX	Zinc and Zinc Alloys

*Metals and alloys listed in the UNS system of SAE-ASTM assigned to date and included in the Sixth Edition, 1993, of SAE HS-1086, and of ASTM DS-56.

**The five "X" marks represent UNS Numbers and are replaced by five digits when they serve to identify a specific material in the series.

UPSET BUTT WELDING

A nonstandard term *for* UPSET WELDING. *See* STANDARD WELDING TERMS.

UPSET DISTANCE

The total reduction in the axial length of the workpieces from the initial contact to the completion of the weld. In flash welding the upset distance is equal to the platen movement from the end of flash time to the end of upset. See STANDARD WELDING TERMS.

UPSET FORCE

The force exerted at the faying surfaces during upsetting. See STANDARD WELDING TERMS.

UPSET TIME

The time during upsetting. See STANDARD WELDING TERMS.

UPSET WELDING (UW)

A resistance welding process that produces coalescence over the entire area of faying surfaces or progressively along a butt joint by the heat obtained from the resistance to the flow of welding current through the area where those surfaces are in contact. Pressure is used to complete the weld. See STANDARD WELDING TERMS. *See* Figure U-3.

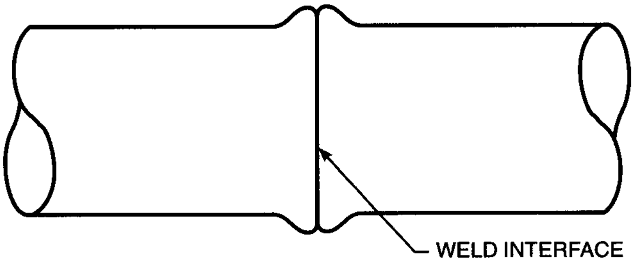


Figure U-3—Upset (Non-Fusion) Weld

Principles of Operation. With this process, welding is essentially done in the solid state. The metal at the joint is resistance-heated to a temperature where recrystallization can rapidly take place across the faying surfaces. A force is applied to the joint to bring the faying surfaces into intimate contact and then upset the metal. Upset hastens recrystallization at the interface and, at the same time, some metal is forced outward from this location. This tends to purge the joint of oxidized metal.

Process Variations

Upset welding has two variations:

(1) Joining two sections of the same cross section end-to-end (butt joint)

(2) Continuous welding of butt joint seams in roll-formed products such as pipe and tubing.

The first variation can also be accomplished by flash welding and friction welding. The second variation is also done with high-frequency welding.

Butt Joints. A wide variety of metals in the form of wire, bar, strip, and tubing can be joined end-to-end by upset welding. These include carbon steels, stainless steels, aluminum alloys, brass, copper, nickel alloys, and electrical resistance alloys.

Sequence of Operations. The essential operational steps to produce an upset welded butt joint are as follows:

(1) Load the machine with the parts aligned end-to-end

(2) Clamp the parts securely

(3) Apply a welding force

(4) Initiate the welding current

(5) Apply an upset force

(6) Shut off the welding current

(7) Release the upset force

(8) Unclamp the weldment

(9) Return the movable platen and unload the weldment(s).

The general arrangement for upset welding is shown in Figure U-4. One clamping die is stationary and the other is movable to accomplish upset. Upset force is applied through the moveable clamping die or a mechanical backup, or both.

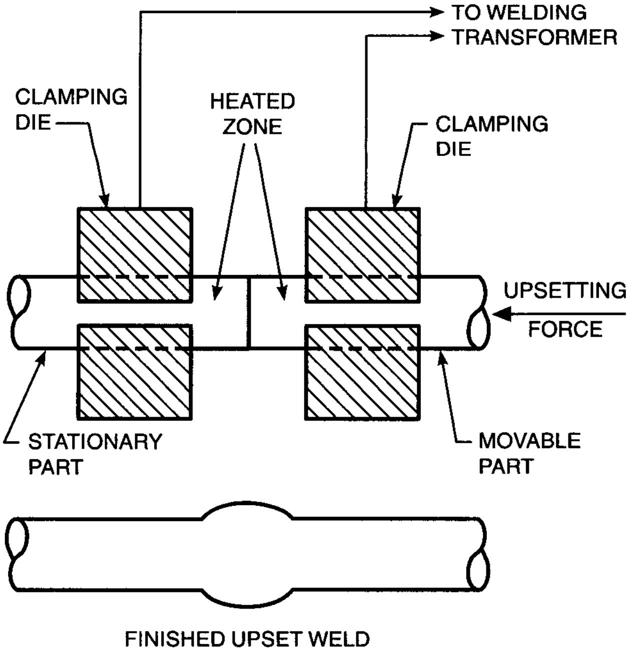


Figure U-4—General Arrangement for Upset Welding of Bars, Rods, and Pipes

Joint Preparation. For uniform heating, the faying surfaces should be flat, comparatively smooth, and perpendicular to the direction of the upsetting force. Prior to welding, they should be cleaned to remove any dirt, oil, oxidation, or other materials that will impede welding.

The contact resistance between the faying surfaces is a function of the smoothness and cleanliness of the surfaces and the contact pressure. This resistance varies inversely with the contact pressure, provided the other factors are constant. As the temperature at the joint increases, the contact resistance changes, but it finally becomes zero when the weld is formed. Upset welding differs from flash welding in that no flashing takes place at any time during the welding cycle.

Generally, force and current are maintained throughout the entire welding cycle. The force is kept low at first to promote high initial contact resistance between the two parts. It is increased to a higher value to upset the joint when the welding temperature is reached. After the prescribed upset is accomplished, the welding current is turned off and the force is removed.

Equipment. Equipment for upset welding is generally designed to weld a particular family of alloys, such as steels, within a size range based on cross-sectional area. The mechanical capacity and electrical characteristics of the machine are matched to that application. Special designs may be required for certain aluminum alloys to provide close control of the upset force.

Electric current for heating is provided by a resistance welding transformer. It converts line power to low-voltage, high-current power. No-load secondary voltages range from about 0.4 to 8 V. Secondary current is controlled by a transformer tap switch or by electronic phase shift.

Basically, an upset welding machine has two platens, one of which is stationary and the other movable. The clamping dies are mounted on these platens. The clamps operate either in straight line motion or through an arc about an axis, depending upon the application. Force for upset butt welding is produced generally by a mechanical, pneumatic, or hydraulic system.

Heat Balance. The upset process is generally used to join together two pieces of the same alloy and same cross-sectional geometry. In this case, heat balance should be uniform across the joint. If the parts to be welded are similar in composition and cross section but of unequal mass, the part of larger mass should project from the clamping die somewhat farther than the other part. With dissimilar metals, the one with higher electrical conductivity should extend farther from the clamp than the other. When upset welding large parts that do not make good contact with each other, it is sometimes advantageous to interrupt the welding current periodically to allow the heat to distribute evenly into the parts.

Applications. Upset welding is used in wire mills and in the manufacture of products made from wire. In wire mill applications, the process is used to join wire coils to each other to facilitate continuous processing. Upset welding is also used to fabricate a wide variety of products from bar, strip, and tubing stock. Wire and rod from 12.7 to 31.8 mm (0.05 to 1.25 in.) diameter can be upset welded.

Weld Quality. Butt joints can be made that have about the same properties as the unwelded base metal. With proper procedures, welds made in wires are difficult to locate after they have passed through a subsequent drawing process. In many instances, the welds are then considered part of the continuous wire.

Upset welds may be evaluated by tension testing. The tensile properties are compared to those of the base metal. Metallographic and dye penetrant inspection techniques are also used.

A common method for evaluating a butt weld in wire is a bend test. A welded sample is clamped in a vise with the weld interface located one wire diameter from the vise jaws. The sample then is bent back and forth until it breaks in two. If the fracture is through the weld interface and shows complete fusion, or if it occurs outside the weld, the weld quality is considered satisfactory.

Continuous Upset Butt Welding

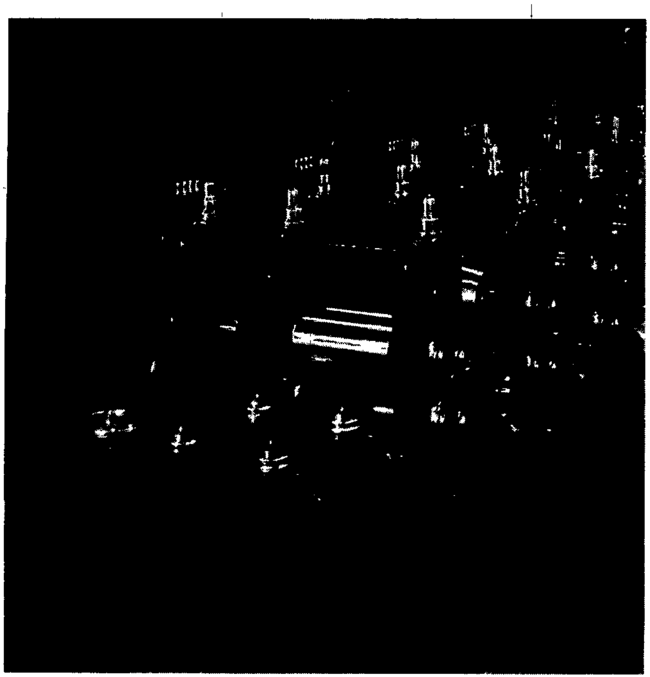
In the manufacture of welded pipe or tubing by continuous upset welding, coiled strip is fed into a set of forming rolls. These rolls progressively form the strip into a cylindrical shape. The edges to be joined approach each other at an angle and culminate in a longitudinal V at the point of welding. A wheel electrode contacts each edge of the tube a short distance from the apex of the V. Current from the power source travels from one electrode along the adjacent edge to the apex, where welding is taking place, and then back along the other edge to the second electrode. The edges are resistance-heated to welding temperature by this current. The hot edges are then upset together by a set of pinch rolls to accomplish the weld.

Equipment. Figure U-5 shows a typical tube mill that uses upset welding to join the longitudinal seam. Figure U-5 (A) shows the steel strip entering the strip guide assembly and the first stages of the forming section. The heat regulator, located behind the forming section, can be adjusted either manually or by phase-shift heat control. Figure U-5 (B) shows a rotary type oil-cooled welding transformer. This welding equipment includes a dressing tool assembly for dressing the welding electrodes without removing them from the welding machine, and a scarfing tool assembly that removes the upset metal after welding. The welded tube then enters the straightening and sizing section, shown in Figure U-5 (C). Following this, the tubing is cut to the desired length.

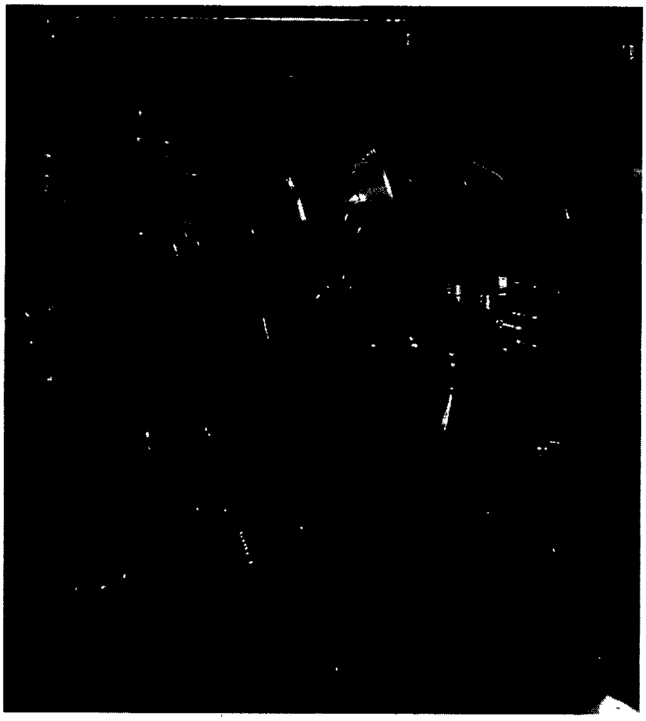
Welding can be done using either a-c or d-c power. Alternating-current machines may be operated on either 60 Hz single-phase power or on power of higher frequency produced by a single-phase alternator. Direct-current machines are powered by a three-phase transformer-rectifier unit.

Welding Procedures. As the formed tube passes through the zone between the electrodes and the pinch rolls, there is a variation in pressure across the joint. If no heat were generated along the edges, this pressure would be maximum at the center of the squeeze rolls. However, since heat is generated in the metal ahead of the squeeze roll center line, the metal gradually becomes plastic and the point of initial edge contact is slightly ahead of the squeeze roll axes. The point of maximum upset pressure is somewhat ahead of the squeeze roll centerline.

The current across the seam is distributed in inverse proportion to the resistance between the two electrodes. This resistance, for the most part, is the contact resistance between the edges to be welded. Pressure is effective in reducing this contact resistance. As the temperature of the joint increases, the electrical resistance will increase and the pressure will decrease. A very sharp thermal gradient caused by the resistance heating at the peaks of the a-c cycle produces a "stitch effect." The stitch is normally of circular cross section, lying centrally in the weld area and parallel to the line of initial closure of the seam edges. It is the hottest portion of the weld. The stitch area is molten while the area between stitches is at a lower temperature. The patches of molten metal are relatively free to flow under the influence of the motor forces (current and magnetic flux) acting on them. Consequently, they are ejected from the stitch area. If the welding heat is excessive, too much metal is ejected and pinhole leaks may result. With too little heat, the individual stitches will not overlap sufficiently, resulting in an interrupted weld.



(A) STRIP GUIDE ASSEMBLY AND FIRST STAGES OF THE FORMING SECTION



(B) ROTARY TYPE OIL-COOLED WELDING TRANSFORMER

Figure U-5—Typical Tube Mill Using Upset Welding for Joining the Longitudinal Seam

(C) STRAIGHTENING AND SIZING SECTION

Figure U-5 (Continued)—Typical Tube Mill Using Upset Welding for Joining the Longitudinal Seam

The longitudinal spacing of the stitches must have some limit. The spacing is a function of the power frequency and the travel speed of the tube being welded. With 60 Hz power, the speed of welding should be limited to approximately 0.45 m/sec (90 ft/min). To weld tubing at higher speeds than this requires welding power of higher frequency.

It is desirable to close the outside corners of the edges first as the formed tube moves through the machine so that the stitches will be inclined forward. This condition is known as an inverted V. The advantages of using an inverted V are twofold: (1) the angle deviation from the vertical reduces the forces tending to expel any molten metal in the joint, and (2) the major portion of the solid upset metal is extruded to the outside where it is easily removed. The tubing is normally formed so that the included angle of the V is about 5 to 7°. *See also* HIGH-FREQUENCY UPSET WELDING *and* INDUCTION UPSET WELDING.

UPSLOPE TIME

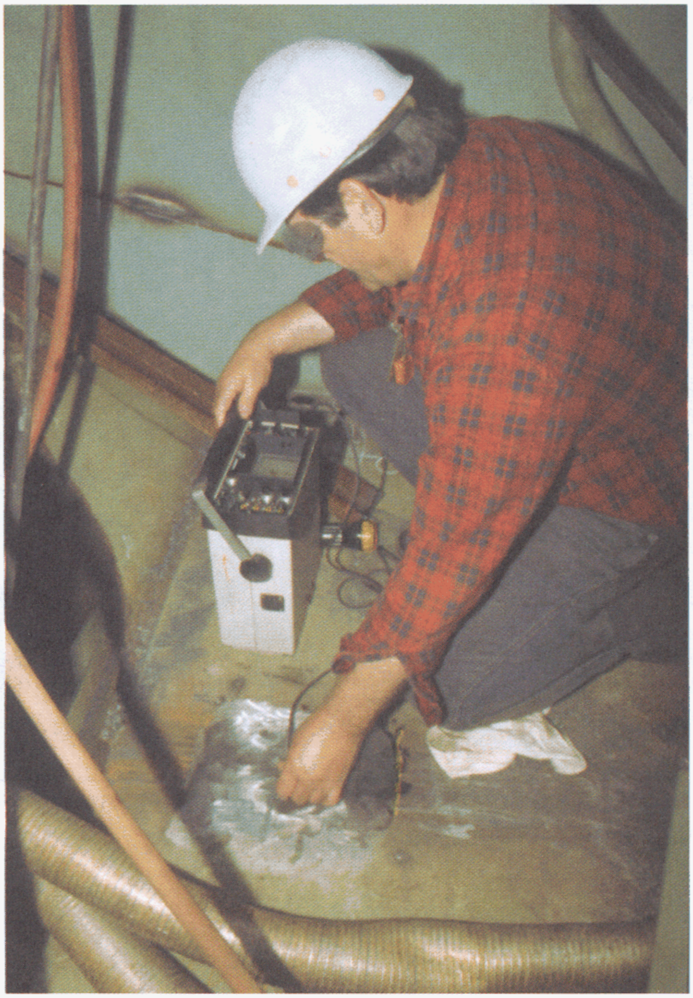
See AUTOMATIC ARC WELDING UPSLOPE TIME *and* RESISTANCE WELDING UPSLOPE TIME.

URANIUM

(Chemical symbol: U). A heavy, metallic element occurring in nature, obtained from its ores as the fissionable isotope U-235. Finely divided uranium powder is pyrophoric and care must be exercised to prevent fires. Atomic number, 92; atomic weight, 238.07; melting point 1132°C (2070°F). Uranium is used principally in nuclear applications and research.

USABILITY

A measure of the relative ease of application of a welding filler metal to make a sound weld. See STANDARD WELDING TERMS.



Ultrasonic testing of a weld section introduces beams of high-frequency sound waves into the weld to detect and locate internal discontinuities

Welders set up to weld ends of rails using the electrogas process. Thermite welding is also used to provide continuous-welded railroad tracks.

V

VACUUM BRAZING

A nonstandard term for various brazing processes that take place in a chamber or retort below atmospheric pressure.

VACUUM CHAMBER

A container voided of air and other matter to provide a controlled atmosphere in which highly reactive metals such as titanium, zirconium and tantalum are welded. Various welding processes, such as electron beam welding, diffusion bonding and welding, and furnace brazing are performed in a vacuum.

A vacuum chamber, sometimes called a "dry box," is evacuated by a pumping system. The chamber provides a completely sealed enclosure which allows a wide visual range so that all stages of the welding operation can be observed. It may also provide access ports for placing or removing parts without contaminating the atmosphere, and remote control devices to manipulate the weldment. Refinements of the system can allow placement of parts in all positions, multiple glove openings, automatic gas controls, and other accessories and equipment specific to the particular manufacturing requirement.

Applications. The nuclear power and the aerospace industries have applications for controlled-atmosphere welding systems. Extreme corrosion problems encountered in the nuclear industry and the need for materials with low neutron absorption characteristics create numerous applications in which such materials as zirconium and zircaloy-2 must be welded under ideal conditions.

A demand for materials with high strength-to-weight ratios and the capability to retain strength at high temperatures, such as titanium and beryllium, has similarly directed aircraft manufacturers to controlled-atmosphere welding.

A basic controlled atmosphere system is comprised of a vacuum chamber and pumping console, purification trains, power supplies, travel and rotational fixtures, air locks, fully automatic operational controls, and other accessories.

Highly reactive metals readily absorb oxygen, nitrogen and hydrogen when heated to temperatures above 316°C (600°F), which is detrimental to their mechanical and corrosion resistant properties.

For gas tungsten arc welding, the vacuum chamber is a pressure-tight vessel in which the work, GTAW torch, fixtures and power leads can be installed and which can be evacuated to a range of 0.1 to 5 microns, then refilled with helium or argon at atmospheric pressure.

The vacuum chamber atmosphere can be further purified of residual air (due to insufficient pump-down or leakage during refilling) by holding an arc for several minutes on a scrap piece of the alloy to be welded. The operation is halted when weld beads free of discoloration are observed.

Helium, argon, or a mixture of the two may be used as a shielding gas. The most important consideration in the choice between argon and helium as an inert gas for welding is their individual arc characteristics. The normal GTAW welding voltage in an argon atmosphere is from 10 to 12 volts direct current electrode negative (DCEN), and 16 to 20 volts in helium. These values are for similar arc lengths.

For this reason, when all other variables are held constant and equal, power input is greater with helium at the same welding current. It is difficult to strike an arc in helium at less than 30 amperes, whereas an arc can be initiated in argon at 10 amperes. For this reason, it is generally necessary to use argon on thin materials to prevent excessive penetration or burn-through.

The most common vacuum chamber is a cylindrical vessel with removable plates for loading, and for access to the operator's protective gloves extended inside. Specifications for construction of the vessel require that it have the capability to withstand vacuums in the order of 10^{-4} mm of mercury. As an alternate to a steel vessel, rigid or flexible plastic containers have been used successfully.

While normal design procedures for GTAW can be followed, preference should be given those avoiding the use of filler wire to reduce possible contamination from wire surface impurities.

VACUUM PLASMA SPRAYING (VPSP)

A thermal spraying process variation using a plasma spraying gun confined to a stable enclosure *that is partially evacuated. See* STANDARD WELDING TERMS.

VACUUM TUBE

A predecessor of solid state electronics. An electron tube evacuated sufficiently high to allow electrons to move with low interaction with remaining molecules of air or gas.

Although they have been largely replaced by solid state electronics, vacuum tubes of interest to the welding industry are the *thyratron*, which changes alternating current into direct current and regulates the flow, and the *ignitron*, which also changes high-voltage alternating current into direct current. The ignitron depends on the presence of liquid mercury inside the tube. Some tubes, such as the ignitron, are housed in large tanks which have running water to cool parts of the tube because of the high heats that are generated. *See* ELECTRONIC TUBE.

VANADIUM

(Chemical symbol: V). A rare bright white ductile metallic element usually found in nature as a compound of lead or lead and copper. It is used in the production of steel to promote control of grain size and provide corrosion resistance and hardenability. The addition of vanadium tends to produce fine grain structure during the heat treating process. Because of this property, vanadium often eliminates the harmful effects of overheating. Once used in armor plate, its principal application is in high-speed steels.

VAN STONE JOINT

This is a type of bolted flange pipe joint in which the ends of the pipe are heated and flanged outward to form circular contacting flanges. A gasket is placed between the flanged pipe ends and the bolted flanges are slipped over the flanged pipe ends and tightened to draw the pipe ends tightly together.

VALVE

A device with a movable part which starts, stops, or regulates the flow of liquids or gases.

VALVE, Hydraulic Back-Pressure

See WATER SEAL.

VAPOR FLUX

A flux that is brought to the oxyfuel gas torch by passing acetylene through a liquid flux held in a dispenser. The dispenser is connected in the acetylene line between the regulator and the torch so that all of the acetylene passes through it. The flux in a vapor form is picked up by the acetylene and carried through the hose and torch to the point of welding. Vapor flux provides automatic fluxing and accurately regulates the amount of flux used; it permits continuous welding without stopping to reflux the rod.

VARIABLE RESISTOR

A resistor that can be changed or adjusted to different values.

V-BLOCK

A jig made of a casting with a V-shaped notch used to hold shafts or rods in alignment while they are welded. Small jobs are facilitated by using V-blocks.

VENTILATION

In welding, brazing, cutting, or bonding operations, a system of removing fumes, vapors, or gases from the workplace and replacing them with fresh air. Refer to ANSI/ASC Z-49.1 *Safety in Welding, Cutting and Allied Processes.*

VERTICAL-DOWN

A nonstandard term for DOWNHILL.

VERTICAL POSITION

See STANDARD WELDING TERMS. *See also* VERTICAL WELDING POSITION.

VERTICAL POSITION, Pipe Welding

A nonstandard term for the 2G position in pipe welding.

VERTICAL WELD

A butt or fillet weld with its linear direction vertical or inclined at an angle less than 45° to the vertical; made by fusion welding.

VERTICAL WELDING POSITION

The welding position in which the weld axis, at the point of welding, is approximately vertical, and the weld face lies in an approximately vertical plane. See STANDARD WELDING TERMS. *See* Appendix 4, Figure C.

VERTICAL-UP

A nonstandard term for UPHILL.

V-GROOVE WELD

A type of groove weld. See STANDARD WELDING TERMS. *See* Appendix 6.

VICKERS HARDNESS TEST (HV)

The Vickers hardness test is an indentation test that measures a metal's resistance to deformation using a diamond pyramid indenter. A standard method for using this method is available in ASTM E92, *Vickers Hardness of Metallic Materials. See* HARDNESS TESTING.

VISIBLE RAYS

See EYE PROTECTION.

VISUAL INSPECTION

The most extensively used nondestructive examination of weldments. It is a primary method of determining important information about conformity to specifications. Visual inspection does not normally require special equipment; however, the requirements are that the inspector is knowledgeable and has good vision.

Advantages. Visual inspection should be the primary evaluation method of any quality control program. It can, in addition to flaw detection, discover signs of possible fabrication problems in subsequent operations, and can be incorporated in process control programs. Prompt detection and correction of flaws can result in significant cost savings. Conscientious visual inspection before, during, and after welding can detect many of the discontinuities that would be found later by more expensive nondestructive examination methods.

Equipment. Auxiliary lighting equipment may be needed to assure good visibility. If the area to be inspected is not readily visible, the inspector may use mirrors, borescopes, flashlights or other aids.

Inspection of welds usually includes quantitative as well as qualitative assessment of the joint. Numerous standard measuring tools are available to make various measurements, such as joint geometry and fit-up, weld size, weld reinforcement height, misalignment, and depth of undercut. Contact pyrometers and crayons should be used to verify that the preheat and interpass temperatures called for in the welding procedure are being used.

Prior to Welding. Before welding, the base metal should be examined for conditions that tend to cause weld defects. Scabs, seams, scale, or other harmful surface conditions may be found by visual examination. Plate laminations may be observed on cut edges. Dimensions should be confirmed by measurement. Base metal should be identified by type and grade. Corrections should be made before work proceeds.

After the parts are assembled for welding, the inspector should check the weld joint for root opening, edge preparation and other features that might affect the quality of the weld. The inspector should check the following conditions for conformance to the applicable specifications:

(1) Joint preparation, dimensions, and cleanliness

(2) Clearance dimensions of backing strips, rings, or consumable inserts

(3) Alignment and fit-up of the pieces being welded

(4) Welding process and consumables

(5) Welding procedures and machine settings

(6) Specified preheat temperature

Inspection During Welding. Visual inspection is the primary method for controlling quality during welding. Some of the aspects of fabrication that can be checked include the following:

(1) Treatment of tack welds

(2) Quality of the root pass and the succeeding weld layers

(3) Proper preheat and interpass temperatures

(4) Sequence of weld passes

(5) Interpass cleaning

(6) Root condition prior to welding a second side

(7) Distortion

(8) Conformance with the applicable procedure

The most critical part of any weld is the root pass because many weld discontinuities are associated with the root area. Competent visual inspection of the root pass may detect a condition that would result in a discontinuity in the completed weld. Another critical root condition exists when second-side treatment is required of a double welded joint. This includes removal of slag and other irregularities by chipping, arc gouging, or grinding down to sound metal.

The root opening should be monitored as welding of the root pass progresses. Special emphasis should be placed on the adequacy of tack welds, clamps, or braces designed to maintain the specified root opening to assure proper joint penetration and alignment.

Inspection of successive layers of weld metal usually concentrates on bead shape and interpass cleaning, sometimes with the assistance of workmanship standards. Standards show examples of joints similar to those in manufacture in which portions of successive weld layers are shown. Each layer of the production weld may be compared with the corresponding layer of the workmanship standard. Each weld layer should be visually checked by the welder for surface irregularities and adequate interpass cleaning to avoid subsequent slag inclusions or porosity.

After Welding. The following are among the items that can be checked by visual inspection:

(1) Final weld appearance
(2) Final weld size
(3) Extent of welding
(4) Dimensional accuracy
(5) Amount of distortion
(6) Postweld heat treatment.

Most codes and specifications describe the type and size of discontinuities which can be accepted. Many of the following discontinuities on the surface of a completed weld can be found by visual inspection:

(1) Cracks
(2) Undercut
(3) Overlap
(4) Exposed porosity and slag inclusions
(5) Unacceptable weld profile.

The weld surface should be thoroughly cleaned of oxide and slag in order to accurately detect and evaluate discontinuities.

When a postweld heat treatment is specified, the operation should be monitored and documented by an inspector. Items of importance in heat treatment may include the following:

(1) Area to be heated
(2) Heating and cooling rates
(3) Holding temperature and time
(4) Temperature measurement and distribution
(5) Equipment calibration.

Discretion should be used when judging the quality of a weld from the visible appearance alone. Acceptable surface appearance does not prove careful workmanship or subsurface weld integrity; however, proper visual inspection procedures before and during fabrication can increase product reliability over that based only on final inspection.

VOLATILE

Capable of vaporizing at a relative low temperature.

VOLT

A measurement of electrical potential and electromotive force calculated between two points on a conducting wire carrying a constant current of one ampere, when the power dissipated between the points is one watt. *See* ELECTRICAL UNITS.

VOLT-AMPERE

The unit of apparent power; it is the product of volts times amperes in a given electrical circuit.

VOLT-AMPERE CURVE

A plot of output-voltage values versus output-current values usually used to describe the static characteristic of a welding power source.

Static volt-ampere characteristics are generally published by the power supply manufacturer. There is no universally recognized method by which dynamic characteristics are specified. The user should obtain assurance from the manufacturer that both the static and dynamic characteristics of the power supply are acceptable for the intended application.

Constant Current

Typical volt-ampere (V-A) output curves for a conventional constant-current power source are shown in Figure V-1. It is sometimes called a *drooper* because of the substantial downward (negative) slope of the curves. The power source might have open circuit voltage adjustment in addition to output current control. A change in either control will change the slope of the volt-ampere curve.

The effect of the slope of the V-A curve on power output is shown in Figure V-1. With curve A, which has an 80 V open circuit, a steady increase in arc voltage from 20 to 25 V (25%) would result in a decrease in current from 123 to 115 A (6.5%). The change in current is relatively small. Therefore, with a consumable electrode welding process, electrode melting rate would remain fairly constant with a slight change in arc length.

Setting the power source for 50 V open circuit and more shallow slope intercepting the same 20 V, 123 A position will give volt-ampere curve B. In this case, the same increase in arc voltage from 20 to 25 V would decrease the current from 123 to 100 A (19%), a significantly greater change. In shielded metal arc welding, the flatter V-A curve would give a skilled welder the opportunity to vary the current substantially by changing the arc length. This could be useful for out-of-position welding because it would enable the welder to control the electrode melting rate and molten pool size. Generally, however, less skilled welders would prefer the current to stay constant if the arc length should change.

Constant Voltage

A typical volt-ampere curve for a constant-voltage power source is shown in Figure V-2. This power source does not have true constant-voltage output. It

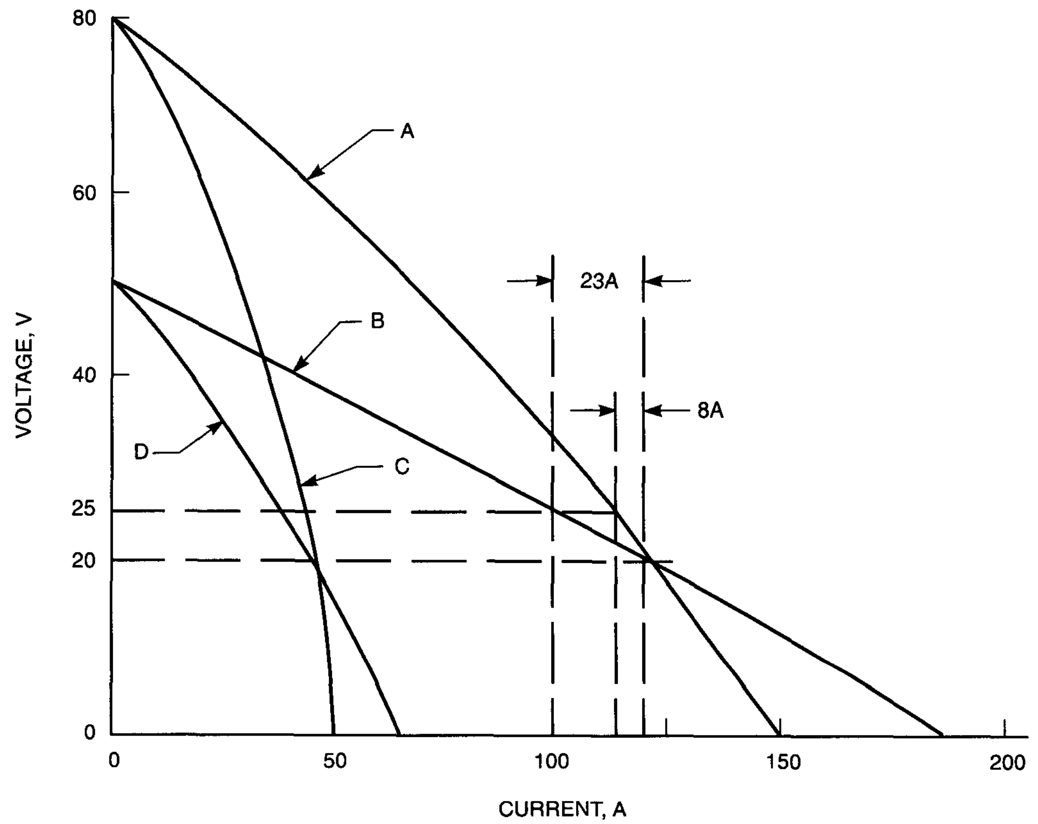


Figure V-1—Typical Volt-Ampere Characteristics of a "Drooping" Power Source with Adjustable Open Circuit Voltage

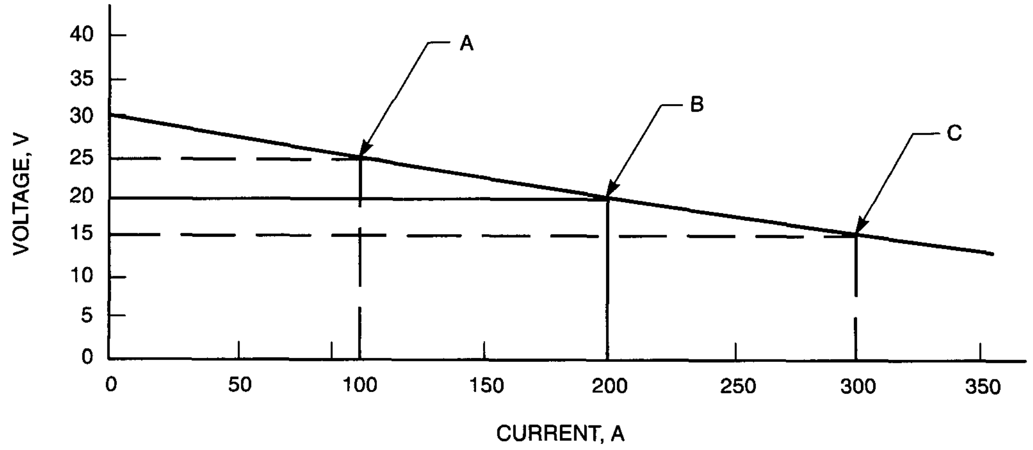


Figure V-2—Volt-Ampere Output Relationship for a Constant Voltage Power Source has a slightly downward (negative) slope because internal electrical impedance in the welding circuit causes a minor voltage drop in the output. Changing that impedance will alter the slope of the volt-ampere curve.

Starting at point B in Figure V-2, the diagram shows that an increase or decrease in voltage to A or C (5 V or 25%) produces a large change in amperage (100 A or 50%). This V-A characteristic is suitable for constant-feed electrode processes, such as gas metal arc, submerged arc, and flux cored arc welding, in order to maintain a constant arc length. A slight change in arc length (voltage) will cause a fairly large change in welding current. This will automatically increase or decrease the electrode melting rate to regain the desired arc length (voltage). This effect has been called *self regulation.* Adjustments are sometimes provided with constant-voltage power sources to change or modify the slope or shape of the V-A curve. If done with inductive devices, the dynamic characteristics will also change.

Combined Constant-Current and Constant-Voltage

Electronic controls can be designed to provide either a constant-voltage or constant-current output from a single power source so that it can be used for a variety of welding and cutting purposes.

Electronically controlled outputs can also provide output curves that are a combination of constant current and constant voltage, as shown in Figure V-3. The top part of the curve is essentially constant current; below a certain trigger voltage, however, the curve switches to constant voltage. This type of curve is beneficial for shielded metal arc welding (SMAW) to assist starting and to avoid electrode stubbing (sticking in the puddle) if a welder uses too short an arc length.

VOLTAGE, ARC

The voltage across the arc; i.e., the voltage across the gaseous zone of the welding arc; it varies with the length of the arc.

VOLTAGE DROP

The difference in voltage between two points in an electric circuit caused by resistance opposing the flow of current.

VOLTAGE, OPEN CIRCUIT

The voltage between the terminals of the welding power source when no current is flowing in the welding circuit.

VOLTAGE, WELDING ARC

The voltage measured between the electrode holder and the base metal immediately adjacent to the arc. It is the sum of the arc-stream voltage, the cathode drop, the anode drop, the drop in the electrode and the contact drop between the electrode holder and the electrode.

VOLTAGE REGULATOR

An automatic electrical control device for maintaining a constant voltage supply to the primary of a welding transformer. See STANDARD WELDING TERMS.

VOLTMETER

An instrument which measures voltage.

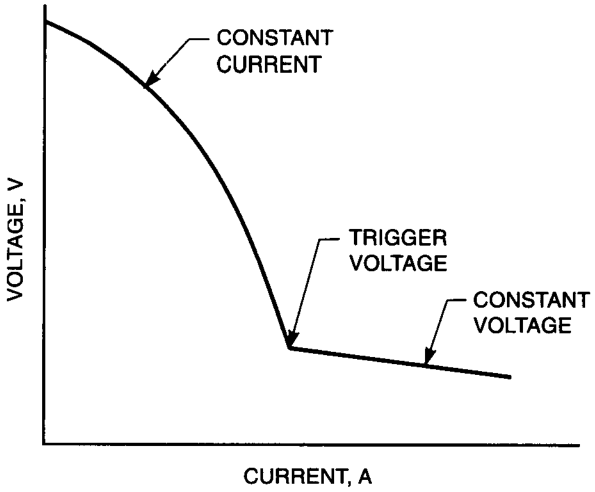


Figure V-3—Combination Volt-Ampere Curve

W

WARP

A state of being bent or twisted out of true, or out of alignment. The amount of warp that occurs during welding of sheet and plate material depends on the amount of heat that spreads away from the weld and through the parent metal. Some warping occurs when welding heat relieves strains left in the metal after rolling. Warping can be reduced by using jigs, chill bars, and plates to absorb excess heat. The backstep weld sequence also helps reduce warp. *See* EXPANSION AND CONTRACTION; SHEET METAL WELDING, PREHEAT, *and* BACKSTEP SEQUENCE.

WASHING

Melting the surplus metal on the outer surface of a weld to obtain an esthetically pleasing weld and to ensure complete fusion.

WASTER PLATE

See STACK CUTTING *and* THERMAL CUTTING.

WATERGLASS

See SODIUM SILICATE.

WATER JET CUTTING

Water jet cutting, also called *hydrodynamic machining*, severs metals and other materials using a high-velocity water jet. The jet is formed by forcing water through a 0.1 to 0.6 mm (0.004 to 0.024 in.) diameter orifice in a man-made sapphire under high pressure (207 to 414 MPa [30 000 to 60 000 psi]). Jet velocities range from 520 to 914 m/s (1700 to 3000 ft/s). At these speeds and pressures the water erodes many materials rapidly, acting like a saw blade. The water stream, with a flow rate of 0.4 to 19 L/min (0.1 to 5 gal/min), is usually manipulated by a robot or gantry system, but small workpieces may be guided manually past a stationary water jet.

Metals and other hard materials are cut by adding an abrasive in powder form to the water stream. With this method, called *hydroabrasive machining* or *abrasive jet machining*, the abrasive particles (often garnet) are accelerated by the water and accomplish most of the cutting. Higher flow rates of water are required to accelerate the abrasive particles.

Materials are cut cleanly, without ragged edges (unless the traverse speed is too high), without heat, and generally faster than on a band saw. A narrow, 0.8 to 2.5 mm (0.030 to 0.100 in.), smooth kerf is produced. There is no problem of thermal delamination, or deformation, when water jet cutting is properly applied.

The wide application range and lack of heat are the major advantages of water jet cutting. The versatility of the process is demonstrated by the simultaneous cuts through carbon steel, brass, copper, aluminum, and stainless steel shown in Figure W-1.

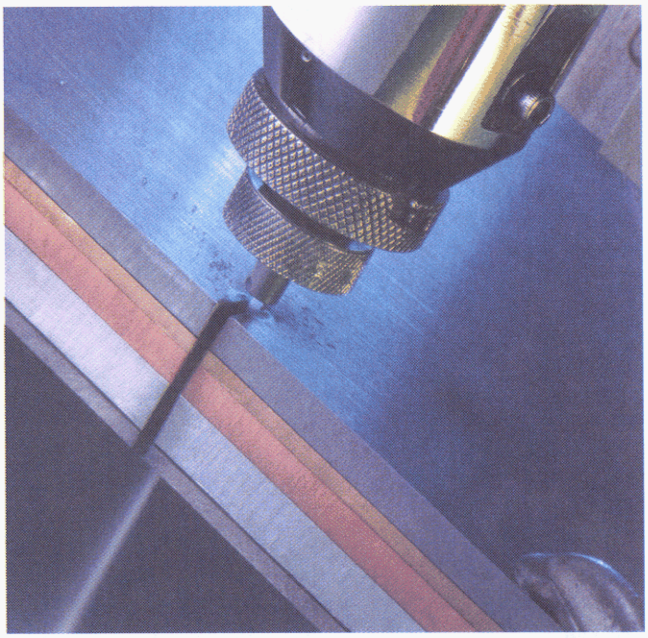


Figure W-1—Abrasive Water Jet Stack Cutting of Various Metals

Water jet and abrasive water jet systems compete with such processes as band saws, the reciprocating knife, flame cutting, plasma, and laser cutting. They can handle materials that are damaged by heat from thermal processes, or materials that gum up mechanical cutting tools. In some cases, they can cost-effectively replace three operations: rough-cutting, milling, and deburring of contoured shapes. The wide range of materials which may be cut appears in Table W-1.

Table W-1
Cutting Speeds on Various Materials with Abrasive Water Jet

Material	Thickness		Travel Speed	
	mm	in.	mm/s	in./min.
Aluminum	3.2	0.125	17	40
Aluminum	12.7	0.50	8	18
Aluminum	19.0	0.75	2	5
Brass	3.2	0.125	8.5	20
Brass	10.8	0.425	2	5
Bronze	25.4	1.0	0.5	1
Copper	1.6	0.063	15	35
Copper	15.9	0.625	3	8
Lead	50.8	2.0	3	8
Carbon steel	19.1	0.75	3	8
Cast iron	38.1	1.5	0.5	1
Stainless steel	2.5	0.1	11	25
Stainless steel (304)	25.4	1.0	2	4
Stainless steel (304)	101.6	4.0	0.5	1
Armor plate	19.1	0.75	4	10
Inconel	15.9	0.625	3	8
Inconel 718	31.8	1.25	0.5	1
Titanium	0.6	0.025	25	60
Titanium	12.7	0.500	5	12
Tool steel	6.4	0.250	4	10
Ceramic (99.6% aluminum)	0.6	0.025	2.5	6
Fiberglass	2.5	0.100	85	200
Fiberglass	6.4	0.250	42	100
Glass	6.4	0.250	42	100
Glass	19.1	0.75	17	40
Graphite/epoxy	6.4	0.250	34	80
Graphite/epoxy	25.4	1.0	6	15
Kevlar	9.5	0.375	17	40
Kevlar	25.4	1.0	1.3	3
Lexan	12.7	0.5	5	12
Metal-matrix composite	3.2	0.125	13	30
Pheonolic	12.7	0.5	4	10
Plexiglass	4.4	0.175	21	50
Rubber belting	7.6	0.300	85	200

WATER SEAL

A hydraulic protective device installed in an acetylene pipeline to provide positive flashback protection. The liquid seal quenches flashbacks and prevents them from reaching other parts of the piping system.

WATER WASH

The forcing of exhaust air and fumes from a spray booth through water so that the vented air is free of thermal sprayed particles or fumes. See STANDARD WELDING TERMS.

WATT

A unit of electric power equal to voltage multiplied by amperage. One horsepower is equal to 746 watts. Named for J. Watt, a Scottish engineer, a watt is a unit of power consumption that standardizes and allows comparison between different rates of consumption.

WATT HOUR

A unit of work or energy equivalent to the power of one watt operating for one hour.

WATT HOUR METER

An instrument that records watt-hours of power consumption.

WAVE SOLDERING (WS)

An automatic soldering process where workpieces pass through a wave of molten solder. See STANDARD WELDING TERMS. *See* DIP SOLDERING.

WAX PATTERN, Thermite Welding

Wax molded around the workpieces to the form desired for the completed weld. See STANDARD WELDING TERMS.

WEAVE BEAD

A type of weld bead made with transverse oscillation. See STANDARD WELDING TERMS.

WEAVING

A technique of depositing weld metal in which the electrode sweeps back and forth across the joint in a semi-circular motion. Weaving increases the width of the deposit, decreases overlap and assists slag formation. Sometimes called *wash welding. See* WEAVE BEAD.

WELD

A localized coalescence of metals or nonmetals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler material. See STANDARD WELDING TERMS.

WELDABILITY

The capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service. See STANDARD WELDING TERMS.

WELD AXIS

A line through the length of the weld, perpendicular to and at the geometric center of its cross section. See STANDARD WELDING TERMS.

WELD BEAD

A weld resulting from a pass. See STANDARD WELDING TERMS. *See also* STRINGER BEAD *and* WEAVE BEAD.

WELD BONDING

A resistance spot welding process variation in which the spot weld strength is augmented by adhesive at the faying surfaces. See STANDARD WELDING TERMS.

WELD BRAZING

A joining method that combines resistance welding with brazing. See STANDARD WELDING TERMS.

WELD CLEANING

See EDGE PREPARATION.

WELD CORROSION

In stainless steel, a condition of lowered resistance to corrosion caused by carbide precipitation.

When stainless steel that has not been stabilized with titanium or another stabilizing element is heated to a temperature ranging between 500 and 900°C (930 and 1650°F), which occurs during welding, chromium carbide precipitates along the grain boundaries, reducing the corrosion resistance at these locations. The corrosion does not occur in the weld itself but in the heat-affected zone adjacent to the weld. This loss of corrosion resistance can be eliminated by heat treating. The welded part should be heated to 1100°C (2010°F) and quenched in water.

WELD CRACK

A crack located in the weld metal or heat-affected zone. See STANDARD WELDING TERMS. *See also* Appendix 9.

WELD DELAY TIME

In spot and projection welding, a delay in the weld process that ensures the proper sequence of mechanical functions in relation to electrical functions.

WELDED SCULPTURE

Art created through the use of a welding process. Welding is a highly adaptable and versatile medium for the artist or sculptor. Many different materials and areas of creativity are possible. Artwork can be created by joining material to build an object, or by removing material from larger pieces to achieve a desired effect. Many sculptors use a combination of the two techniques, using both arc and oxyfuel gas welding and cutting.

The use of welding techniques in modern sculpture has developed gradually. Until recently, artists used age-old methods of casting to create three-dimensional metal figures.

Pablo Picasso was one of the first artists to experiment with welding. Through the ages, the development of sculpture has essentially been a concern with mass, space and volume, leaving linear expression to the draftsman or painter. However, during the 1930s two very distinct movements with strongly opposed philosophies were creating the new ideas that would liberate sculpture from the restrictions of the foundry. One group, the Surrealists, commanded the most immediate attention with their attempts to suggest the activities of the subconscious mind. The second group, the Constructives, achieved the most far-reaching technical influence with their concern for the formal arrangement of planes expressed through modern industrial materials. Both of these schools of thought had numerous and talented practitioners, and these basic approaches continue to influence welded sculpture.

In the past, much of the welded sculpture had been produced with the oxyacetylene torch. Currently, the well-equipped sculptor probably has a small SMAW or GMAW outfit in his studio for creating artwork from materials such as aluminum and stainless steel, as well as the mild steels. An example of welded sculpture is shown in Figure W-2.

WELDER

One who performs manual or semiautomatic welding. See STANDARD WELDING TERMS.

Figure W-2—Orpheus, a Welded Bronze Sculpture by Richard Hunt

WELDER CERTIFICATION

Written verification that a welder has produced welds meeting a prescribed standard of welder performance. See STANDARD WELDING TERMS. *See also* CERTIFIED WELDER.

WELDER PERFORMANCE QUALIFICATION

The demonstration of a welder's ability to produce welds meeting prescribed standards. See STANDARD WELDING TERMS.

Welder, welding operator, and tack welder qualification tests determine the ability of the persons tested to produce acceptably sound welds with the process, materials, and procedure called for in the tests. Qualification tests are not intended to be used as a guide for welding during actual construction, but rather to assess whether an individual has a required minimum level of skill to produce sound welds. The tests cannot foretell how an individual will perform on a particular production weld. For this reason, complete reliance should not be placed on qualification testing of welders. The quality of production welds should be determined during and following completion of actual welding.

Various codes, specifications, and governing rules generally prescribe similar, though frequently somewhat different, methods for qualifying welders, welding operators, and tack welders. The applicable code or specification should be consulted for specific details and requirements. *See* QUALIFICATION AND TESTING.

WELDER REGISTRATION

The act of registering a welder certification or a photostatic copy of the welder certification. See STANDARD WELDING TERMS.

WELD FACE

The exposed surface of a weld on the side from which welding was done. See STANDARD WELDING TERMS. *See* Figure W-3.

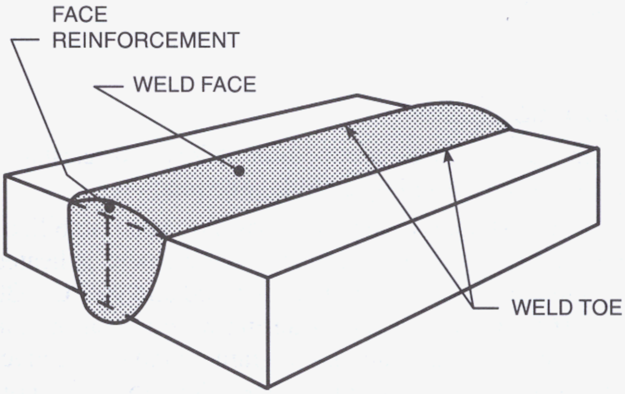


Figure W-3—Certain Parts of a Weld

WELD FACE UNDERFILL

See STANDARD WELDING TERMS. *See* Appendix 8, (E) *and* (F). *See also* UNDERFILL.

WELD GAUGE

A device designed for measuring the shape and size of welds. See STANDARD WELDING TERMS.

WELD GROOVE

A channel in the surface of a workpiece or an opening between two joint members that provides space to contain a weld. See STANDARD WELDING TERMS. *See* Appendix 6.

WELDING

A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal. See STANDARD WELDING TERMS. *See also* Appendix 3, Master Chart of Welding and Allied Processes.

WELDING ARC

A controlled electrical discharge between the electrode and the workpiece that is formed and sustained by the establishment of a gaseous conductive medium, called an "arc plasma." See STANDARD WELDING TERMS.

WELDING BLOWPIPE

A nonstandard term for OXYFUEL GAS WELDING TORCH.

WELDING, BUTT

Welding that joins metal along the edges, without involving planar surfaces. *See* BUTT WELD *and* WELD JOINT.

WELDING CABLE

An insulated conductor, usually copper, that carries electric current from the welding power supply to the torch and then from the workpiece back to the power supply. Cables should be inspected periodically to assure that insulation is not cracked or damaged and that fittings are tight.

The diameter or size of cable required for a given application depends on the welding or cutting current and the distance from the power supply to the work site. Recommended cable sizes are listed in Table C-1.

The use of the steel frame of a building in place of a copper workpiece cable is a widespread but poor practice. This is especially true if the frame of the building is riveted. In this case there is likely to be a considerable voltage drop across riveted joints, and this drop will vary as the riveted connections warm up due to I^2R heating. Weld quality is almost certain to suffer from this practice; it is far better to use a copper cable as the workpiece lead.

WELDING CURRENT

See STANDARD WELDING TERMS. *See also* AUTOMATIC ARC WELDING CURRENT *and* RESISTANCE WELDING CURRENT.

Current for welding is controlled by a welding power source. The typical output of a welding power source may be alternating current, direct current, or both. It may be either constant current, constant voltage or both. It may also provide a pulsing output mode. Selecting the correct power source depends on the current output required for each of the arc welding processes. *See* VOLT-AMPERE CURVE.

WELDING CYCLE

The complete series of events involved in the making of a weld. See STANDARD WELDING TERMS. *See* Appendix 19.

WELDING ELECTRODE

A component of the welding circuit through which current is conducted and that terminates at the arc, molten conductive slag, or base metal. See STANDARD WELDING TERMS. *See also* ARC WELDING ELECTRODE, CARBON ELECTRODE, COVERED ELECTRODE, ELECTROSLAG WELDING ELECTRODE, FLUX CORED ELECTRODE, METAL CORED ELECTRODE, METAL ELECTRODE, RESISTANCE WELDING ELECTRODE, *and* TUNGSTEN ELECTRODE.

Electrodes used for welding carbon steels and alloy steels have been standardized by the specifications of the American Welding Society. ANSI/AWS A5.1, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding* covers electrodes for welding mild steel. Low-alloy steels appear under ANSI/AWS A5.5, *Specification for Low Alloy Steel Covered Arc Welding Electrodes.*

ANSI/AWS A5.4, *Specification for Stainless Steel Welding Electrodes for Shielded Metal Arc Welding* covers stainless steel arc welding electrodes with various nickel and chromium contents. *See* STEEL, STAINLESS, Arc Welding.

Copper and copper bearing alloy arc welding electrodes appear under ANSI/AWS A5.7, *Specification for Copper and Copper Alloy Bare Welding Rods and Electrodes. See* COPPER ALLOY WELDING.

Aluminum arc welding electrodes appear under ANSI/AWS A5.3, *Specification for Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding. See* ALUMINUM. *See also* ELECTRODES.

WELDING FILLER METAL

The metal or alloy to be added in making a weld joint that alloys with the base metal to form weld metal in a fusion welded joint. See STANDARD WELDING TERMS.

WELDING FITTING

See PIPE WELDING, Forged Fittings for Welding.

WELDING FORCE

See STANDARD WELDING TERMS. *See also* DYNAMIC ELECTRODE FORCE, ELECTRODE FORCE, FORGE FORCE, FRICTION WELDING FORCE, STATIC ELECTRODE FORCE, THEORETICAL ELECTRODE FORCE, *and* UPSET FORCE.

WELDING FUMES

Welders, welding operators, and other persons in the area must be protected from overexposure to fumes and gases produced during welding, brazing, soldering, and cutting. Overexposure is exposure that is hazardous to health, and exceeds the permissible limits specified by a government agency. Such recognized authorities are the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), Regulations 29 CFR 1910.1000; the American Conference of Governmental Industrial Hygienists (ACGIH) in its publications *Threshold Limit Values for Chemical Substances* and *Physical Agents in the Workroom Environment.* Persons with special health problems may have unusual sensitivity that requires even more stringent protection.

Fumes and gases are usually a greater concern in arc welding than in oxyfuel gas welding, cutting, or brazing because a welding arc may generate a larger volume of fume and gas, and greater varieties of materials are usually involved.

Protection from excess exposure is usually accomplished by ventilation. Where exposure would exceed permissible limits with available ventilation, respiratory protection must be used. Protection must be provided not only for the welding and cutting personnel but also for other persons in the area.

Refer to *Industrial Ventilation, A Manual of Recommended Practice*, Cincinnati: American Conference of Governmental Industrial Hygienists (latest edition).

Arc Welding. Fumes and gases from arc welding and cutting cannot be classified simply. Their composition and quantity depend on the base metal composition; the process and consumables used; coatings on the work, such as paint, galvanizing, or plating; contaminants in the atmosphere, such as halogenated hydrocarbon vapors from cleaning and degreasing activities; and other factors.

Various gases are generated during welding. Some are a product of the decomposition of fluxes and electrode coatings. Others are formed by the action of arc heat or ultraviolet radiation emitted by the arc on atmospheric constituents and contaminants. Potentially hazardous gases include carbon monoxide, oxides of nitrogen, ozone, and phosgene or other decomposition products of chlorinated hydrocarbons, such as phosgene.

Helium and argon, although chemically inert and nontoxic, are simple asphyxiants, and could dilute the atmospheric oxygen concentration to potentially harmful low levels. Carbon dioxide (CO_2) and nitrogen can also cause asphyxiation.

Ozone may be generated by ultraviolet radiation from welding arcs. This is particularly true with gas shielded arcs, especially when argon is used. Photochemical reactions between ultraviolet radiation and chlorinated hydrocarbons result in the production of phosgene and other decomposition products.

Exposure Factors. The single most important factor influencing exposure to fume is the position of the welder's head with respect to the fume plume. When the head is in such a position that the fume envelops the face or helmet, exposure levels can be very high. Therefore, welders must be trained to keep their heads to one side of the fume plume. In some cases, the work can be positioned so the fume plume rises to one side.

Ventilation. Ventilation has a significant influence on the amount of fumes in the work area, and hence the welder's exposure. Ventilation may be local, where the fumes are extracted near the point of welding, or general, where the shop air is changed or filtered. The appropriate type will depend on the welding process, the material being welded, and other shop conditions. Adequate ventilation is necessary to keep the welder's exposure to fumes and gases within safe limits.

The bulk of fume generated during welding and cutting consists of small particles that remain suspended in the atmosphere for a considerable time. As a result, fume concentration in a closed area can build up over time, as can the concentration of any gases evolved or used in the process. The particles eventually settle on the walls and floor, but the settling rate is low compared to the generation rate of the welding or cutting processes. Therefore, fume concentration must be controlled by ventilation.

Adequate ventilation is the key to control of fumes and gases in the welding environments. Natural, mechanical, or respirator ventilation must be provided for all welding, cutting, brazing, and related operations. The ventilation must ensure that concentrations of hazardous airborne contaminants are maintained below recommended levels. These levels must be no higher than the allowable levels specified by the U.S. Occupational Safety and Health Administration or other applicable authorities.

Respiratory Protective Equipment. Where natural or mechanical ventilation is not adequate or where protection from toxic materials require a supplement to ventilation, respiratory protective equipment must be used. Respirators with air lines, or face masks that give protection against all contaminants are generally preferred. Air-supplied welding helmets are also available commercially. Filter-type respirators, approved by the U.S. Bureau of Mines for metal fume, give adequate protection against particulate contaminants that are less toxic than lead, provided they are used and maintained correctly. Their general use is not recommended, however, because of the difficulty in assuring proper use and maintenance. They will not protect against mercury vapor, carbon monoxide, or nitrogen dioxide. For these hazards an air line respirator, hose mask, or gas mask is required.

Special Ventilation Situations

Welding in Confined Spaces. Special consideration must be given to the safety and health of welders and other workers in confined places. Gas cylinders must be located outside of the confined space to avoid possible contamination of the space with leaking gases or volatile material. Welding power sources should also be located outside to reduce danger of engine exhaust and electric shock.

A means for removing persons quickly in case of emergency must be provided. Safety belts and lifelines, when used, should be attached to the worker's body in a manner that avoids the possibility of the person becoming jammed in the exit. A trained helper should be stationed outside the confined space with a preplanned rescue procedure to be put into effect in case of emergency.

Welding of Containers. Welding or cutting on the outside or inside of containers or vessels that have held dangerous substances presents special hazards. Flammable or toxic vapors may be present, or may be generated by the applied heat. The immediate area outside and inside the container should be cleared of all obstacles and hazardous materials.

When repairing a container in place, entry of hazardous substances released from the floor or the soil beneath the container must be prevented. The required air-supplied respirators or hose masks are those accepted by the U.S. Bureau of Mines or other recognized agency. For more complete procedures, refer to AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting Containers that Have Held Hazardous Substances.* Miami: American Welding Society (latest edition). When welding or cutting inside of vessels that have held dangerous materials, the precautions for confined spaces must also be observed.

Highly Toxic Materials. Certain materials which are sometimes present in consumables, base metals, coatings, or atmospheres for welding or cutting operations, have permissible exposure limits of 1.0 mg/m^3 or less. Among such materials are the following metals and their compounds:

(1) Antimony
(2) Arsenic
(3) Barium
(4) Beryllium
(5) Cadmium
(6) Chromium
(7) Cobalt
(8) Copper
(9) Lead
(10) Manganese
(11) Mercury
(12) Nickel
(13) Selenium
(14) Silver
(15) Vanadium

Base metals and filler metals that may release some of these materials as fume during welding or cutting are shown in Table W-2.

Manufacturer's Material Safety Data Sheets should be consulted to determine if any of these highly toxic materials are present in welding filler metals and fluxes being used. Material Safety Data Sheets should be requested from suppliers. However, welding filler metals and fluxes are not the only source of these materials. They may also be present in base metals, coatings, or other sources in the work area. Radioactive materials under Nuclear Regulatory Commission jurisdiction require special considerations.

Table W-2
Possible Toxic Materials Evolved During Welding or Thermal Cutting

Base or Filler Metal	Evolved Metals or Their Compounds
Carbon and low alloy steels	Chromium, manganese, vanadium
Stainless steels	Chromium, manganese, nickel
Manganese steels and hardfacing materials	Chromium, cobalt, manganese, nickel, vanadium
High copper alloys	Beryllium, chromium, copper, lead, nickel
Coated or plated steel or copper	Cadmium*, chromium, copper, lead, nickel, silver

*When cadmium is a constituent in a filler metal, a warning label must be affixed to the container or coil. Refer to ANSI/ASC Z49.1, *Safety in Welding and Cutting*. New York: American Standards Institute (latest edition).

When toxic materials are encountered as designated constituents in welding, brazing or cutting operations, special ventilation precautions must be taken to assure that the levels of these contaminants in the atmosphere are at or below the limits allowed for human exposure. All persons in the immediate vicinity of welding or cutting operations involving toxic materials must be similarly protected. Unless atmospheric tests under the most adverse conditions establish that exposure is within acceptable concentrations, the following precautions must be observed.

Confined Spaces. Whenever any toxic materials are encountered in confined space operations, local exhaust ventilation and respiratory protection must be used.

Indoors. When any toxic materials are encountered in indoor operations, local exhaust (mechanical) ventilation must be used. When beryllium is encountered, respiratory protection in addition to local exhaust ventilation is essential.

Outdoors. When any toxic materials are encountered in outdoor operations, respiratory protection approved by the Mine Safety and Health Association (MSHA) the National Institute of Occupational Safety and Health (NIOSH), or other approving authority may be required.

Persons should not consume food in areas where fumes that contain materials with very low allowable exposure limits may be generated. They should also practice good personal hygiene, such as washing hands before touching food, to prevent ingestion of toxic contaminants.

Fluorine Compounds. Fumes and gases from fluorine compounds can be dangerous to health, and can burn the eyes and skin on contact. Local mechanical ventilation or respiratory protection must be provided when welding, brazing, cutting, or soldering in confined spaces involving fluxes, coatings, or other material containing fluorine compounds.

When such processes are employed in open spaces, the need for local exhaust ventilation or respiratory protection will depend upon the circumstances. Such protection is not necessary when air samples taken in breathing zones indicate that all fluorides are within allowable limits. However, local exhaust ventilation is always desirable for fixed-location production welding and for all production welding of stainless steels when filler metals or fluxes containing fluorides are used.

Fumes Containing Zinc. Compounds may produce symptoms of nausea, dizziness, or fever (sometimes called "metal fume fever"). Welding or cutting where zinc may be present in consumables, base metals, or coatings should be done as described for fluorine compounds.

Measurement of Exposure

The American Conference of Governmental Industrial Hygienists (ACGIH) and the U.S. Department of Labor, Occupational Health and Safety Administration (OSHA) have established allowable limits of airborne contaminants. They are called *threshold limit values* (TLVs), or permissible exposure limits (PELs).

The TLV (a registered trade mark of the ACGIH) is the concentration of an airborne substance to which most workers may be repeatedly exposed, day after day, without adverse effect. In adapting these to the working environment, a TLV-TWA (Threshold Limit Value-Time Weighted Average) quantity is defined. TLV-TWA is the time weighted average concentration for a normal 8-hour workday or 40-hour workweek to which nearly all workers may be repeatedly exposed without adverse effect. TLV-TWA values should be used as guides in the control of health hazards, and should not be interpreted as sharp lines between safe and dangerous concentrations.

TLVs are revised annually as necessary. They may or may not correspond to OSHA permissible exposure limits (PEL) for the same materials. In many cases, current ACGIH values for welding materials are more stringent than OSHA levels.

The only way to assure that airborne contaminant levels are within the allowable limits is to take air samples at the breathing zones of the personnel involved. An operator's actual on-the-job exposure to welding fume should be measured following the guidelines provided in ANSI/AWS F1.1, *Method for Sampling Airborne Particulates Generated by Welding and Allied Processes.* This document describes how to obtain an accurate breathing zone sample of welding fume for a particular welding operation. Both the amount of the fume and the composition of the fume can be determined in a single test using this method. Multiple samples are recommended for increased accuracy. When a helmet is worn, the sample should be collected inside the helmet in the welder's breathing zone.

WELDING GENERATOR

A generator used for supplying current for welding. See STANDARD WELDING TERMS.

WELDING GROUND

A nonstandard and incorrect term for WORKPIECE CONNECTION.

WELDING GOGGLES

Goggles with tinted lenses, used during welding or oxygen cutting, which protect the eyes from harmful radiation and flying particles. *See* Appendix 18.

WELDING HEAD

The part of a welding machine in which a welding gun or torch is incorporated. See STANDARD WELDING TERMS.

WELDING HELMET

A device equipped with a filter plate designed to be worn on the head to protect eyes, face, and neck from arc radiation, radiated heat, spatter or other harmful matter expelled during some welding and cutting processes. See STANDARD WELDING TERMS.

Helmets are generally constructed of pressed fiber or fiberglass insulating material. A helmet should be light in weight and should be designed to give the welder the greatest possible comfort. Some helmets have an optional "flip lid," a dark filter plate covering the opening in the shield. It can be flipped up so the welder can see to chip slag from the weld and be protected from flying slag. Slag can cause serious injury if it strikes a person, particularly while it is hot. It can be harmful to the eyes whether it is hot or cold.

WELDING HOOD

A nonstandard term for WELDING HELMET.

WELDING JIG

See JIG *and* FIXTURE.

WELDING LEADS

The workpiece lead and electrode lead of an arc welding circuit. See STANDARD WELDING TERMS. *See* Figure D-5.

WELDING MACHINE

Equipment used to perform the welding operation. For example, spot welding machine, arc welding machine, and seam welding machine. See STANDARD WELDING TERMS.

WELDING MACHINE

See ARC WELDER, ARC WELDING, *and* RESISTANCE WELDING.

WELDING OPERATOR

One who operates adaptive control, automatic, mechanized, or robotic welding equipment. See STANDARD WELDING TERMS.

WELDING OPERATOR QUALIFICATION (ASME B&PV Code)

When welding under the specifications of the ASME Boiler and Pressure Vessel Code, each employer is responsible for qualifying all the welders and welding operators employed by the company with responsibility for welding according to specifications of a code. However, to avoid duplication of effort, the employer may accept a Welder/Welder Operator Performance Qualification (WPQ) made by a previous employer (subject to the approval of the owner or the agent of the owner) on piping using the same or an equivalent procedure in which the essential variables are within the limits established in Section IX of the ASME Boiler and Pressure Vessel Code.

An employer accepting such qualification tests by a previous employer is required to obtain a copy of the WPQ showing the name of the employer by whom the welders or welding operators were qualified, the dates of such qualification, and evidence that the welder or welding operator has maintained qualification with Q-322 of Section IX of the Code. The employer then prepares and signs the record accepting responsibility for the ability of the welder or welding operator.

WELDING, OVERHEAD

See OVERHEAD WELDING POSITION.

WELDING POSITION

The relationship between the weld pool, joint, joint members, and welding heat source during welding. See STANDARD WELDING TERMS. *See* Appendix 4. *See also* FLAT WELDING POSITION, HORIZONTAL WELDING POSITION, OVERHEAD WELDING POSITION, *and* VERTICAL WELDING POSITION.

WELDING POWER SOURCE

An apparatus for supplying current and voltage suitable for welding. See STANDARD WELDING TERMS. *See also* CONSTANT CURRENT POWER SOURCE, CONSTANT VOLTAGE POWER SOURCE, WELDING GENERATOR, WELDING RECTIFIER, *and* WELDING TRANSFORMER.

WELDING PROCEDURE

The detailed methods and practices involved in the production of a weldment. See STANDARD WELDING TERMS. *See also* WELDING PROCEDURE SPECIFICATION.

WELDING PROCEDURE QUALIFICATION RECORD (WPQR)

A record of welding variables used to produce an acceptable test weldment and the results of tests conducted on the weldment to qualify a welding procedure specification. See STANDARD WELDING TERMS.

WELDING PROCEDURE SPECIFICATION (WPS)

A document providing the required welding variables for a specific application to assure repeatability by properly trained welders and welding operators. See STANDARD WELDING TERMS.

A WPS document contains all of the instructions required to produce a weldment. Standards such as ANSI/AWS B2.1, *Specification for Welding Procedure and Performance Qualification*; ANSI/AWS D1.1, *Structural Welding Code—Steel*; ASME *Boiler and Pressure Vessel Code,* and others specify the welding variables that are required to be addressed on the WPS. *See* STANDARD WELDING PROCEDURE SPECIFICATION.

WELDING RECTIFIER

A device in a welding power source for converting alternating current to direct current. See STANDARD WELDING TERMS.

WELDING ROD

A form of welding filler metal, normally packaged in straight lengths, that does not conduct the welding current. See STANDARD WELDING TERMS. *See* Appendix 10.

Welding rods, like welding electrodes, are designed to meet the needs of the industry. In some instances the same rod is suitable for use with either the GTAW process or oxyacetylene welding (OAW).

The use of a bare welding rod for either application is satisfactory, since the molten weld puddle is shielded. In oxyfuel gas welding, the gas envelope around the weld puddle may be carburizing, oxidizing, or neutral, depending on the gas regulation. In gas tungsten arc welding, an inert gas shields the weld puddle.

Nonferrous materials such as aluminum or bronze, when used with OAW, generally require a flux to shield the weld puddle and to clean the base metal to ensure a more satisfactory weld. The flux may be externally applied or, in some instances, may be applied by coating the rod with the flux.

The American Welding Society maintains specifications for welding rods, including those used for iron and steel, copper and copper alloy, corrosion-resistant chromium and chromium nickel, aluminum and aluminum alloy, nickel and nickel alloy, cast iron, titanium and titanium alloy, magnesium alloy, and composite surfacing. Specifications for steel rods are available from the American Welding Society in AWS A5.2, *Specification for Carbon and Low Alloy Steel Rods for Oxyfuel Welding.*

WELDING SCHEDULE

A written statement, usually in tabular form, specifying values of parameters and the welding sequence for performing a welding operation. See STANDARD WELDING TERMS.

WELDING SEQUENCE

The order of making welds in a weldment. See STANDARD WELDING TERMS.

WELDING SYMBOL

A graphical representation of a weld. See STANDARD WELDING TERMS.

Standard welding symbols are used to indicate specified welding, brazing, and nondestructive examination information on engineering drawings. The symbols convey design requirements to the welding shop in a concise manner, and provide an accurate means for welding personnel to adhere to original designs.

A welding symbol can be used, for example, to specify the type of weld, groove design, weld size, welding process, face and root contours, sequence of operations, length of weld, and other information. In cases where all information cannot be conveyed by a symbol alone, supplementary notes or dimensional details, or both, are sometimes required to provide the shop with complete requirements. The designer must be sure that the requirements are fully presented on the drawing or specifications.

Nondestructive examination requirements for welded or brazed joints can also be specified with symbols. The specific inspection methods to be used are indicated on the symbols. The appropriate inspection methods depend on the quality requirements with respect to discontinuities in welded or brazed joints.

The complete system of symbols is described in ANSI/AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, published by the American Welding Society, Miami, Florida; latest edition. This publication should be consulted when selecting the appropriate symbols for describing the desired joint and inspection requirements.

Nondestructive testing methods, procedures, and the type of discontinuities that each method will reveal are contained in ANSI/AWS B1.10, *Guide for the Nondestructive Inspection of Welds,* Miami, Florida: American Welding Society; latest edition.

In practice, most designers will need only a few of the many available symbols. The following information describes the fundamentals of the symbols and how to apply them.

Basic Weld Symbols. The terms *weld symbol* and *welding symbol* have different meanings. A weld symbol indicates the required type of weld or braze. The welding symbol includes the weld symbol and supplementary information (see Appendix 7). A complete welding symbol consists of the following elements:

(1) Reference line
(2) Arrow
(3) Basic weld symbol
(4) Dimensions and other data
(5) Supplementary symbols
(6) Finish symbols
(7) Tail
(8) Specification, process, or other references

All elements need not be used unless required for clarity.

Location of Elements. The elements of a welding symbol have standard locations with respect to each other. *See* Appendix 7.

Location Significance of Arrow. The arrow element in a welding symbol in conjunction with the reference line determines the arrow side and the other size of a weld, as shown in Appendix 7. The arrow side is always closest to the reader when viewed from the bottom of the drawing.

The symbol depicting an arrow side weld is always placed below the reference line. The weld symbol depicting an other-side weld is placed above the reference line; i.e., away from the reader. Welds on both sides of a joint are shown by placing weld symbols on both sides of the reference line.

Some weld symbols have no arrow or other-side significance. However, supplementary symbols used in conjunction with these weld symbols may have significance. For example, welding symbols for resistance spot and seam welding have no side significance, but GTAW, EBW, or other spot and seam welds may have arrow and other-side significance.

References. When a specification, process, test, or other reference is needed to clarify a welding symbol, the reference is placed in a tail on the welding symbol. For example, the letters CJP may be used in the tail of the arrow to indicate that a complete joint penetration groove weld is required, regardless of the type of weld or joint preparation. The tail may be omitted when no specification, process, or other reference is required with a welding symbol.

Dimensions. Dimensions of a weld are shown on the same side of the reference line as the weld symbol. The size of the weld is shown to the left of the weld symbol, and the length of the weld is placed on the right. If a length is not given, the weld symbol applies to that portion of the joint between abrupt changes in the direction of welding or between specified dimension lines. If a weld symbol is shown on each side of the reference line, dimensions are required to be given for each weld, even though both welds are identical.

SI units are preferred to U.S. customary units when specifying dimensions. Examples of dimensioning for typical fillet welds are shown in Appendix 7.

If a weld in a joint is to be intermittent, the length of the increments and the pitch (center-to-center spacing) are placed to the right of the weld symbol.

The location on the symbol for specifying groove weld root opening, groove angle, plug or slot weld filling depth, the number of welds required in a joint, and other dimensions are shown in Appendix 7. *See also* WELD SYMBOL.

WELDING TECHNIQUE

The details of a welding procedure that are controlled by the welder or welding operator. See STANDARD WELDING TERMS.

WELDING TERMS

Words specific to the welding industry that are used by welders and associates through common and standardized usage.

A system of standardized welding terms has been developed by the American Welding Society to accurately state and convey information. Standard welding terms are identified as such in this encyclopedia. Standard definitions following the terms are printed in italics. *See* STANDARD WELDING TERMS.

WELDING TEST POSITION DESIGNATION

A symbol representation for a fillet weld or a groove weld, the joint orientation and the welding test position. See STANDARD WELDING TERMS. *See* Appendix 4.

WELDING TIP

That part of an oxyfuel gas welding torch from which the gases issue. See STANDARD WELDING TERMS.

WELDING TORCH

See STANDARD WELDING TERMS. *See also* GAS TUNGSTEN ARC WELDING TORCH, OXYFUEL GAS WELDING TORCH, *and* PLASMA ARC WELDING TORCH.

WELDING TRANSFORMER

A transformer used for supplying current for welding. See STANDARD WELDING TERMS.

WELDING VOLTAGE

See STANDARD WELDING TERMS. *See also* ARC VOLTAGE.

WELDING WHEEL

A nonstandard term for RESISTANCE WELDING ELECTRODE.

WELDING WIRE

A form of welding filler metal, normally packaged as coils or spools, that may or may not conduct electrical current depending upon the welding process with which it is used. See STANDARD WELDING TERMS. *See also* WELDING ELECTRODE *and* WELDING ROD.

WELD INTERFACE

The interface between weld metal and base metal in a fusion weld, between base metals in a solid-state weld without filler metal, or between filler metal and base metal in a solid-state weld with filler metal. See STANDARD WELDING TERMS.

WELD INTERVAL, Resistance Welding

The total of all heat and cool times, and upslope time, used in making one multiple-impulse weld. See STANDARD WELDING TERMS. *See* Figure I-1. *See also* WELD TIME.

WELD JOINT MISMATCH

Misalignment of the joint members. See STANDARD WELDING TERMS. *See* Figure W-4.

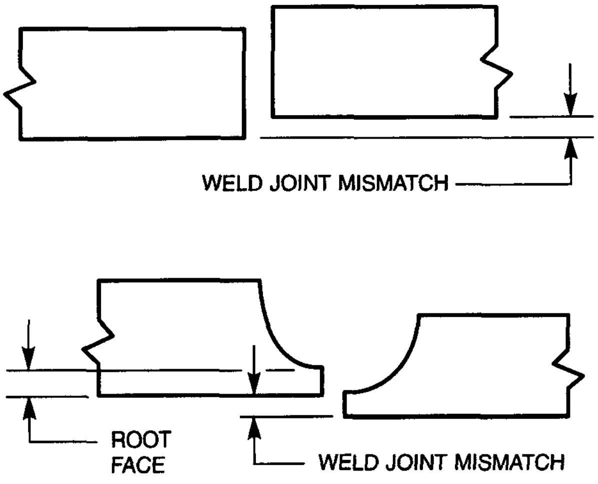


Figure W-4—Weld Joint Mismatch

WELD LINE

A nonstandard term for WELD INTERFACE.

WELDMENT

An assembly whose component parts are joined by welding. See STANDARD WELDING TERMS.

WELD METAL

Metal in a fusion weld consisting of that portion of the base metal and filler metal melted during welding.

See STANDARD WELDING TERMS. *See also* MIXED ZONE *and* UNMIXED ZONE.

Weld metal is an admixture of melted base metal and deposited filler metal, if filler is used. Typical weld metals are rapidly solidified and have a fine-grain dendritic microstructure. In most arc welding processes filler metal is added. Some welds are composed of only remelted base metal; for example, electron beam and resistance welds are made without filler metal.

Microstructure. The microstructure of weld metal is considerably different from that of the base metal of similar composition. The difference in microstructure is not related to chemical compositions, but to different thermal and mechanical histories of the base metal and the weld metal.

The structure of the base metal is a result of a hot rolling operation and multiple recrystallization of the hot-worked metal. In contrast, the weld metal has a solidified or cast structure and has not been mechanically deformed. This structure and its attendant mechanical properties are the direct result of the sequence of events that occur as the weld metal solidifies. These events include reaction of the weld metal with the gases in the vicinity of the weld and with nonmetallic liquid phases (slag or flux) during welding, and also reactions that took place in the weld after solidification.

Solidification. The unmelted portions of grains in the heat-affected zone at the solid-liquid interface serve as nucleation sites for weld metal solidification. Metals grow more rapidly in certain crystallographic directions. Therefore, favorably oriented grains grow for substantial distances, while the growth in others that are less favorably oriented is blocked by faster growing grains. As a result, weld metal often exhibits a macrostructure, described as columnar, in which the grains are relatively long and parallel to the direction of heat flow. This structure is the natural result of the influence of favorable crystal orientation on the competitive nature of solidification grain growth. Weld metal solidification of most commercial metals involves microsegregation of alloying and residual elements. This action is associated with, and in large measure, responsible for the formation of *dendrites.* A dendrite is a structural feature which reflects the complex shape taken by the liquid-solid interface during solidification.

Strengthening Mechanisms. Practical methods for strengthening weld metal are fewer than for base metal. For example, weld metal is not usually cold-worked. However, there are four mechanisms for strengthening weld metal, and where applicable, mechanisms are additive:

(1) Solidification grain structure

(2) Solid solution strengthening

(3) Transformation hardening

(4) Precipitation hardening

The first mechanism is common to all welds, and the second is applicable to any alloy type, but the third and fourth apply to only specific groups of alloys. *See* MIXED ZONE *and* UNMIXED ZONE.

WELD METAL AREA

The area of weld metal as measured on the cross section of a weld. See STANDARD WELDING TERMS. *See* Figure W-5.

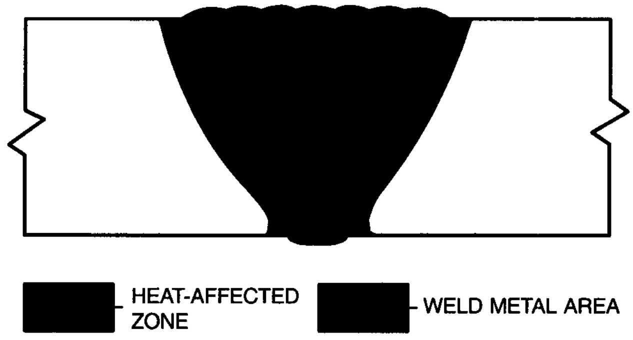


Figure W-5—Parts of a Weld

WELD METAL CRACK

See STANDARD WELDING TERMS. *See* Appendix 9.

WELD METAL ZONE (WMZ)

That portion of the weld area consisting of weld metal. See Figure W-5.

WELDOR

A nonstandard term for WELDER.

WELD PASS

A single progression of welding along a joint. The result of a pass is a weld bead or layer. See STANDARD WELDING TERMS.

WELD PASS SEQUENCE

The order in which the weld passes are made. See STANDARD WELDING TERMS. *See also* LONGITUDINAL SEQUENCE *and* CROSS-SECTIONAL SEQUENCE.

WELD PENETRATION

A nonstandard term for JOINT PENETRATION and ROOT PENETRATION.

WELD PERIOD

The time required to complete one cycle of a resistance welding operation. In pulsation welding, the weld period includes the "cool time" intervals.

WELD POOL

The localized volume of molten metal in a weld prior to its solidification as weld metal. See STANDARD WELDING TERMS.

WELD PUDDLE

A nonstandard term for WELD POOL.

WELD RECOGNITION

A function of an adaptive control that determines changes in the shape of the weld pool or the weld metal during welding, and directs the welding machine to take appropriate action. See STANDARD WELDING TERMS. *See also* JOINT RECOGNITION *and* JOINT TRACKING.

WELD REINFORCEMENT

Weld metal in excess of the quantity required to fill a joint. See STANDARD WELDING TERMS. *See also* FACE REINFORCEMENT *and* ROOT REINFORCEMENT.

WELD ROOT

The points, shown in a cross section, at which the weld metal extends furthest into a joint and intersects the base metal. See Figure W-6.

WELD SEAM

A nonstandard term for JOINT, SEAM WELD, WELD, or WELD JOINT.

WELD, SINGLE V

See V-GROOVE WELD.

WELD SIZE

See STANDARD WELDING TERMS. *See also* EDGE WELD SIZE, FILLET WELD SIZE, GROOVE WELD SIZE, PLUG WELD SIZE, PROJECTION WELD SIZE, SEAM WELD SIZE, SLOT WELD SIZE *and* SPOT WELD SIZE.

WELD SIZE GAUGE

A gauge that measures the size of a weld, the amount of convexity and the amount of reinforcement.

In Figure W-7, (A), (B), and (C) illustrate how the weld size gauge is used to determine the various dimensions of a weld.

(1) To determine the size of a fillet weld, place the gauge against the toe of the shortest leg of the fillet and slide the pointer out until it touches the structure. Read "Fillet Weld Leg Length" on the face of the gauge. *See* Figure W-7(A).

(2) To determine the size of a concave fillet weld, place the gauge against the structure and slide the pointer out until it touches the face of the fillet weld. Read "Concavity" on the face of the gauge. *See* Figure W-7(B).

(3) To determine the reinforcement of a butt weld, place the gauge so that the reinforcement will come between the legs of the gauge and slide the pointer out until it touches the face of the weld. The reinforcement is indicated on the face of the gauge. *See* Figure W-7(C).

WELD SYMBOL

A graphical character connected to the welding symbol indicating the type of weld. See STANDARD WELDING TERMS. *See also* WELDING SYMBOL.

WELD TAB

Additional material that extends beyond either end of the joint, on which the weld is started or terminated. See STANDARD WELDING TERMS. *See also* RUNOFF WELD TAB *and* STARTING WELD TAB.

WELD THROAT

See STANDARD WELDING TERMS. *See also* ACTUAL THROAT, EFFECTIVE THROAT, *and* THEORETICAL THROAT.

WELD TIME

See STANDARD WELDING TERMS. *See also* AUTOMATIC ARC WELDING WELD TIME *and* RESISTANCE WELDING WELD TIME.

WELD TOE

The junction of the weld face and the base metal. See STANDARD WELDING TERMS. *See* Figure W-2.

WELD VOLTAGE

See STANDARD WELDING TERMS. *See also* ARC VOLTAGE.

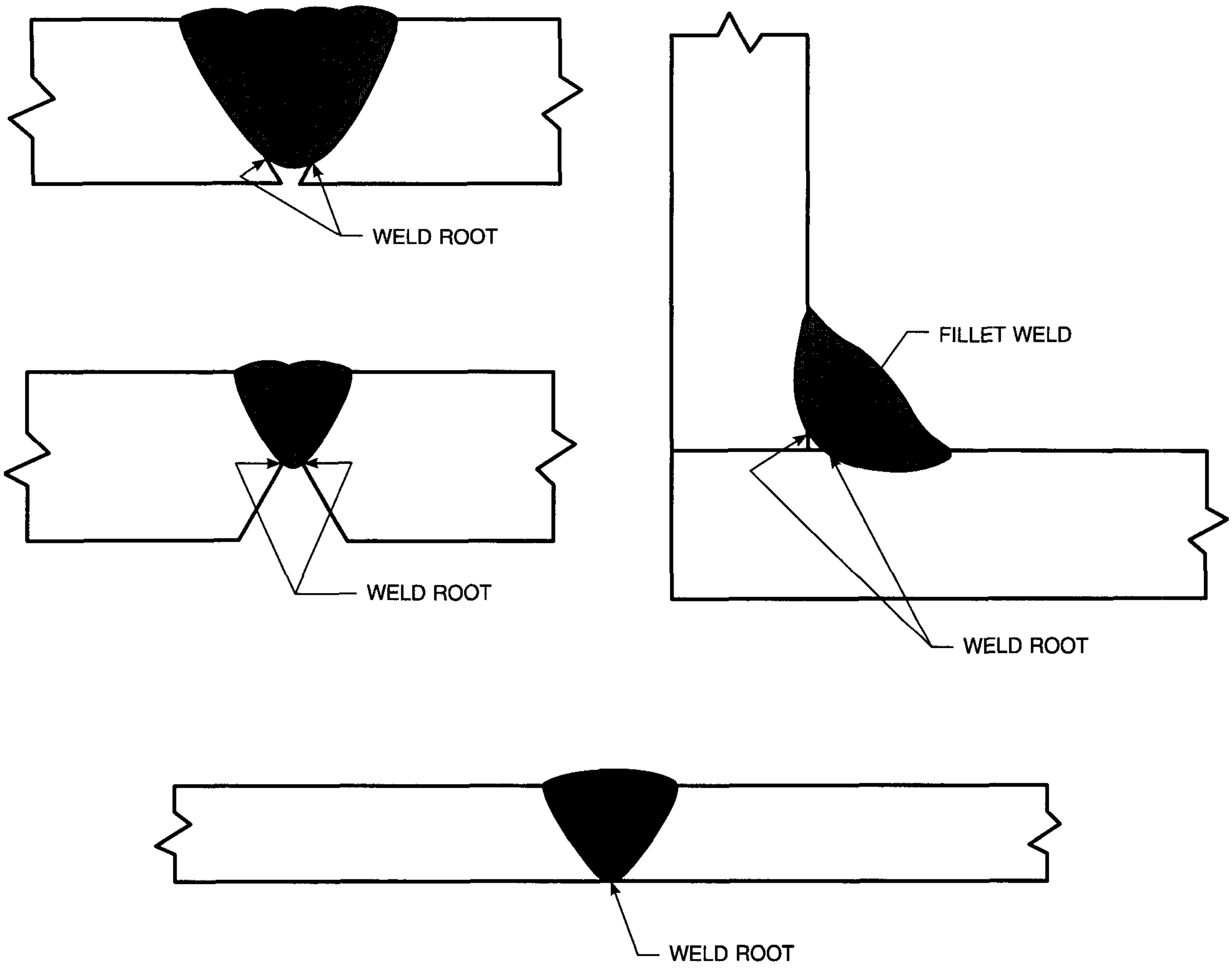


Figure W-6—Illustrations Showing Weld Roots

WELDING DEFECTS, CAUSES AND CORRECTIONS

Poor Fusion

Causes of poor fusion: Low welding current; improper weaving technique; improper electrode diameter; poor joint preparation; hurried welding speed.

Corrections: The electrode should be small enough to reach the bottom of the joint; for a given electrode, current should increase with plate thickness to properly deposit metal and penetrate the plates; weaving should sweep outward enough to melt sides of the joint; deposited metal should fuse into the plates, not curl away from them.

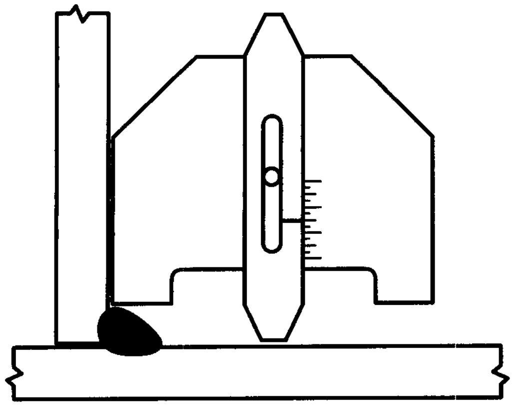
Porosity

Causes of porosity: Excessive arc length; insufficient puddling; unsound base metal; moisture in electrode coating.

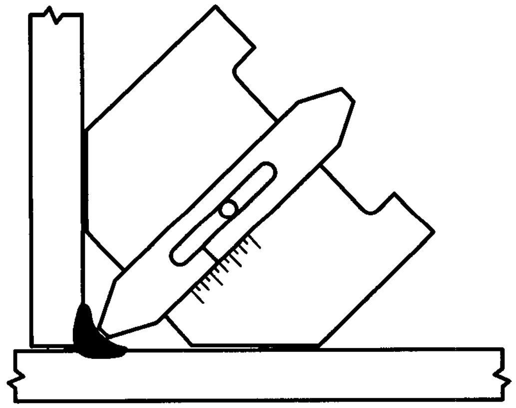
Corrections: Shorter arc required, especially on stainless steels; sufficient puddling of molten metal to allow trapped gas to escape; proper weaving technique; appropriate welding current; sound base metal selection; dry electrodes.

Incomplete Penetration

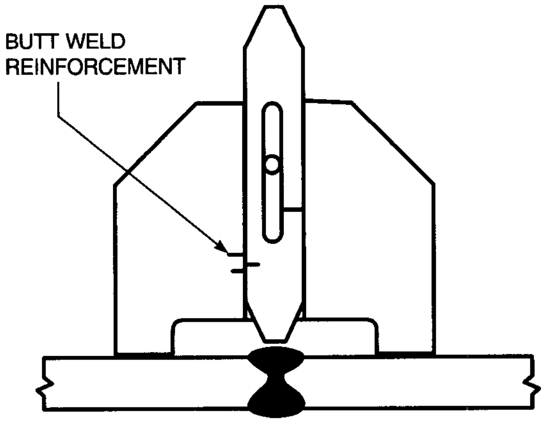
Causes of incomplete penetration: Improper joint preparation; electrode too large; insufficient welding current; hurried welding speed.



(A) MEASURING A FILLET WELD



(B) MEASURING A CONCAVE FILLET WELD



(C) MEASURING THE REINFORCEMENT OF A BUTT WELD

Figure W-7—Measuring with a Weld Size Gage

Corrections: Allow proper free space at bottom of weld; use electrodes of appropriate diameter in narrow groove; use sufficient welding current and proper welding speed; use a backup bar; chip or cut out the back of the joint and deposit a backing bead.

Brittleness

Causes of brittleness: Air-hardening of base metal; improper heating; unsatisfactory electrodes.

Corrections: Preheating of medium-carbon and certain alloy steels at 150 to 260°C (300 to 500°F); proper preheating; controlled cooling. Multiple-layer welds tend to anneal hard zones; stress relieving at 600 to 650°C (1100 to 1200°F) after welding generally softens hard areas formed during welding. Austenitic electrodes are sometimes desirable on air-hardening steels; the increased weld ductility compensates for the brittleness of the heat-affected areas in the base metal.

Arc Blow

Causes of arc blow: Magnetic fields force the arc away from the point at which it is directed, particularly at the ends of joints and in corners when welding with direct current.

Corrections: Place the workpiece connection in the direction of arc blow; clamp the workpiece cable to the work at two or more locations; weld toward the direction of the blow; hold a short arc; change the magnetic path around the arc by using steel blocks, or magnetic shunts; use a-c welding.

Undercutting

Causes of undercutting: Excessive welding current; improper electrode technique; mismatch between electrode design and weld position.

Corrections: Use a moderate welding current and proper welding speed; use an electrode that produces a puddle of the proper size; proper weaving technique; proper positioning of the electrode relative to a horizontal fillet weld. *See* UNDERCUT.

Distortion

Causes of distortion: Improper joint preparation or clamping; non-uniform heating of the parts; improper welding sequence.

Corrections: Clamp or tack parts properly to resist shrinkage; pre-form parts to compensate for weld shrinkage; distribute welding deposit to avoid localized overheating; preheat heavy structures; remove rolling or forming strains before welding; proper welding sequence, determined from a study of the structure. *See* DISTORTION.

Cracked Welds

Causes of cracked welds: Joint too rigid; welds too small for size of parts joined; poorly executed welds; improper joint preparation; unsuitable electrode.

Corrections: Design the structure and develop a welding procedure to eliminate rigid joints; design weld size appropriate to parts; make a full size weld in short sections; develop a welding sequence that leaves the ends of the joint free to move as long as possible; proper fusion; preheating; prepare uniform joints.

Irregular Surface

Causes of irregular surface: Excessive welding current; improper weaving technique; improper voltage; overheating of the workpiece; inherent characteristics of the electrode.

Corrections: Change to proper welding technique; use proper welding current; use proper voltage; use proper welding speed.

Irregular Weld Quality

Causes: Wrong electrode; improper technique; excessive current; electrode used in wrong position; improper joint design.

Corrections: Prepare the joint properly; match the electrode to the weld position; weld with uniform weave, proper rate of travel, and proper welding current.

Residual Stresses

Causes of residual stress: Joints are too rigid; improper welding sequence.

Corrections: Make the weld in several passes; peen each deposit; stress relieve finished product at 600°C to 650°C (1100°F to 1200°F) for one hour per inch of thickness; develop procedure that permits all parts to be free to move as long as possible.

Corrosion

Causes of corrosion: improper type of electrode diminishes corrosion resistance of the weld compared to the parent metal; improper weld deposit for the corrosive media; the metallurgical effect of welding; and improper cleaning of the weld.

Corrections: Use electrodes that provide equal or better corrosion resistance than the parent metal; when welding austenitic stainless steel the analysis of the steel and the welding procedure should be correct to avoid carbide precipitation: this condition can be corrected by heating to 1040°C–1150°C (1900 to 2100°F) followed by quenching; proper cleaning of materials such as aluminum to prevent corrosion.

Spatter

Causes of spatter: The inherent properties of certain electrodes; excessive welding current; the type or diameter of rod used; an excessively long arc; arc blow.

Corrections: Use proper type of electrode; proper welding current; proper arc length; reduce arc blow; use anti-spatter adjacent to the weld to prevent spalls from welding to the work.

Warping of Thin Plates

Causes of warping: Shrinkage of the deposited weld metal; local overheating at the joint; improper joint preparation; unsuitable clamping of the parts.

Corrections: Select electrode with high welding speed and moderate penetrating properties; weld rapidly to prevent over-heating of the plates adjacent to the weld; do not permit excessive space between the parts; clamp parts adjacent to the joint; use a back-up bar to cool them rapidly; use a welding sequence such as the backstep or skip procedure; peen the joint edges thinner than the body of the plate before welding. The elongated edges will pull back to the original shape when the weld shrinks.

WETTING

The phenomenon whereby a liquid filler metal or flux spreads and adheres in a thin continuous layer on a solid base metal. See STANDARD WELDING TERMS.

WHIPPING

A manual welding technique in which the arc or flame is manipulated to alternate backwards and forwards as it progresses along the weld path. See STANDARD WELDING TERMS.

WHITE METAL WELDING

The term *white metal* denotes castings that typically fall into three general classes according to their composition: zinc, aluminum, and magnesium. Lead and tin alloy castings differ because they require soldering rather than welding.

The weight of the metal identifies the type of alloy. Of the three, magnesium alloy is lightest, followed by aluminum alloy. Zinc alloy, nearly as heavy as iron, is heaviest. The commonly used aluminum and magnesium alloys melt at 585 to 645°C (1080 to 1195°F). The zinc alloys melt at 385°C (725°F).

Welding Zinc Alloy Die Castings

Total production of zinc alloy die castings is much greater than aluminum or magnesium and therefore zinc castings are more commonly encountered. Arc welding is not practical for repairing broken zinc castings because the arc temperature is so much higher than the melting point of zinc. Special techniques must be used with oxyfuel gas welding. The temperature of a neutral torch flame is about 3200°C (5800°F), although when using a considerable excess of acetylene, as this type of welding requires, the temperature of the flame is somewhat lower.

Torch Tip. Since the oxyacetylene flame is much hotter than necessary, welding this alloy requires a very small welding tip, about the size of a No. 72 drill bit.

Applying Heat. The excess acetylene flame should burn yellow but should not coat the metal with soot. The welding rod required is an alloy that will flow smoothly at the right temperature.

Since the melting temperature of the alloy is relatively low, too much heat will ruin the casting.

Joint Preparation. Preparation includes forming a V in the crack, or if broken all the way through, grinding or filing the edges to an angle of about 45°, and then lining up the parts on a carbon block. Chromium- or nickel-plated parts require the removal of plating from the weld site. Welder's clay, used as a support under the weld, prevents the metal from flowing away or sagging.

Applying heat to the casting will cause the metal to flow. Turn the flame parallel to the surface, and maintain heat with the side of the flame. Heat the welding rod to the melting point, and touch the rod to the joint; the rod should flow into the V with complete fusion. Repeat this operation until the break fills completely. Unless the rod penetrates into the weld and breaks the surface tension, the rod will lie on the surface without fusing.

Puddling is only necessary when the operator has piled the rod on top of the weld instead of fusing it to the base metal. Heat the base metal and rod to a flowing temperature, and using a bronze rod as a puddler, work the rod into the base metal. Welding these alloys requires very careful manipulation of the torch and patience from the welder.

Determine whether the metal is weldable by attempting a weld on a small part of the break where little harm will be done.

Welding Magnesium Die Castings

Magnesium die castings are the industry's lightest structural metal, weighing approximately two-thirds as much as aluminum and less than one-quarter as much as iron or steel. The low-weight characteristic is due to the high magnesium content of the alloys, which is usually between 90% and 98%.

Oxyacetylene welds on magnesium alloys require a rod and a special flux. Any flux left in the weld will promote corrosion. After welding, the part requires a thorough rinse with hot water and treatment with a chrome pickle solution. It is then ready for painting. *See* MAGNESIUM ALLOYS, Weldability.

WIDMANSTATTEN STRUCTURE

A crystal formation in the microstructure of a metal that occurs when a new solid phase forms from a parent solid phase, such as ferrite from austenite. The new phase generally develops plates parallel to lattice planes of a single form in the parent phase, as in the four families of octahedral planes in austenite. On the polished and etched surface the traces of the plates intersect in a geometrical pattern. Needles and polyhedra may also form. The orientation of the lattice in the new phase is related to the orientation of the lattice in the parent phase. This structure is frequently seen in cast steel and in overheated wrought steel that cools too quickly, but may occur in any alloy in which a phase change occurs.

WIPED JOINT

A joint made with solder having a wide melting range and with the heat supplied by the molten solder poured onto the joint. The solder is manipulated with a hand-held cloth or paddle so as to obtain the required size and contour. See STANDARD WELDING TERMS.

WIRE FEED SPEED

The rate at which wire is consumed in arc cutting, thermal spraying, or welding. See STANDARD WELDING TERMS.

WIRE FLAME SPRAYING (FLSP-W)

A thermal spraying process variation in which the surfacing material is in wire form. See STANDARD WELDING TERMS. *See also* THERMAL SPRAYING.

WIRE STRAIGHTENER

A device used for controlling the cast and helix of coiled wire to enable it to be easily fed through the wire feed system. See STANDARD WELDING TERMS.

WIRE WELDING

A term derived from the continuous welding wire that serves as an electrode in semi-automatic gas metal arc welding (GMAW) and distinguishes GMAW from shielded metal arc welding (SMAW). *See* GAS METAL ARC WELDING.

WORK ANGLE

The angle less than 90 degrees between a line perpendicular to the major workpiece surface and a plane determined by the electrode axis and the weld axis. In a T-joint or a corner joint, the line is perpendicular to the nonbutting member. This angle can also be used to partially define the position of guns, torches, rods, and beams. See STANDARD WELDING TERMS. *See also* DRAG ANGLE, PUSH ANGLE, *and* TRAVEL ANGLE.

WORK ANGLE, Pipe

The angle less than 90° between a line that is perpendicular to the cylindrical pipe surface at the point of intersection of the weld axis and the extension of the electrode axis, and a plane determined by the electrode axis and a line tangent to the pipe at the same point. In a T-joint, the line is perpendicular to the nonbutting member. This angle can also be used to partially define the position of guns, torches, rods, and beams. See STANDARD WELDING TERMS. *See also* DRAG ANGLE, PUSH ANGLE, *and* TRAVEL ANGLE.

WORK COIL

See STANDARD WELDING TERMS. *See also* INDUCTION WORK COIL.

WORK CONNECTION

A nonstandard term for WORKPIECE CONNECTION.

WORK LEAD

A nonstandard term for WORKPIECE LEAD.

WORKPIECE

The part that is welded, brazed, soldered, thermal cut, or thermal sprayed. See STANDARD WELDING TERMS.

WORKPIECE CONNECTION

The connection of the workpiece lead to the workpiece. See STANDARD WELDING TERMS. *See* Figure D-5.

WORKPIECE LEAD

The electrical conductor between the arc welding current source and workpiece connection. See STANDARD WELDING TERMS. *See* Figure D-5.

WORMHOLE POROSITY

A nonstandard term when used for PIPING POROSITY.

WRINKLE BENDING

Wrinkle bending is a technique which has been used to custom-bend sections of pipe on a job site. Using an oxyacetylene flame, the technique consists of heating one or more narrow bands of the pipe wall at right angles to the pipe axis about two thirds of the way around the pipe circumference. When these bands are heated to a red heat, the section is bent to the desired curvature, either by hand or with some mechanical means. The force required depends on the diameter and wall thickness of the pipe. Usually one section is heated at a time and bent about 20°. Additional sections are heated and bent until the required bend is obtained. When done correctly, the pipe wall extends outward and does not restrict the bore. *See* PIPE WELDING.

WROUGHT IRON

A fibrous ferrous material consisting of approximately 1 to 4% by weight of a slag component dispersed as elongated stringers in a matrix of low-carbon steel or iron. The slag consists mostly of iron oxide and some silica. The analysis of the iron matrix is about 0.03% carbon, 0.05% manganese, 0.10% phosphorus, 0.020% sulfur, and 0.01% silicon; the remainder is iron. Wrought iron can be identified by macroetch examination, which reveals numerous small stringers of non-metallic slag throughout the metal section.

The term *iron* is commonly used to describe a number of different ferrous materials. Wrought iron is different from any of the other ferrous metals, such as commercially pure iron, steel, or cast iron. The nonrusting slag fibers in wrought iron are responsible for this difference. Pure iron, steel, and cast iron do not contain slag.

WROUGHT IRON WELDING

The joining of wrought iron by fusion. Wrought iron can be welded using the arc, resistance, oxyfuel gas, and hammer welding processes.

In general, the procedure for welding wrought iron is the same as for welding mild steel, with slight modification. The fusion temperature of wrought iron is somewhat higher than that for mild steel. Fusion welding temperatures range between 1480 and 1540°C (2700 and 2800°F).

Arc Welding

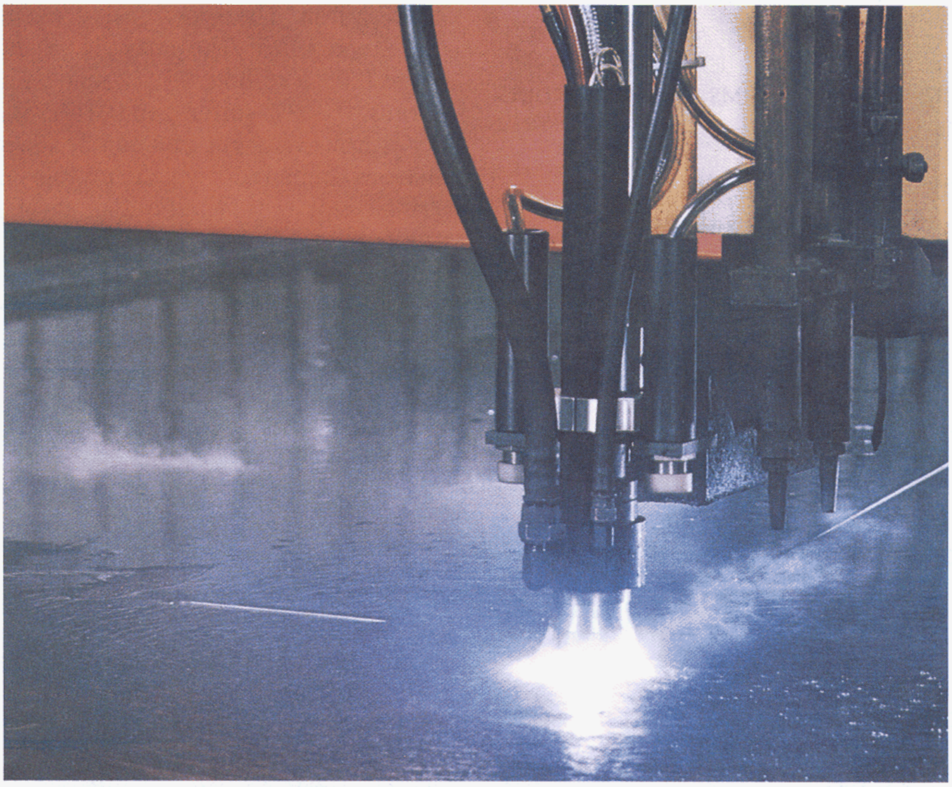
The shielded metal arc welding (SMAW), gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) processes can be used to weld wrought iron. The higher temperatures necessary for welding wrought iron are attainable by slightly decreasing the welding speed below that used for mild steel welding. At the reduced speed the pool of molten metal immediately following the arc remains molten for a longer period of time, which allows better degasification and affords removal of the entrained slag. This results in sound weld metal.

Oxyfuel Gas Welding

Wrought iron has inherently superior welding characteristics because of the self-fluxing action of the iron silicate, or slag. This self-fluxing action provides protection during heating, providing an environment conducive to a strong, uniform weld.

During the oxyfuel gas welding of most other ferrous metals, a fluxed or greasy-appearing surface occurs when the temperature is sufficiently high for fusion. In wrought iron, however, a greasy appearance occurs initially, due to the fluxing action of the slag, at temperatures between 1150 and 1200°C (2100 and 2200°F). These temperatures are below the fusion temperature of the base metal and are too low for the application of filler metal. After the "greasy" surface appears, therefore, the process requires continued heating to raise the base metal to fusion temperature.

Consistent maintenance of a puddle of molten metal is required for fusion welding. The end of the rod stays immersed as metal is deposited. The edges of the molten puddle and the surrounding colder metal fuse to form a solid joint. Metal deposition occurs only via the molten puddle, not directly from the rod. To obtain a sound weld without the oxides that produce porosity, the molten puddle must be undisturbed. Excessive puddling or agitation of the molten pool causes undue exposure of the molten metal to the atmosphere, resulting in the formation and entrapment of oxide in the weld.



Plasma arc cutting using a water shroud on the torch nozzle

Photo courtesy of Hypertherm, Inc.

X

XENON

(Chemical symbol: Xe). A rare, heavy, colorless, inert gas. Xenon is present in the atmosphere to the extent of one part in twenty million by volume. It is used in electronic control components. Atomic number, 54; atomic weight, 131.30.

X-RAY

A form of radiant energy derived from the bombardment of a material by electrons in a vacuum at a high voltage. The wave length of these rays is between 10^{-11} and 10^{-8} cm.

X-RAY TESTING OF WELDS

A nondestructive radiographic testing procedure which uses X-rays or gamma rays to penetrate the weldment or brazement to detect and indicate discontinuities. An image is rendered on photographic film, sensitized paper, a fluorescent screen, or an electronic radiation detector.

Photographic film is normally used to retain a permanent record of the test. The print from the developed film is known as a *radiograph*, and the science of making and interpreting such photos is called *radiography.* A radiograph produced by X-rays is called an *exograph.*

X-rays most suitable for welding inspection are produced by high-voltage X-ray machines. The wavelengths of the X-radiation are determined by the voltage applied between elements in the X-ray tube. Higher voltages produce X-rays of shorter wave lengths and increased intensities, resulting in greater penetrating capability. Typical applications of X-ray machines for various thickness of steel are shown in Table X-1. The penetrating ability of the machines may be greater or lesser with other metals, depending on the X-ray absorptionproperties of the particular metal. X-ray absorption properties are generally related to metal density.

The use of X-ray machines for examination of welds has been largely supplanted by various isotopes that provide a radiation source. Among them are Cobalt-60, Cesium-137, and Iridium-192. The approximate thickness limitations in steel for these radioisotopes are shown in Table X-2.

Table X-1
Approximate Thickness Limitations of Steel for X-Ray Machines

	Approximate Maximum Thickness	
Voltage, kV	**mm**	**in.**
100	8	0.33
150	19	0.75
200	25	1
250	50	2
400	75	3
1000	125	5
2000	200	8

Table X-2
Approximate Thickness Limitations of Steel for Radioisotopes

		Useful Thickness Range	
Radioisotope	**Approximate Equivalent X-Ray Machine, kV**	**mm**	**in.**
Iridium-192	800	12–65	0.5–2.5
Cesium-137	1000	12–90	0.5–3.5
Cobalt-60	2000	50–230	2.0–9.0

The advantages and limitations of the sources of radiation are shown in Table X-3.

Historical Background

In 1895 Professor Konrad Roentgen of the University of Wurtzburg, Bavaria, first observed the effects of X-radiation while passing an electric current through a vacuum tube. The Roentgen rays, as they were officially named after the discoverer, quickly became known as *X-rays* because of their enigmatic origin and qualities.

The importance of X-rays in the medical field is well known. Industrial X-ray applications lagged considerably behind medical, but by the 1930s, radiography had begun to grow into a powerful metalworking inspection tool.

Table X-3
Advantages and Limitations of Radiation Sources

Radioisotopes	X-Ray Machines
Advantages	
(1) Small and portable	(1) Radiation can be shut off
(2) No electric power required	(2) Penetrating power (kV) is adjustable
(3) No electrical hazards	(3) Can be used on all metals
(4) Rugged	(4) Radiographs have good contrast and sensitivity
(5) Low initial cost	
(6) High penetrating power	
(7) Access into small cavities	
(8) Low maintenance costs	
Limitations	
(1) Radiation emitted continuously by the isotope	(1) High initial cost
(2) Radiation hazard if improperly handled	(2) Requires source of electrical power
(3) Penetrating power cannot be adjusted	(3) Equipment comparatively fragile
(4) Radioisotope decays in strength, requiring recalibration and replacement	(4) Less portable
(5) Radiographic contrast generally lower than with x-rays	(5) Tube head usually large in size
	(6) Electrical hazard from high voltage
	(7) Radiation hazard during operation

In 1918, steel of 25 mm (1 in.) thickness represented the absolute limit of X-ray penetration. As equipment manufacturers improved the process by raising the voltage across the tube elements, however, increased thickness of metal could be radiographically examined.

H. H. Lester, a physicist at the Watertown Arsenal, Watertown, Massachusetts, was one of the pioneers in the radiography of metal sections. In 1924, Lester conducted radiographic examinations of castings which were to be installed in the United States' first 8.3 MPa (1200 psi) steam pressure power plant for the Boston Edison Company, Radiographic inspection of the welded joints of pressure vessels soon followed. In 1930, the United States Navy specified that X-ray tests must be made of the main longitudinal and circumferential joints of welded boilerdrums. Subsequently, the 1931 ASME Boiler Code made X-ray examination of welded seams mandatory for power boiler drums and other pressure vessels designed for severe service conditions. Other code requirements for X-ray testing followed.

Applications

X-ray weld testing is particularly well suited to butt joints, where weld and parent metals lie in the same plane. The rays penetrate the metal without damaging it, and the entire weld may be readily inspected.

Fundamentals

X-rays are produced in an evacuated tube through the impact of a high-velocity electron stream on a metal plate, or target, at the anode (positive electrode) of the tube. The electrons are "boiled" from the cathode (negative electrode) by means of a heated filament and are accelerated by impressing an extremely high potential (on the order of hundreds of kilovolts) across the tube. X-ray voltages may reach as high as one million volts. The currents however, are extremely low, usually on the order of 6 to 25 milliamperes.

Since they are much shorter in wave length than visible light, X-rays can penetrate solid objects. They do not, however, penetrate all objects with equal facility, but are absorbed to a degree depending on the thickness and density of the material. Since density is a function of atomic weight, the heavier metals offer the greatest resistance to the passage of X-rays. Lead, a substance with the high atomic weight of 207.20, has a very high degree of X-ray absorption and so is used as shielding against X-rays.

Like visible light, X-rays will travel in straight lines unless deflected. As a result, the projected image of an object will be accurate in size and shape. When the image is recorded on film, it becomes a "shadow picture" dependent on the thickness and density of each partthrough which the rays travel.

X-rays darken a photographic film in much the same way as visible light. The less dense regions of a weld offer the least resistance to the passage of X-rays. These portions, consequently, will show darkest when the weld is radiographed. Denser regions, offering greater X-ray resistance, will permit fewer rays to reach the film and will show as areas of comparative whiteness. The process based on this principle permits the quick detection of weld faults. Such welding defects as porosity, slag inclusion, cracks, lack of fusion, gas pockets and blowholes all show up in radiographs as dark areas.

The most important factor of any nondestructive weld test method is the ability of the inspector to correctly interpret the indications of discovered defects. Only through careful study of many radiographs exhibiting known defects can such ability be gained. The common welding faults revealed by radiographs are (in order of frequency): porosity, entrapped slag, cracks and lack of fusion.

When there are defects and the weld must be chipped out, finding the exact location and depth of the defect will facilitate the task of the welder or gouger. This can be done with double exposure radiation. In this method, exposures are made from two different angles on the same film or on separate films. The distances are measured between the two positions of the radiation source and between each position of the identification markers on the surfaces of the plate. Images of both the marker and the defect are projected on the film. By comparing the known distances and solving similar triangles, the exact location of the fault is readily found. This enables the welder to begin work on the side closest to the defect and remove, then replace, a minimum of weld metal.

X-ray Diffraction

X-ray equipment can also be used to investigate the properties of weld metals by creating and examining diffraction patterns. These are produced by localizing a narrow beam of X-rays through a tube, passing the X-rays through pinholes, then through a small, thin sample of the material to be investigated. A film held behind the sample will show a dark central spot surrounded by a collection of rays, rings, and spots. This is called the *diffraction pattern*, and its analysis makes it possible to peer into the molecular structure of matter and visualize the arrangement of the molecules themselves. Diffraction analysis is very important in the steel and alloying industries, where stresses and strains are a vital factor.

X-ray diffraction patterns can indicate the ductility of the weld metal or parent metal, and also the presence of strained areas. In practice, it is customary to make a number of patterns to determine the condition of various areas of the metal: in the center of the weld, at the edge of the weld near the line of fusion, the edge of the parent metal near the line of fusion, two or more points in the parent metal which have undergone considerable changes in temperature during welding, and finally, a point in the parent metal far enough removed from the weld so that it can safely be assumed to be unaffected by the heat. It should be noted that although only very small specimens are needed for investigation by means of diffraction patterns, considerable care must be exercised in preparing specimens to be sure that the patterns will not show conditions introduced by the method of preparation itself, which were not originally present in the specimens. *See* RADIOGRAPHIC EXAMINATION. *See also* RADIOGRAPHY.

Submerged arc welding in a shipyard

Photo courtesy of Ingalls Shipyard

Fume extracting welding gun removes a significant volume of fume from the welder's breathing zone

Y

Y-CONNECTION

A star connection; the joining together of one end of each phase of a three-phase electrical machine.

YELLOW BRASS

Common brass usually containing about 70% copper and 30% zinc. *See* COPPER ALLOY WELDING.

YIELD POINT

The load in Pascals (pounds per square inch) at which an increase in deformation occurs and increases without an increase in load during a tensile test. Only a few materials have a specific yield point; steel is one of these materials.

YIELD STRENGTH

The stress level at which metal exhibits a specified elongation under load, or deviation from proportionate reaction to stress and strain. Yield strength is the stress level, expressed in Pascals (pounds per square inch), at which a material exhibits a specific limiting permanent set.

YOUNG'S MODULUS

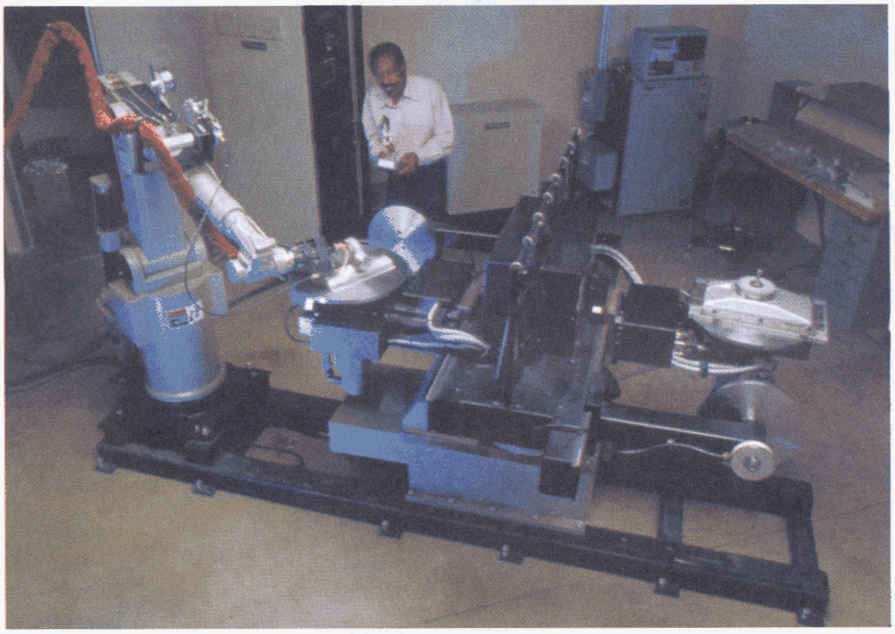
See MODULUS OF ELASTICITY.

YTTRIUM

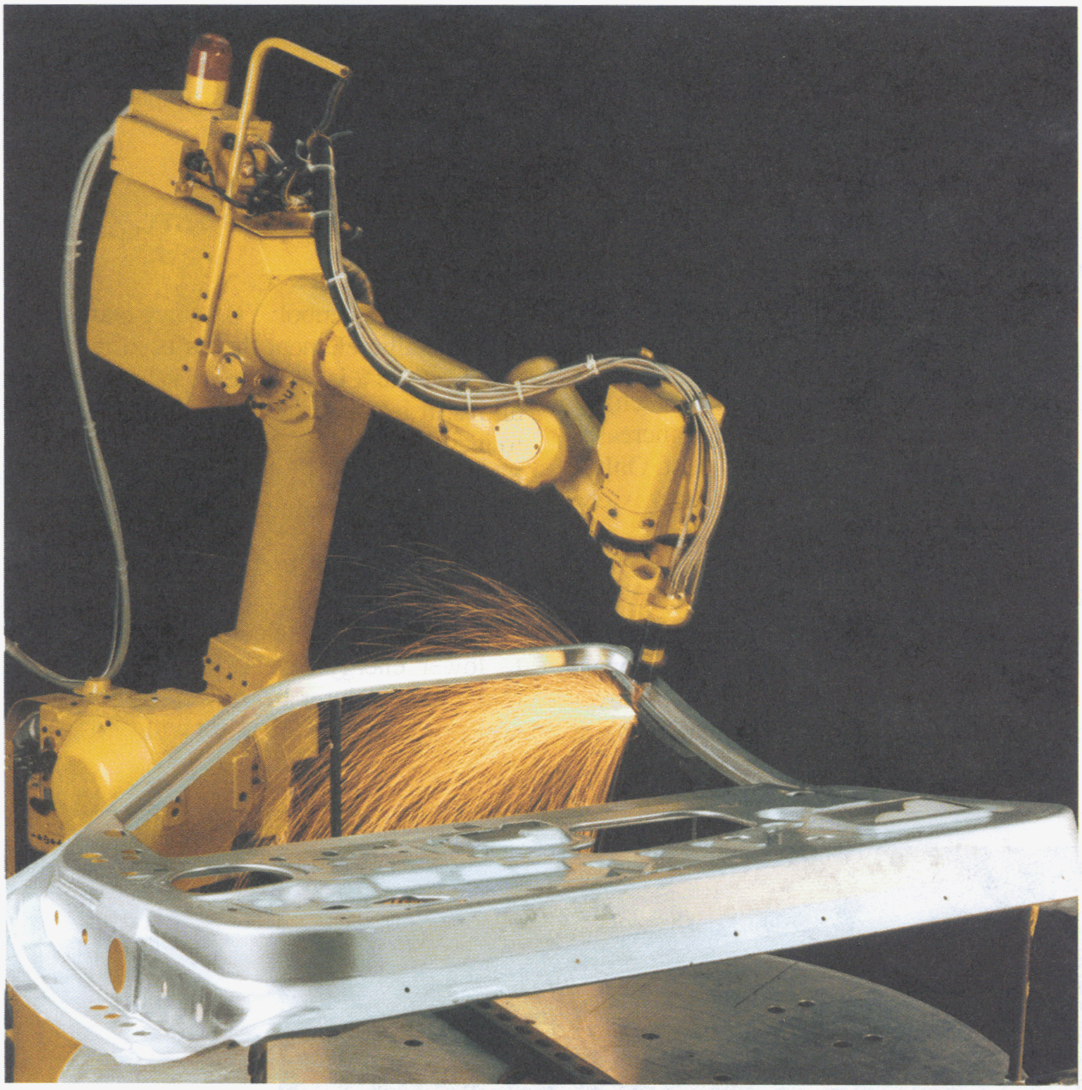
(Chemical symbol: Yt). A rare earth. Yttrium is a silvery metallic element that is used in thermal spraying processes, and is of strategic value in high-temperature alloys. It is added to magnesium and aluminum alloys to increase strength. Atomic number, 39; atomic weight 88.92, density 5.51 g/cm^3 (0.199 lb/in.^{3}), with a melting point of approximately 1538°C (2800°F).

YTTRIUM-ALUMINUM-GARNET (YAG)

A rod-like crystal medium that emits coherent radiation by stimulated electronic or molecular transitions to lower energy levels. It is used with neodymium (Nd-YAG) in laser beam welding, cutting and related processes. *See* LASER BEAM WELDING.



A technician checks a robotic welding system



Robot-mounted laser cutting a car door frame

Z

ZERENER PROCESS

This early (circa 1885) process employed two carbon rods fastened in a holder so that their ends converged. An arc was drawn between the converging ends and caused to impinge on the work by means of a powerful electromagnet. This was also known as the "electric blowpipe" method of welding. It required so much skill that it was impractical for general use.

ZERO POTENTIAL

A condition existing in an electric circuit when there is no voltage present.

ZERO WELDING

A term sometimes used to describe a resistance welding procedure, which uses refrigerated electrodes for welding aluminum. The process involves welding with electrodes chilled to –17°C (0°F), which improves the operating life of the electrode. *See* REFRIGERATED WELDING.

ZINC

(Chemical symbol: Zn). A lustrous, bluish-white metallic element alloyed with copper to form brass, and is also used in solders. Zinc is used in protective coatings on galvanized iron and other metals. Atomic number, 30; atomic weight, 65.37; melting point, 419.4°C (786.9°F). Specific gravity ranges from 7.0 to 7.2.

Pure zinc is ductile; in commercial form, zinc is brittle at room temperature, but becomes ductile when slightly heated. At a temperature of 200°C (392°F), it can be powdered. At temperatures between 100 and 150°C (212 and 302°F) this metal becomes malleable and can be rolled into sheets or drawn into wire. Zinc is capable of a high surface polish; it oxidizes slowly in air. When molten zinc solidifies, it expands somewhat, so that when it is used in die casting, sharp, well defined castings can be produced. Zinc is readily attacked by mineral acids, and dissolves when boiled with caustic soda or potash solution.

ZINCATE

A material compounded or formed by the reaction of zinc or zinc oxide with alkaline solutions.

ZINC-COATED STEEL

See GALVANIZED IRON, WELDING.

ZINC FUMES

A grayish powder given off during the welding of brass, bronze or galvanized material. These fumes produce nausea. *See* WELDING FUMES.

ZIRCONIUM

(Chemical symbol: Zr). A lustrous, steel-gray, somewhat brittle metal with a high melting point. It is used as an alloying agent in iron and aluminum, and is also used in nuclear reactors. Atomic number, 40; atomic weight, 91; melting point, 2350°C (4262°F); specific gravity, 6.25.

Zirconium is very hard and is sometimes used in hardfacing material because of its resistance to corrosion. When steel is alloyed with small amounts of zirconium, fine grain size is produced, and no aluminum additions to steel are required.

Automatic roll spot seam welding systems designed to weld roofs of van bodies for an automobile manufacturer produce welded roofs at the rate of 72/hr/station. There are four roll spot welding units per station.

Photo courtesy of Newcor

Appendix 1
History of Welding and Cutting

One of the earliest references to metalworking and the metalworker's name appears in the Old Testament of the Bible. Genesis 4, verse 22, King James version states "...and Zillah, she also bare Tubal-Cain, an instructor of every artificer in brass and iron." The New International version states, "Zillah also had a son, Tubal-Cain, who forged all kinds of tools out of bronze and Iron." The Living Bible states, "To Lamech's other wife Zillah, was born Tubal-Cain. He opened the first foundry, forging instruments of bronze and iron." A welded iron headrest for Tutankhamen, believed to be from Syria, was crafted in 1350 BC.

Milestones

1836 — Acetylene gas discovered by Edmund Davy.

1856 — The principle of resistance welding believed to be discovered by physicist James Joule, England.

1862 — Woehler produced acetylene gas from calcium carbide.

1876 — John A. Tobin (USA), patented the alloy known as *Tobin Bronze*, a high-strength copper-tin-zinc bronze.

1881 — One of the earliest carbon arc welding machines invented by De Meritens (France).

1881 — Dr. R. H. Thurston (United States) completed a six-year study and exhaustive tests on the strength and ductility of a series of copper-zinc bronzes.

1882 — Patent granted to Robert A. Hadfield (England) for austenitic manganese steel which he called *Hadfield Steel.*

1885 — Elihu Thompson (USA) awarded a patent on a resistance welding machine.

1885 — Carbon arc welding developed by Benardos & Olszewski (Russia).

1889–90 —First arc welding with bare wire electrodes by C. L. Coffin (USA).

1890 — Concept of welding in an oxidizing medium originated by Coffin (USA).

1890 — First oxyfuel gas cutting bank robbery attempted by a Mr. Brown (England).

1892 — Calcium carbide manufactured by Willson and Morehead (USA).

1895 — Konrad Roentgen (Bavaria), observed the effects of X-radiation while passing an electric current through a vacuum tube.

1895 — LeChatelier (France) credited with discovering the oxygen-acetylene flame.

1896 — Reports of the first electric-welded tube production in Cleveland, Ohio.

Circa 1900 — Hans Goldschmidt, Goldschmidt AG West Germany (Orgotheus Inc. USA) discovered that the exothermic reaction between a mixture of aluminum powder and a metal oxide can be initiated by an external heat source for thermite welding.

1900 — The first oxyacetylene torches were made by Fouche and Picard (France).

1901 — The oxygen lance was invented by Menne (Germany).

1904 — Avery (USA) invented a portable cylinder for acetylene-powered auto headlights; produced by the Concentrated Acetylene Company (CAC).

1906 — CAC bought by Prest-O-Lite, forerunner of Linde Division, Union Carbide Corporation.

1907 — Acetylene cutting used to demolish the old Grand Central Station in New York; completed at 80% below projected cost.

1907–10 — Coated electrodes developed by O. Kjellberg (Sweden).

1909 — Plasma arc system using a gas vortex stabilized arc invented by Schonherr.

1911 — The first oxyfuel gas welded pipeline, 11 miles long, constructed by Philadelphia and Suburban Gas Company.

1912 — Production of the first commercial oxyacetylene welded tubing in this country reported.

1912 — First all-steel automobile body joined by resistance spot welding produced at the Edward G. Budd Company, Philadelphia.

Circa 1912 — Ford Motor Company developed welding techniques in plant laboratory for Model T production.

1913 — Acetylene cylinder developed by Avery and Fisher (Indianapolis).

1917 — Arc welding used during World War I to repair engines in 109 captured German ships; after repairs, ships were used to send 500 000 U.S. troops to France.

1917 — Webster & Southbridge Gas and Electric Company, Massachusetts, welded 11 miles of

3-inch pipe with electric arc welding machines.

1919 — American Welding Society founded by Comfort A. Adams.

1920 — First all-welded-hull ship, the steamer *Fulagar*, launched (England).

Circa 1920 — The Johnson Process for producing electric resistance welded steel tubing patented.

Circa 1920 — The first welded tanker, the *Poughkeepsie Socony*, was launched (USA).

Circa 1920 — Flux cored wires for hardfacing introduced.

1922 — Prairie Pipeline Company completed an 8-inch, 140-mile line carrying crude oil from Mexico to Jacksboro, Texas, using oxyacetylene welding.

1923 — First storage tank "floating roof" completed; designed to float welded roof on stored petroleum or chemical product, with tank walls designed to telescope to increase or decrease tank size.

1924 — All-welded natural gas pipeline14 miles long built by Magnolia Gas Company (USA) using acetylene welding.

1924 — Radiography used by H. H. Lester to examine castings to be installed in the United States' first 8.3 MPa (1200 psi) steam pressure power plant for the Boston Edison Company.

1926 — Solid extruded coating for shielded metal arc welding electrodes introduced by A. O. Smith Co. (USA).

1926 — First patents for flux cored wire granted to Stoody (USA).

1926 — M. Hobart and P. K. Devers issued separate U.S. patents for developments in arc welding using helium as a shielding gas.

1927 — First solo transatlantic flight achieved by Lindberg in Ryan monoplane; fuselage based on structure of all-welded steel alloy tubing.

1928 — First structural welding code, *Code for Fusion Welding and Gas Cutting in Building Construction* published by American Welding Society; forerunner of D.1.1, *Structural Welding Code—Steel.*

1930 — Continuous welded rail introduced by the Central Georgia Railroad for track through two tunnels. Welded rail used in open track two years later.

Circa 1930 — Atomic hydrogen welding developed as method of welding metals other than carbon and low-alloy steels.

1931 — Welded steel structure of Empire State Building completed.

1933 — First arc-welded pipeline joined without backing rings constructed by H.C. Price from Oklahoma City to Thall, Kansas.

1933 — Golden Gate Bridge, San Francisco, world's highest suspension bridge (incorporating 87 750 tons of welded steel) opened to traffic.

1934 — Unfired Pressure Vessel Code issued jointly by API-ASME (USA).

1935 — Submerged arc welding developed by Linde Air Products Co. (USA).

1940 — First all-welded ship built in United States, the *Exchequer*, launched from Ingalls Shipyard.

1941 — Gas Tungsten Arc Welding, ("Heliarc") invented by Meredith (USA).

1941 — First American 60-ton tank completed; welding becomes critical to the production of ships, planes, armored tanks and weapons in World War II.

1943 — Curtiss-Wright welds hollow steel propeller blades using atomic hydrogen, submerged arc, and shielded metal arc processes.

1943 — Vera Anderson named national champion woman welder of the United States in a contest held at Ingalls Shipbuilding, Pascagula, Mississippi.

1949 — The first all-welded Ford automobile was produced using arc and resistance welding.

1950 — First spray transfer patent for gas metal arc welding, by Muller, Gibson and Anderson, marketed by Air Reduction Sales Company (USA).

Circa 1950 — Electroslag welding first used for production in Russia.

1953 — Patent for constricted plasma arc torch issued to R.M. Gage (USA).

1954 — Self-shielded flux cored wire introduced by Lincoln Electric (USA).

1954 — First atomic submarine, *The Nautilus*, is placed in U.S. Naval service.

1955 — Constricted arc (plasma arc) developed and introduced by Linde Division, Union Carbide Corporation (USA).

1956 — Friction welding invented (Russia).

Circa 1957 — Carbon dioxide (CO_2) used for short circuiting transfer, gas metal arc welding (USA, Britain, and Russia).

1960 — First laser beam produced using a ruby crystal (USA).

1960s —Pulsed power gas metal arc welding introduced by Airco (USA).
1961 — First public disclosure of electron beam welding by Stohr, French Atomic Energy Commission (France).
1962 — Electrogas welding patent issued, assigned to Arcos (Belgium).
1964 — "Hot wire" welding processes and "one-knob" (Synergic Control) gas metal arc welding process control patented by Manz (USA).
1965 — The St. Louis Arch built from 142 welded stainless steel sections and erected as a tribute to the city and a memorial to westward expansion.
1965 — Welded space craft, Apollo 10, launched to the moon (USA).
1967 — World's first undersea pipeline hot tap engineered and welded by Frank Pilia (USA) for Linde Division, Union Carbide Corporation, in the Gulf of Mexico.
1968 — Development and manufacture of HY-130 steel for pressure vessels and ship hulls completed as a result of $2.3 million research effort by U.S. Steel aided by Naval Ship Engineering Center.
1968 — Critical corner pieces welded in place in the first 22 floors of the John Hancock Center, Chicago; this steel structure consequently welded to a height of 1107 feet.
1969 — Plasma arc hot-wire cladding process introduced by Linde Division, Union Carbide Corporation.
1970s —Transistor-controlled inverter welding power introduced (world wide).
1977 — Alaska Pipeline completed; 2500 tons of filler metals used in 100 000 welds, spanning 798 miles from Prudhoe Bay to Valdez.
1980s —Semiconductor circuits and computer circuits used to control welding and cutting processes (world wide).
1980s —Vapor phase reflow soldering used for printed circuit boards.
1983 — American Welding Institute (AWI) established as American Welding Technology Application Center.
1983 — "Spaceship Earth," 160-ft. diameter geodesic dome at Epcot Center constructed with submerged arc and shielded metal arc welding processes; inspected with approximately 4000 radiographs.
1984 — Edison Welding Institute established by the State of Ohio to improve welding technology used in manufacturing.
1990s —Inverter technology dominates power supply designs. Reduced size and weight of equipment is the result (world wide).
1991 — Friction stir welding introduced and used successfully to weld the 2000, 5000, and 6000 series of aluminum sheet alloys.
1993 — Robotically controlled CO_2 laser beam process used to weld U.S. Army's Abrams Main Battle Tank.

Historical Perspectives

The following is an abridgement of an article, "*In the Beginning*," written by Hal Stacey, and published in the Welding Journal, Volume 73, by the American Welding Society, Miami, Florida, June, 1994.

Welding is an ancient science, so old that its roots have been lost in antiquity. One of the principles of metalworking that seems to have been passed down over the centuries, however, is that when iron is softened and rendered plastic by heating in a fire, it will, under suitable conditions, unite or "weld." Because few implements or articles of iron or steel can survive the attack of rust indefinitely, little direct evidence remains as to exactly when welding originated. The art of working and hardening steel, an advanced stage in metalworking that doubtless took centuries to reach, was commonly practiced 30 centuries ago in Greece and is mentioned by Homer.

It is probable that the principles of welding were discovered, lost and rediscovered repeatedly by ancient peoples the world over, since it has been proven that primitive tribes on different continents, with no apparent means of communicating with one another, developed and used the same basic methods of smelting, shaping and treating iron.

By the time of the Renaissance, welding with fire had become an established practice, and the craftsmen of that period were highly skilled in the art. The parts to be joined were properly shaped and then reheated to the correct temperature in a forge or furnace before being hammered, rolled or pressed together. Biringuccio's *Pyrotechnia*, published in 1540, contains several references to such operations. In one case, a square piece of steel was welded to the end of an iron rod for use in turning cannon bores. In another, cracked bells were made whole again by a method of welding. It is obvious that Biringuccio was intrigued by the latter application, for he wrote, "This seems to me an ingenious thing, little used, but of great usefulness."

Forge welding of iron developed into an industry of considerable proportions and, until about 1890, was the only method available. When the two iron parts reached the proper temperature, they were forced together by various means, often being hung from cranes to facilitate the operation. Then, with the heat maintained at a certain temperature, the ends were struck repeatedly with a sledge hammer for a definite period. That done, the part was withdrawn from the fire and finished on an anvil. Forge welding is still practiced to some extent today.

The Electric Arc. Credit for the concept of modern welding is generally given to Sir Humphrey Davy because of his discovery of the electric arc. In 1810, while experimenting with the emerging science of electricity, Davy discovered that an arc could be created by bringing two terminals of a comparatively high voltage electric circuit near one another. This arc, which cast a bright light and gave off a considerable amount of heat, could be struck and maintained at will, and its length and intensity could be varied within limits determined by the voltage of the circuit and the type of terminals utilized. At that time it was regarded as a curiosity with no practical use; Sir Davy did not apply the name "arc" to his discovery until 20 years later.

The arc was put to its first practical use in 1881, when carbon-arc street lamps were introduced. Shortly after, the electric furnace made its appearance. One of the earliest furnaces was installed by the Cowles Brothers in 1886 at Milton Staffordshire, England.

Arc welding experiments were first undertaken by DeMeritens in 1881. In his experiments the various parts of a lead battery plate were welded using a carbon arc as the heat source.

In the early 1890s, Lloyd and Lloyd of Birmingham, England, established an arc welding shop, very well equipped for that era, which was capable of welding wrought iron pipes up to a foot in diameter. In 1902, the Baldwin Locomotive Works established an extensive welding shop in Pennsylvania for locomotive repair and maintenance, using the carbon arc process on a large scale.

Patent Records

Patent literature may be the most authentic source of information about the early history of electric arc welding. Nickolas Von Benardos perfected and patented a carbon arc welding process. The patents were filed on this process in Petrograd, Russia, on December 3, 1885, and issued May 17, 1887. Benardos and Stanislav Olczewski received a German patent covering welding with a single carbon arc. In this process, fusion was obtained by drawing an arc between a carbon electrode and the work to be welded. Metal was added from an auxiliary source and fed into the arc or molten pool.

In 1889, Zerener introduced the process that consists of drawing an arc between two carbon electrodes positioned at about 60° to each other and deflecting the arc outward by means of an electromagnet placed between the electrodes. This method did not come into much commercial use because the heat was less concentrated and there was less available heat in proportion to the energy consumed.

Research was going on concurrently in the United States, as evidenced by the patent for an arc welding process granted in 1889 to Charles Coffin of Detroit. This was the beginning of a great era in the welding industry, since the metal electrode suggested by Coffin supplied not only fusion heat to the metal being welded, but also the extra weld metal necessary for a good joint. In this process, the filler metal was supplied by excess metal along the weld line or by a metal rod held in the welder's hand.

In England, Slavianoff's work on a similar process culminated in a patent awarded to him in 1889. However, there was little use for Slavianoff's method for several years because suitable metal electrodes were difficult to obtain. For this reason, industrial use of the carbon arc was limited during the years up to 1910, when the development of covered electrodes by O. Kjellberg of Sweden opened up a wide variety of commercial applications.

Welding and World War I

United States' entry into World War I in Europe posed a problem: how to produce the ships needed to transport the materials of war. Seeking a solution, the government set up the U.S. Shipping Board, Emergency Fleet Corporation to cope with the demand for shipping. Professor Comfort A. Adams of Harvard was appointed to head a committee to investigate the situation. The committee met for the first time in July, 1917.

Adams' committee visited England and discovered that the British were using arc welding to an increasing extent. Gas shortages had forced them to cut down on gas welding, and so they were using arc welding with both bare and flux-covered electrodes in the production of bombs, mines and torpedoes. Also, they had initiated the construction of a ship with an all-welded-hull. This steamer, the *Fulagar*, was built at the Commell-Lairds shipyard and launched in 1920.

Having viewed all this, the American committee became enthusiastic converts to welding as a production tool, returned to the United States, and began to set up welding production methods for the necessary war materials. During this flurry of industrial activity, the production campaign itself seemed to turn into a battle between the proponents of gas, arc and spot welding, with skirmishes over the relative merits of carbon and metallic electrodes, fluxed and bare metal electrodes, and direct and alternating current.

The Emergency Fleet Corporation and its subcommittee on welding had accomplished much toward the use of welding in ship construction. The war emergency also resulted in the use of welding for many applications previously considered inadvisable. By this time, improvements in electrical equipment, welding electrodes and process controls were developed so that welding could be safely and economically used for general manufacturing of most metal products and an increasing number of structural projects.

Several notable uses of welding in construction included the three-span, 500-foot, all-welded bridge erected in 1923 in Toronto, Canada. As the economy, strength and tightness of arc welded joints became better known, arc welding was used to construct storage tanks for fuel oil, gasoline and distillate. An example was the monumental job undertaken in Lancaster, Pennsylvania, in erecting a 1-million gallon capacity standpipe, which towered 127 feet high over the surrounding countryside.

After the London Naval Treaty of 1930, the United States Navy, which had contributed greatly to welding research, turned to welding more and more often in order to reduce weight and stay within the Treaty limitations. Also, a welded merchant ship was built in Charleston, South Carolina in 1930. It was the forerunner of hundreds of welded ships that would be built for use in World War II.

During the 1930s, the United States Army became interested in welding, and much of Ordnance's material was redesigned at the Watertown Arsenal for production by welding. Ingalls Shipbuilding Corporation added to these the first all-welded ship built in America, the *Exchequer,* launched in October, 1940.

The year 1932 was established as a reference standard by manufacturers of welding wire in the United States. Approximately 18.3 million pounds were produced that year. Just four years later, wire production had jumped to 111 million pounds. In 1940, 199 million pounds were produced, and in 1943, wire production reached a wartime peak of over a billion pounds.

Arc welding has grown into a very large and important industry. It is used not only for the manufacture of almost everything made of metal, but it is the maintenance tool which keeps railroads, truck fleets, steel mills, power plants, waterworks, refineries, and other vital national industries functioning.

Welding and Shipbuilding

During World War I, welding was involved in a history-making episode concerning 109 German ships that were in American ports when war first broke out. The German high command issued an order to the captains of those ships to sabotage the vessels, especially the boilers. The Germans reasoned that the Americans would not have enough time to repair them before the war's end.

Welding was used to repair all of these ships, and the job was completed within eight months. These same ships were used later to transport 500 000 "doughboys" to France. The repairs resulted in savings to the taxpayers of $20 million.

Reference: Excerpted from Irving, Bob, "*What Welding Accomplished Way Back When,*" Volume 73, (1), Welding Journal, American Welding Society, Miami, Florida. 1994.

After World War I ended, the welding industry turned its attention to domestic affairs. The American Welding Society, founded by Comfort A. Adams, was formally organized in 1919. In the 1920s, oxyacetylene welding continued to be an important and popular process, but arc welding was beginning to be used in such applications as long-distance pipelines. The Johnson process was patented for electric resistance welded steel tubing. Flux cored wires for hardfacing was introduced. Significant developments were made in shielded metal arc welding processes and electrodes.

The severe economic depression of the early 1930s was felt worldwide. As a result, many welding applications involved the salvage, repair, and maintenance of existing equipment. In spite of difficult economic conditions, however, progress in welding technology continued. In the early 1930s, atomic hydrogen welding was developed as a method of welding metals other than carbon and low-alloy steels, and in 1935, submerged arc welding was developed and made commercially available. During the 1930s, continuous welded rail was introduced in the railroad industry and shortly became standard practice for rail lines. Notable examples of welded steel structures built during the 1930s were the Empire State Building and the San Francisco Bay Bridge. Welding was used in the fabrication of automobiles, ships, aircraft, railcars and track; boilers, pressure vessels, piping and tubing, tanks, containers, and countless industrial, commercial, and household products.

The end of World War I did not assure the anticipated era of peace. The political adjustments and economic aftermath of the World War led to instability and unrest in almost every nation and in some countries, dictators were able to take over governments. After only twenty years, when Germany invaded Poland on September 1, 1939, the world was again at war. The United States entered World War II on December 7, 1941, when Pearl Harbor was attacked by Japan. Again the welding industry's priority was production of ships, aircraft, armored tanks, weapons, and equipment for the war effort.

World War II

The following is an abridgement of an article written by Bob Irving, *What Welding Accomplished Way Back When*, published in Volume 73 (1) of the Welding Journal by the American Welding Society, Miami, Florida; 1994.

Shipbuilding

Welding reached its zenith during World War II with the enormous U.S. effort in shipbuilding. A total of 2710 Liberty ships were built to American Bureau of Shipping (ABS) class. Eighteen new shipyards were established to build these badly needed vessels. The production speed in many of these new yards was unprecedented. The record set for fabricating one complete Liberty ship was four days, 15 hours, and 30 minutes.

In the early years of World War II, a great number of Liberty ships and T-2 tankers sailed in convoys across the Atlantic Ocean, through the Norwegian Sea, then through the Barents Sea to the port of Murmansk in the former Soviet Union, delivering military equipment and supplies to the Russian (Red) Army. If the ships could make it through the attacks from the German Luftwaffe and the torpedoes from the U-boats, both of which were based in Norway, there was also a third obstacle: the notches formed by welds that hadn't been ground off. These notches often acted as crack starters, and the extreme cold of that part of the world caused many cracks to propagate while the ships were still at sea. As a result, the chances of U.S. maritime ships making it through this one-two-three punch were about one out of two.

In what could have been interpreted as a warning, a Welding Research Council Committee in the late 1930s had determined that steel plate had to have the following chemical limitations in order to assure sound weldability: 0.26% carbon, 1.00% manganese, 0.04% sulfur, and 0.04% phosphorus. Several major steel companies said they could not make a steel with this chemistry; there was no precedent for doing so.

In 1944, our yards began to build the larger and faster Victory ships (see Figure 1-1). A total of 531 of these ships were built. Five hundred and twenty five T-2 tankers were also built during the war, and it was a T-2 tanker named *Schenectady* that made the naval history books. Tied up after sea trials at an outfitting dock in Portland, Oregon, the *Schenectady* broke into two pieces.

In March, 1941, Senator Harry Truman, a Democrat from Missouri, was appointed chairman of the Senate Special Committee to Investigate the National Defense Program. Known as the Truman Committee, this seven-man group of senators was formed to look into manufacturing problems in the defense industry, and the *Schenectady* was high on its agenda. According to a report of an investigation conducted by the American Bureau of Ships, some of the steel used in this ship was of a very poor quality and was most directly responsible for the failure of the T-2 tanker. About 5% of the steel delivered to the shipyard for the construction of the *Schenectady* was "out of spec" because of its high sulfur and phosphorus contents.

In a special hearing on the matter, Senator Homer Ferguson, a Republican and a member of the committee, asked the president of the steel company responsible for delivering the steel the following question: "If a customer asks you for a strength of 60 000 pounds, the breaking point on a test, and you give him a product of 57 000 pounds, but you represent to him in figures that you have tested it and it did test 60 000 pounds, is that a misrepresentation of a material fact?"

"Yes, sir," the company president replied. The hearing lasted five hours. At the end, the steel company president promised the members of the Truman Committee that "someone would walk the plank" within his organization over this business of false representation.

Figure 1-1—In 1944, U.S. Shipyards Started to Build the Victory Class of Ships

Photo courtesy of the American Bureau of Shipping

Investigation

Cracking in ships became such a problem that, in April 1943, the Secretary of the Navy established a board of investigation to inquire into the design and methods of construction of welded steel merchant ships. In the board's third and final report, it was recorded: "Impact tests of steel samples taken from vessels which had suffered fractures indicated that, in many cases, the steel was notch sensitive, i.e., that its ability to absorb energy in the notched condition, and especially at low temperature, was inadequate. In addition, it was found that some samples of the steel furnished to shipyards under existing physical requirements were also notch sensitive."

Brittle Fracture

The incidents involving cracking during World War II caused a lot of people to think about brittle fracture. A 1954 report indicated that 80 ships built during the war actually broke in half and another 1000 ships suffered major cracks. Although everyone talked about the problem of brittle fracture and how it triggered long, severe cracks in many of those ships, brittle fracture was also the cause of failure in a number of vessels in Boston in 1919, and those vessels were riveted.

In order to better understand brittle fracture, George Irwin of the Naval Research Laboratory (NRL) introduced the theory of fracture mechanics. Developed largely to overcome the kinds of brittle fracture that took place on Liberty Ships during World War II, Irwin's theory was soon put into practice by two other NRL engineers, P. P. Puzak and Bill Pellini. The development of fracture mechanics achieved international stature. Irwin's work laid the foundation for the fracture mechanics methods that are used for the design and operation of fracture-critical structures over the entire world, and is one of the most enduring contributions to science and engineering made by the Naval Research Laboratory.

In the late 1950s, Pellini conducted the critical experiment that led to the decision to use HY-80 steel in pressure hull submarine construction, when he demonstrated that the fracture safety of HY-80 was superior to that of T-1 steel. Using explosives to deform a two-inch-thick sample consisting of the two steels welded together, he showed that the T-1 had a tendency to fracture in the heat-affected zone near the weld. The impact was entirely visual. No analysis was necessary.

In its work with high-strength steels for submarines, the Naval Research Laboratory's Welding Section, headed at the time by Puzak, did much to call attention to the effects of hydrogen and certain combinations of alloy elements in weld metal and its effect on the cracking tendency of weld metals and the heat-affected zones of base metals. Puzak worked closely with the welding engineers in shipyards to develop and document fabrication procedures which would minimize the cracking of HY-80 welds during fabrication. Such documentation was needed because of the cracking incidents that had been occurring on submarines fabricated from HY-80 steel. At one time, Admiral Hyman Rickover tried to convince the Navy to return to the steel formerly used, but Pellini argued the case successfully for HY-80 steel.

Presidential Commendation

President Franklin Roosevelt had many good things to say about welding in a letter he wrote Prime Minister Winston Churchill in the early years World War II. Churchill is said to have read a part of Roosevelt's letter to the members of the House of Commons:

> *"Here there had been developed a welding technique which enables us to construct standard merchant ships with a speed unequaled in the history of merchant shipping."*

The "technique" the President was referring to was undoubtedly submerged arc welding (SAW). The Linde Air Products Company's version of this process was first introduced to industry in 1937. The submerged arc, or Unionmelt process, was capable of joining steel plate as much as 20 times faster than any other welding method.

Roosevelt was not the only president who publicly expressed appreciation for the welding industry. President Dwight D. Eisenhower commended the founder of the American Welding Society, Dr. Comfort Avery Adams. On April 8, 1957, the President sent Dr. Adams a congratulatory telegram on the occasion of the 38th Annual Meeting of AWS in Philadelphia:

> *"Dr. Adams has achieved an outstanding record of public service and has won the abiding esteem and affection of his fellows in the engineering profession. His career is an inspiration and a challenge."*—Dwight D. Eisenhower, President, United States of America.

It was fitting that the official name of the 1957 convention was the AWS Adams National Meeting. At a banquet in his honor, Dr. Adams reminisced about his days during World War I when he was appointed by President Woodrow Wilson to serve as chairman of the Welding Committee of the Emergency Fleet Corporation. A goal of the corporation was to provide welded ships for the war effort. The goal was not met in time. At the banquet, Dr. Adams smiled and said, "It's probably just as well."

Tankers and Supertankers

As shipbuilding moved into the 1960s, several unusually great demands were placed on oceangoing vessels. Two examples were the liquefied natural gas (LNG) tanker (see Figure 1-2) and the supertankers. Different designs of LNG tankers featured tanks or compartments welded from stainless steel, Invar, or aluminum. A special facility was constructed by General Dynamics Corporation outside of Charleston, South Carolina, where huge aluminum hemispheres were joined together by mechanized gas metal arc welding. As each sphere was completed, it was loaded on a barge, then delivered up the coast to the main shipyard in Quincy, Massachusetts, where the ship was being built. The barge then returned to Charleston to pick up the next sphere for delivery. The tankers were designed to house five spheres.

Storage tanks were also being built to contain the gas onshore. The alloy of choice in this application was 9% nickel steel, a metal that was also selected for liquid gas cylinders. The welds were made using a high-nickel filler metal.

Supertankers. The closing of the Suez Canal in 1956 triggered a boom in oil supertankers. In 1971, the *Nisseki Maru*, a 367 000-ton-deadweight tanker was launched from a Japanese shipyard. At the time, the *Nisseki Maru* was believed to have been the largest tanker the world. Larger tankers were to follow.

The Offshore Oil Industry. The vessels needed for the exploration of undersea hydrocarbons were natural offshoots of shipbuilding. The first mobile, offshore drilling rig, a pontoon-supported unit known then as a submersible, began operating in 1949.

Figure 1-2—Complete with Welded 5083 Aluminum Tanks to Contain Liquified Natural Gas, the LNG *Leo* is Shown Here

Photo courtesy of the American Bureau of Shipping

Later, the North Sea became the proving ground for thick welds capable of sustaining high impact loads at low temperatures. Huge platforms were fabricated in Scotland and in Norway to reap the rewards of oil and gas in such areas as the Ekofisk and the Brent fields. Structures had to stand up to waves 15 m (50 ft) in height and winds of 112 to 210 km/h (70 to 130 miles/h).

Interest in North Sea oil and gas was strong, but when the 1973 oil crisis hit, the rush became a roar. The search for oil and gas offshore increased to such a degree that by the end of 1974, the ABS had classed 145 mobile offshore drilling units. Drill ships and submersibles were also being classed.

Earlier in time, in September, 1950, the seesaw battle between oil tankers and pipelines tilted in the direction of pipelines with the completion of the 1670-km (1040-mile) Trans-Arabian Pipeline or Tapline in the Middle East. This pipeline was designed to replace 7200 miles of sea journey from the Persian Gulf through the Suez Canal.

According to Daniel Yergin in his Pulitzer Prize winning book, *The Prize,* the annual throughput of the Trans-Arabian Pipeline was the equivalent of 60 tankers in continuous operation from the Persian Gulf, via the Suez Canal, to the Mediterranean. King Ibn Saud said at the time, "The oil it carried would fuel the recovery of Europe."

Cross-Country Pipelines

Welding has always played an extremely important role in pipeline construction. The first welding of pipe joints by the oxyfuel process was on a 17.7-km (11-mile) line constructed by the Philadelphia & Suburban Gas Company in 1911. In 1917, Webster & Southbridge Gas and Electric Company of Massachusetts used an electric machine to weld 11 miles of 3-in. diameter pipe. An early name in the electric welding of pipelines was Electra Welding Company. (This company has grown to become one of the largest pipeline contractors in the United States as H. C. Price Company.) In 1922, an Electra Welding crew traveled to Caney, Kansas, where it worked on a field pipeline and repaired a large oil field tank bottom for Empire Pipeline Company, using electric welding.

In 1924, Magnolia Gas Company of Dallas, Texas, completed what is described as the first long-distance, all-welded natural gas pipe line. It extended for 344 km (214 miles), and ran from the Webster Parish field in Louisiana to Beaumont, Texas. The line consisted of 41- and 46-cm (16- and 18-in.) telescoped pipe, acetylene welded. In 1933, the H. C. Price Company completed the first electric-welded pipeline without the use of a backup ring inside the pipe. The line was built for Phillips Petroleum Company and ran from Oklahoma City to Thrall, Kansas.

In the Golden Anniversary issue of *The Oil and Gas Journal,* Noah Wagner of the Prairie Pipeline Company was mentioned, ostensibly as a pioneer in the acetylene welding of pipeline. Wagner is credited by the magazine with introducing acetylene welding to pipeline work in 1920. Some time later, the company welded a 225-km (140-mile), 20-cm (8-in.) line from Mexia to Hensley, Texas.

The first seamless pipe supplied by the mills was introduced in 1928. Electric-welded pipe was introduced shortly after. The two types of pipe still compete against one another.

At the 1934 Oil Show in Tulsa, a new speed record in pipeline welding was set when an automatic oxyacetylene welding system made a circumferential weld in 6.4-mm (1/4-in.) wall, 305-mm (12-in.) diameter pipe in 8 minutes. The equipment was a product of the Linde Air Products Company.

Arc Welding

It was just about at that time, however, that acetylene welding met its match: a very crude covered electrode. Some of the core wires of these electrodes were little more than rusty wire, a wire similar to the type used for cattle fencing. In some instances, the electrode covering was wet newspaper, but it welded pipe much faster than any acetylene welding system.

The first electric welding used to construct new steel roofs on large oil field tanks was done by Welding Engineering Company (later known as H. C. Price). The emergence of shielded metal arc welding electrodes in the early 1930s made it possible to weld entire field storage tanks for the petroleum industry. This change in joining technique dramatically improved the tanks' evaporation elimination and fire protection.

The Alaska Pipeline

Stories about the Alaska pipeline continued for years: how some welders were making $90 000 per year, or about the tremendous job rush to Alaska from the lower 48. One of the best reports on the pipeline appeared in *National Geographic;* it contained a fair amount of information on welding. This important project involved the joining of 1.2-m (48-in.) diameter, 12.7-mm (1/2-in.) wall, high-strength steel pipe. The pipe had been made in Japan since no American pipe mill was equipped to handle such a large size.

Severe weather conditions added to the usual construction problems.

This was also a project in which organizations concerned with the environment interjected a major voice. At one point, trenching had to be stopped completely because the workers had come upon a *polar bear in hibernation*. What to do? After weeks of consultation with all sorts of experts, the decision was made to leave the bear alone and to trench around him.

Environmental organizations were also involved, indirectly and early in the project, with the selection of welding electrodes. Metallurgists and welding engineers had been working for years to establish procedures. Then, at the eleventh hour, the environmentalists shook their heads and said, "The welds aren't strong enough." They then established new specifications for higher strength welds. The call went out for a cellulosic electrode that would meet these new specs. Only one could be located at the time: it was an E810G electrode from Thyssen, Germany, called Phoenix Cell 80. Before the project was completed, more than 1.5 million pounds of this electrode were consumed in the fabrication of the Alaska pipeline. Of that total, some 550 000 pounds were flown in directly from Germany to Alaska in an emergency airlift.

Later in the construction phase, trouble arose over a certain section of pipeline which had not been inspected properly. Unfortunately, a reporter with one of the wire services misinterpreted the situation, and the next day newspapers across the country were running headlines to the effect that there were "30 000 defective welds in the Alaska pipeline." The Welding Institute interceded and convinced the officials to have some of the weldments examined on a fitness-for-purpose basis at the National Bureau of Standards (now the National Institute of Standards and Technology) in Boulder, Colorado. Using fracture mechanics equipment, engineers there proved that the welds in question were adequate for the intended service.

Prior to the construction of the Alaska pipeline, new pipe mills were being opened throughout the country. Bethlehem Steel held a major press conference in the late 1940s to celebrate the grand opening of its new pipe mill at Steelton, Pennsylvania. It was one of the first users of submerged arc welding.

A prominent inventor, a man named Wally Rudd, was making news with his patented high-frequency resistance welding process. The first installation was at Alcan, Kingston, Ontario, Canada, in 1955 for longitudinal welding of 2- to 6-inch diameter aluminum irrigation pipe. The first installation of the process at a steel pipe mill was at Republic Steel Company in 1956. This particular invention was known as the Thermatool process.

The ASME Code

On May 2, 1930, the first fusion welded boiler drum was tested to destruction at Combustion Engineering, Inc., Chattanooga, Tennessee. Shielded metal arc electrodes produced by C-E were used to fabricate the boiler drum. Actual fabrication was performed by the Hedges-Walsh-Weidner Company, a wholly owned subsidiary of Combustion Engineering. Thirteen months later, the ASME code committee adopted new rules approving the use of welding for boiler drum construction. On June 22, 1931, Combustion Engineering shipped the first commercial land boiler fabricated to these ASME code welding requirements to the Fisher Body Division of General Motors Corporation. The facility was named a National Historic Mechanical Engineering Landmark by ASME in 1980.

The Brown Paper Company, Monroe, Louisiana, is credited with being the first customer to have received a fusion-welded power boiler drum for naval vessels that had been constructed under a specification adopted by the U.S. Navy. The rules were not unlike those written for the ASME Boiler and Pressure Vessel Code committee. This occurred in 1930, during "the great years."

The creation of the ASME Boiler Code was a great milestone in the history of quality control and one in which welding was heavily involved. A. M. Greene, Jr., referred to the period at the end of the 1920s and the beginning of the 1930s as "the great years" in the history of the Code. His first reason for calling those particular years "great" was the advent of fusion welding. During the period of 1928 to 1931, he said, welding was meeting the long service life expectations of designers and fabricators for the shells and components of boilers and pressure vessels.

One of the early methods used for weld testing by Code fabricators was one called "tapping," which appeared to have been a very low technology version of acoustic emission. In the late 1920s, one might see inspectors tapping weld joints with hammers, and listening to the sound through stethoscopes. If the sound were a "dead" one, the weld was thought to be defective.

Nuclear Power

The world's first large-scale nuclear electric power generating station went on line in 1956 at Calder Hall, West Cumberland, England. At the time, this plant was described in a book entitled *Wonders of the World* as "one of the seven wonders of the modern world."

The Vallecitos boiling water reactor, near Pleasanton, California, the first privately owned and operated nuclear power plant, started to deliver significant quantities of electricity to the public utility grid in 1957. General Electric, Pacific Gas and Electric, and Bechtel collaborated on this effort. The reactor was named a historic landmark by the ASME in 1987.

The Shippingport, Pennsylvania, Atomic Power Station was the first commercial central electric generating station in the United States. It was built by Combustion Engineering to Section I rules. The next ones were built to Section VIII rules. Then, finally, Section III came into existence.

Industry ran into a series of welding problems in nuclear fabrication, but only because no one had experience in this field. Electroslag welding was tried, but given up. Strip cladding was first used. There were problems with the copper coating on submerged arc welding wire. Embrittling effects were brought on as a result of radiation on the copper. Then there was stress corrosion cracking of the boiling water reactors. To solve these problems, preferential alloying was used to improve the toughness.

The Auto Capital of the World

Detroit is not only the hub of automobile manufacturing, it is also the scene where the largest amount of welding in the entire world takes place, including both arc welding and resistance welding. One might say that the two came together coincidentally around the turn of the century when John C. Lincoln, the founder of The Lincoln Electric Company, built an electric automobile and initiated the manufacture of equipment to recharge the batteries for such vehicles. The use of welding for the manufacture of automobiles, however, did not take place until many years later. The Ford Motor Company, for example, continued to rivet its cars until 1934, when arc welding was first used to join the frames together. Then in 1937, Ford started to use resistance spot welding. The first all-welded Ford automobile came out in 1949. Both arc and resistance welding were used.

At the front end of the car, there were those who wanted to see an aluminum radiator. R. L. Peaslee said vacuum brazing was used for aluminum radiators to prevent the erosion that had been taking place when the brazing of aluminum was processed in molten flux salt baths. If any salt remained on the part after cleaning, corrosion problems would occur. The first aluminum radiator produced by vacuum brazing was done by Harrison Radiator in New Jersey.

In the early 1960s, C. J. Miller of General Electric's aerospace group in Philadelphia discovered that a magnesium content in the cladding or brazing alloy was the agent that made vacuum brazing of aluminum work. Miller filed five or six patents in this general area. GE never pursued the vacuum brazing process commercially, but instead licensed companies to use the technology and collected royalties from its use.

Recently, aluminum components have begun to be specified in some automobiles. At Ford Motor Company, aluminum hoods, deck-lids, and fenders are specified for various vehicles. Weld bonding (the technique of making resistance spot welds through epoxy) is starting to be used in the production of automobiles having aluminum components. It is interesting that this is the same basic process used for years by the Russians in the fabrication of their aircraft.

Robots

The first robot for resistance spot welding within the Ford Motor Company went into operation in 1961. The robot was built by AM Industries. By 1994, there were more than 500 robots used to control resistance spot welding in the automotive industry.

According to Joseph Engelberger, the chairman and chief executive officer of TRC, Danbury, Connecticut, the first robots for resistance spot welding at General Motors (there were two of them) were installed in 1964. Two years later, GM placed an order for 66 Unimate robots from Unimation to be used in its new Lordstown, Ohio, plant. They were hydraulically operated and used for resistance spot welding.

The early work on electric robots was conducted by Victor Scheinman and several associates in Mountain View, California. Their first electric arm was called the Stanford arm. With backing from General Motors, Unimation finally introduced the Puma electric robot in the early 1970s.

The Early Days of the Jet Engine

There is a long history of successful welding of jet engine components. In the 1970s, the production lines at one of General Electric Aircraft Engine's plants was manned by more than 400 certified welders. A lightweight engine of the 1958 period, the J-79, featured rolled and flash-welded flanges or frames. Two major applications there were gas tungsten arc welding of large diameter A286 steel turbine frames using a Hastelloy W filler metal, and the welding of a Chromalloy alloy steel front frame. The Chromalloy material was developed by GE. The J-79 engine powered the F-4 fighter aircraft and the B-58 bomber. A commercial derivative, the CJ-805 engine, powered the Convair 880.

Unfortunately, the role of welding in the fabrication of the jet engine is on the decline. Replacing it in many areas, particularly the rolled and welded frames, are improved investment castings; however, the titanium fan frames for other engines, especially those specified for the Boeing 747, are too big to be made out of investment castings. As a result, these components are still joined by electron beam welding.

In the United States, the fuselages and wings of aluminum aircraft have always been joined by various types of mechanical fastening devices. In the past, attempts have made to build welded aircraft. One attempt took place in the 1930s in Philadelphia when the Edward G. Budd Company fabricated a welded stainless steel airplane. Called *Pioneer*, Budd's stainless airplane was flown successfully. The plane has since earned a permanent spot at the Franklin Institute in Philadelphia. Budd was convinced that stainless steel had a great future in transportation. Years later, the Budd Company won the first contract to build Metroliner passenger cars for the Northeast corridor. They were also welded from stainless steel.

Rocket to the Moon

On May 18, 1969, the *Apollo 10* manned spacecraft, our "rocket to the moon" was fired into space. The vehicle's main weld was 10 m (33 ft) long, made by automatic gas tungsten arc welding. The vehicle's command module consisted of an outer heat shield of PH 1408 Mo stainless steel honeycomb, and an inner cabin was made from 2014-T6 and 6061-T6 aluminum. Thicknesses were in the 1.5 mm (0.060 in.) range.

Some 24 600 cm (9700 in.) of gas tungsten arc welding were used to join the heat shield assembly. The equipment operated on direct current, straight polarity. Gas shielding consisted of an argon/helium mixture. A total of 63 individual welds, measuring up to 9400 cm (3700 in.) in total length, were made on the inner cabin.

The other component for the *Apollo 10* was the spacecraft's Lunar Module. This component was made mostly of 2219 aluminum; it, too, was welded by the automatic gas tungsten arc process. Manufacturing records indicated that only 15.2 cm (6 in.), or 0.0007%, out of a total of 2950 cm (8640 in.) of welds had to be repaired on five Lunar Modules.

In terms of welding on the *Apollo,* probably the largest participant was Sciaky Brothers, Inc., Chicago. After the mission was accomplished, Sciaky received a congratulatory letter from the prime contractor of the *Apollo* program, the Space Division of North American Rockwell Corporation, Downey, California. Signed by Dale D. Myers, vice president, the letter stated:

> *"Your firm's extensive welding contribution to the* Apollo *program is most highly commended."*

Welding continues to play a vital role in aerospace. One of the more recent innovations in the Space Shuttle program, for example, has been the development and use by NASA of the variable polarity plasma arc welding (VPPAW) machine in the fabrication of the liquid oxygen and liquid hydrogen fuel tanks. These welding machines reduce distortion; reduce the original requirement of from 6 to 12 weld passes to 1 or 2 passes; and eliminate the need for precise joint fitup.

Structural Welding

Welding has been important to the fabrication of buildings and bridges for many years. In 1928, for instance, the steel framework for the four-story Upper Carnegie Building was erected in Cleveland. The 115 tons of steel required was estimated to have been 15% less than that required for a riveted design.

Welded construction received a lot of public attention in the mid 1960s with the John Hancock building in Chicago. "Big John," as it was referred to during its construction, eclipsed the Empire State Building in Manhattan as the world's tallest building.

American Welding Society Structural Code

The popular AWS D1.1, *Structural Welding Code—Steel*, officially came into existence in 1972, though it traces its beginnings to 1928 when the *Code for Fusion Welding and Gas Cutting in Building Construction* was first published by the American Welding Society. "D1.1," as it is familiarly known throughout the steel construction industry, has become the "bible" of that industry. The newer D1.2, *Structural Welding Code—Aluminum*, traces its origin to the same 1928 Code.

Utilities and the Environment

During the depression years, welding was relied on heavily for the fabrication of the huge electrical generating complex known as the Tennessee Valley Authority. Much more would be asked of welding by the utilities in subsequent years. For example, the nation's concern with acid rain opened up a new market for welding. The new market was the fabrication of flue gas desulfurization (FGD) scrubbers for certain utilities throughout the country. The plants in question were burning high-sulfur coal. Effluent from these plants drifted hundreds of miles away, damaging forests and lakes. Many of the FGD scrubbers were as large as the electrical generating plants themselves. The environments within the scrubbers were so severe that designers were soon designating high-nickel and titanium alloys as major materials of construction. The cost became so high that welders were called upon to attach sheet metal sections made out of these expensive materials to the internals of many vessels. The technique soon became known as "wallpapering," and it is moving into other areas of construction as well.

Railroads

In the 1930s, when the shift began from bolted to continuous welded rail, many of the processes were used: first oxyacetylene, then gas pressure welding. Other processes, including submerged arc, gas metal arc, and electroslag welding, have all been tried. At present, resistance flash welding and thermite welding are generally used.

Electrodes with Extruded Coatings

A. O. Smith Corp. made two important contributions to the welding industry in 1927. One was the production of solid electrodes with extruded coatings for arc welding. The other was resistance flash welding equipment capable of producing longitudinal seams of 440-foot lengths of large-diameter pipe in 30 seconds. Low-hydrogen coatings were first used on stainless steel electrodes during the 1930s. The Germans were using a 25Cr/20Ni electrode to weld armor plate. The U.S. Navy wanted industry to develop a similar electrode in this country. This was done at the Philadelphia Navy Yard. Then, in 1942, the War Production Board announced it wanted a cutback in the use of chromium and nickel, so a19Cr/9Ni electrode was developed. The low-hydrogen concept was then used on electrodes for welding armor plate in about the same time period. These types of coverings were finally applied to low-alloy steel electrodes.

The first commercially available iron powder low-hydrogen steel electrode was introduced by Alloy Rods in 1953. It was called Atom Arc.

Process Development

One inventor who played a significant role in the early days of the industrial revolution was Elihu Thomson. In 1877 Thomson read a paper at the Franklin Institute in Philadelphia describing his experiments with an induction coil. Eight years later, he was awarded a patent (the first) on resistance welding.

Credit for the first complete description of *spray transfer, arc welding* is given to Albert Muller, Glenn J. Gibson and Nelson E. Anderson. Their Patent, No. 2,504,868, was awarded on April 18, 1950. It was assigned to the Air Reduction Sales Company.

Flux Cored Arc Welding (FCAW)

The two versions of flux cored arc welding, gas shielded and self shielded, were both developed in the late 1950s. The gas shielded version was developed by Arthur Bernard, president of Bernard Welding Equipment Company. A manufacturer of welding torches, Bernard had no interest in entering the market on a full-fledged basis; instead, he sold the rights to his invention to the National Cylinder Gas Company. The self-shielded version of flux cored arc welding was developed by Tom Black, a research engineer at Lincoln Electric Company.

Gas Tungsten Arc Welding (GTAW)

Originally known as Heliarc welding, gas tungsten arc welding was invented by Russell Meredith, an engineer working for Northrup Aircraft during World War II. The first paper on the process appeared in the *Welding Journal* in 1941. Meredith was awarded three patents on the process, the first of which was Patent No. 413,711, issued on February 24, 1942. The objective had been to develop a process to weld magnesium without the use of flux. On June 15, 1942, Meredith was presented with the prestigious Award of Merit by Frank Knox, Secretary of the Navy. That same year Northrup Aircraft licensed the Linde Air Products Company to further develop and market the process.

Electron Beam Welding (EBW)

The 1960s were exciting years for proponents of electron beam welding (EBW). Numerous high-tech manufacturing companies bought electron beam welding machines, placed them in R&D, and made them the high points of plant tours. In production, some of the feats and near-feats were amazing. Entire wing sections for military aircraft were electron-beam welded within a huge 32-foot long, 10-1/2-foot-wide, 8-foot tall chamber, built by Sciaky Brothers at Grumman Aerospace Corporation, Bethpage, N.Y. This version of EBW traced its beginnings to the French Atomic Energy Commission. Some of the first information about this particular process started to appear in trade publications about 1957. It was being used in France to weld nuclear components.

Predating the French work, an electron beam device was reported in Germany in 1948. In 1959, a scaled-up high-vacuum version of the German process was delivered to an aerospace company in the United States. Eventually the German technology, sold in Europe by Zeiss, was absorbed in this country by the Hamilton Standard Division of United Aircraft Corporation. During the period from 1960 to 1964, approximately 130 high-vacuum EBW machines were delivered to customers in the United States.

General Motors Corporation decided to use the EBW process to weld the Type 409 stainless steel catalytic converters at its AC Spark Plug Division in Milwaukee. The converters were produced to satisfy the needs for GM's passenger cars and trucks. After several decades of operation, these EBW machines are finally being replaced by gas metal arc welding machines, chiefly because of the high cost of maintenance on the EBW machines. Unfortunately, electron beam welding had one main drawback. For the process to work at its best, welding had to take place inside a vacuum chamber.

Laser Beam Welding (LBW)

Though it took many years, EBW finally met its match in laser beam welding. The laser does not have to operate inside a vacuum. Early enthusiasm for the laser even resulted in a system designed to weld an entire car body. This system was ahead of its time, although there are many lasers in automotive production lines, welding parts both under the hood and on the body.

In 1990, Gillette set up 30 industrial lasers in production lines around the world to make the disposable shaving cartridges for its Sensor razor. The laser beam welding machines were 250W Nd:YAG units from Lumonics Corporation, Livonia, Michigan. In order to meet quotas, a requirement of 3 million micro spot welds per hour had to be met, and it was met.

Fiber Optics. The science of fiber optics has found interesting uses in the welding industry. One of its first uses was for visual inspection of welds located in hard-to-approach areas. Fiber optics is now being used to transmit beams emanating from Nd:YAG lasers for welding and cutting. One application of fiber optics enables welders to repair large valves inside naval vessels by taking the fiber optics cable through the hatch, avoiding cutting sections from the ships big enough to allow the valve to be removed and transported to a regular repair facility. Equipment based on this principle is starting to appear on automotive manufacturing lines to replace resistance spot welding.

Laser Beam Patents. In 1958, Charles Towns and Arthur Scala of Bell Laboratories delivered a paper that proposed a basic structure for a device that would produce laser light, but the first operable laser beam welding machines were based on a ruby laser and were operated by Ted Maiman at Hughes Aircraft in 1960. The CO_2 laser and the neodymium: yttrium aluminum garnet (nd:YAG) laser were both invented in 1964 at Bell Laboratories. C. K. N. Patel invented the CO_2 laser.

In 1968, a CO_2 laser was built at the Everett Research Laboratory. This unit appeared to be "scalable" to a high-power process. United Technologies Research Center made deep penetration welds in 1/4 inch thick steel using a CO_2 laser. The patent situation pertaining to lasers, however, continues to be extremely complicated.

Electroslag and Electrogas Welding

During the height of the Cold War in the 1950s, electroslag welding made its debut in the United States in 1959 through a rather circuitous route. This "vertical up" system was introduced in this country by the Arcos Corporation, which had obtained it from an affiliate in Belgium, which had obtained it from the Bratislava Institute of Welding in Czechoslovakia, which had obtained it from the inventor, the Paton Institute of Electric Welding in Kiev, the Ukraine. Many refinements and modifications have been made to the electroslag unit, resulting in machines capable of meeting the standards of United States industry.

In 1976, the American Bureau of Shipping joined with the Maritime Administration to conduct an investigation to determine the limitations on the use of electroslag and electrogas welding. Recently developed flux cored electrodes, lower heat input values and faster travel speeds have improved these processes.

Explosion Welding

The early work in explosion welding was conducted at an underground site in New Jersey by the E. I. Du Pont de Nemours & Company, Inc. An interesting application of this technology came about when Du Pont prepared specially designed transition pieces between aluminum and steel for the United States Coast Guard. Using these pieces, the Coast Guard was able to attach aluminum superstructures to steel ships by welding the aluminum side of the transition joint to the superstructure and the steel side to the steel decking. Other types of ships soon took advantage of this new technology.

Friction Welding

The first friction welding machine used in the automotive industry was built by AMF Industries. It went into operation in a Ford Motor Company plant in Indianapolis, where it was used to weld SAE 5140 steel steering worms to SAE 1010 carbon steel shafts. Caterpillar Tractor sold its first inertia welding machines in 1966 to Schwitzer, used in the manufacture of turbochargers.

Inverters

One of the more important developments in power sources for arc welding has been the inverter. In 1974, the U.S. Maritime Commission expressed interest in the development of a portable 300-ampere welding power source using inverter technology. Jim Thommes was the chief designer of a first-generation prototype unit based on transistors. Almost immediately after it was completed, a second-generation prototype was also developed, this one using semiconductors. The goal had been to develop an inverter power source that could be passed through ship hatches.

Oxyacetylene Cutting

In the early years of metalworking expansion, oxyacetylene cutting was found to be an extremely useful process. One incident involving oxyacetylene cutting occurred in 1908, when crews were trying to dismantle the Quebec bridge, which had fallen into the St. Lawrence River. They had tried dynamite, but that didn't work. Finally, a sales engineer and a few other individuals succeeded in dismantling the bridge using manual torches. Two years later, the same process was used to dismantle the boilers of the battleship *Kentucky* while it was moored at the Norfolk Naval Shipyard. Workers had already spent three months trying to do the job with cold chisels and hacksaws, but were able to do very little dismantling. Using oxyacetylene torches, the boilers were dismantled in 10 days.

Plasma Arc Cutting

Plasma arc cutting was displayed publicly in 1956. The equipment consisted essentially of a gas tungsten arc welding torch with an arc-constricting nozzle. First developed to cut aluminum, the process was expanded to cut stainless steel and other metals.

The Gleeble from Duffers Associates

An important development in weld testing occurred in the mid 1950s, when two professors and one graduate student at Rensselaer Polytechnic Institute developed an instrument capable of simulating and analyzing temperature excursions in weld heat-affected zones. It provided badly needed data. Nicknamed "the Gleeble," it was invented by Ernest Nippes, Warren Savage and Hugo Ferguson. A company, Duffers Associates, was formed to market the Gleeble. Ferguson became its president.

Acknowledgments

American Society for Mechanical Engineers, American Bureau of Shipping, American Petroleum Institute, Naval Research Laboratory, Alloy Rods, ESAB, Ferranti Sciaky Inc., The Lincoln Electric Co., and United Technologies Industrial Lasers. Our appreciation is also extended to Howard Adams, Connie Banas, Bernie Bastian, Dominic Canonico, Brown Cooper, Dan Hauser, James Kovach, Gus Manz, Pat Palvkill, Al Patnik, R. L. Peaslee, Wally Rudd, Tom Siewert, Bob Somers, Dietmar Spindler, James Terrill, David Thomas, Tiny Von Rosenberg, and Eric Whitney.

References

History—Materials Science and Technology Division. 1993. Naval Research Laboratory, Washington.

Cross, W. 1990. *The Code—An Authorized History of the ASME Boiler and Pressure Vessel Code.* The American Society of Mechanical Engineers, New York.

The Procedure Handbook of Arc Welding. 1973. The Lincoln Electric Co., Cleveland.

The *History of American Bureau of Shipping.* 1991. American Bureau of Shipping, Paramus, N.J.

Yergin, D. 1991. *The Prize—The Epic Quest for Oil, Money* & Power. Simon & Schuster, New York.

McCullough, D. 1992. *Truman.* Simon & Schuster, New York.

100 Years of Metalworking. 1955. *Iron Age,* Chilton Co., Philadelphia.

Koelihoffer, L., Manz, A. F., and Hornberger, E. G. 1988. *Welding Processes and Practices.* John Wiley & Sons, New York.

Clark, J. A. 1963. *The Chronological History of the Petroleum and Natural Gas Industries.*

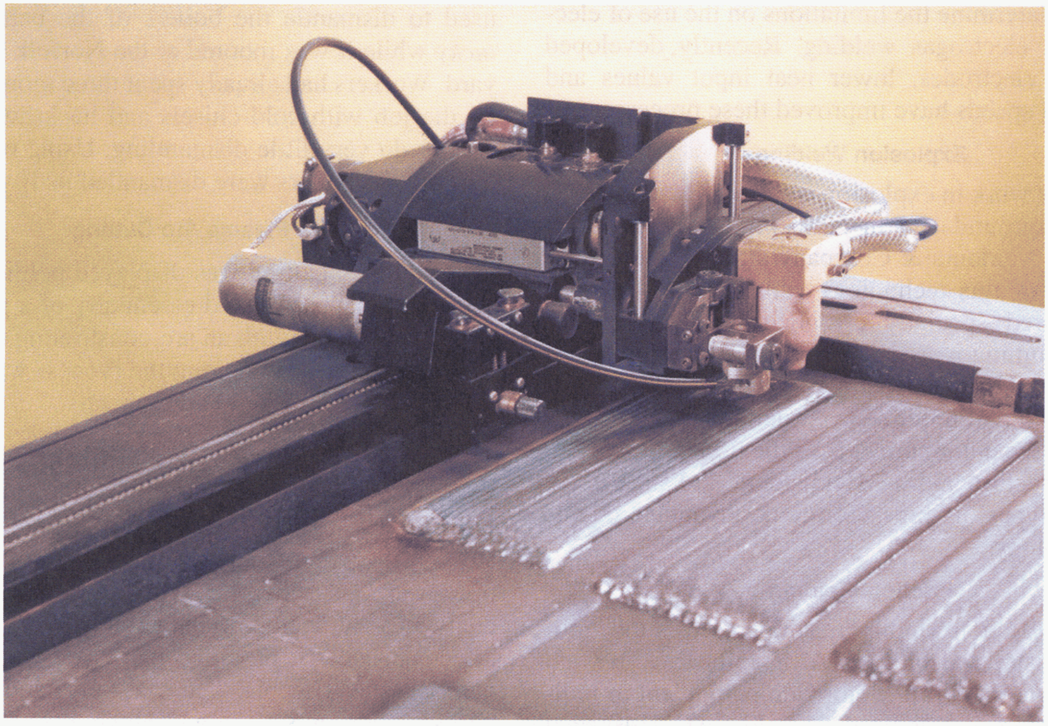
Clark Book Co., Houston, Tex. *Golden Anniversary Number, The Oil and Gas Journal.* May 1951. Petroleum Publishing Co., Tulsa, Okla.

The LTEC Story: Eighty Years in the Making. The ESAB Group, Florence, S. C. Company News.

The New York Times, Nov. 13, 1992.

Stinchcomb, C. 1989. *Welding Technology Today.* Prentice Hall, Englewood Cliffs, N. J.

Moley, R. 1962. *The American Century of John C. Lincoln.* Duell, Sloan and Pearce, New York.



Plasma arc hot wire cladding is used to build up the thickness of metal for hardfacing to increase wear resistance

Appendix 2
Major Associations of the Welding Industry

Abrasives Engineering Society (AES)
108 Elliott Drive
Butler, PA 16001-1118
tel. (412) 282-6210
fax (412) 282-6210

Aluminum Association (AA)
900 19th Street, N.W.
Suite 300
Washington, DC 20006
tel. (202) 862-5100
fax (202) 862-5164

American Association of State Highway and Transportation Officials (AASHTO)
444 N. Capital Street, N.W.
Suite 249
Washington, DC 20001
tel. (202) 624-5800
fax (202) 624-5806

American Bureau of Shipping (ABS)
Two World Trade Center
106th Floor
New York, NY 10048
tel. (212) 839-5000
fax (212) 839-5130

American Gas Association (AGA)
1515 Wilson Boulevard
Arlington, VA 22209
tel. (703) 841-8400
fax (703) 841-8406

American Institute of Mining, Metallurgical and Petroleum Engineers (AIME)
345 East 47th Street
New York, NY 10017
tel. (212) 705-7695
fax (212) 371-9622

American Institute of Steel Construction (AISC)
One E. Wacker Drive
Suite 3100
Chicago, IL 60601-2001
tel. (312) 670-2400
fax (312) 670-5403

American Iron and Steel Institute (AISI)
1101 17th Street, N.W.
Washington, DC 20036-4700
tel. (202) 452-7100
fax (202) 463-6573

American National Standards Institute (ANSI)
11 West 42nd Street
13th Floor
New York, NY 10036-8002
tel. (212) 642-4900
fax (212) 398-0023

American Petroleum Institute (API)
1220 L Street, N.W.
Washington, DC 20005-8029
tel. (202) 682-8000
fax (202) 682-8115

American Railway Engineering Association (AREA)
50 F Street, N.W.
Suite 7702
Washington, D.C. 20001-2183
tel. (202) 639-2190
fax (202) 639-2183

American Society for Nondestructive Testing (ASNT)
1711 Arlingate Lane
P.O. Box 28518
Columbus, OH 43228-0518
tel. (614) 274-6003
fax (614) 274-6899

American Society for Quality Control (ASQC)
P.O. Box 3005
611 East Wisconsin Avenue
Milwaukee, WI 53201-3005
tel. (414) 272-8575
fax (414) 272-1734

American Society for Testing Materials (ASTM)
100 Barr Harbor Drive
W. Conshohocken, PA 19428
tel. (610) 832-9686
fax (610) 832-9668

American Society of Civil Engineers (ASCE)
345 East 47th Street
New York, NY 10017
tel. (212) 705-7496
fax (212) 355-0608

American Society of Mechanical Engineers (ASME)
345 East 47th Street
New York, NY 10017-2392
tel. (212) 705-7722
fax (212) 705-7674

American Society of Safety Engineers (ASSE)
1800 East Oakton
Des Plaines, IL 60018-2187
tel. (708) 692-4121
fax (708) 296-3769

American Water Works Association (AWWA)
6666 W. Quincy Avenue
Denver, CO 80235
tel. (303) 794-7711
fax (303) 794-7310

American Welding Institute (AWI)
10628 Dutchtown Road
Knoxville, TN 37932
tel. (615) 675-2150
fax (615) 675-6081

American Welding Society (AWS)
550 N.W. LeJeune Road
Miami, FL 33126
tel. (305) 443-9353
fax (305) 443-7559

ASM International (ASM)
Route 87
Metals Park, OH 44073
tel. (216) 338-5151
fax (216) 338-4634

Association of American Railroads (AAR)
50 F Street, N.W.
Washington, DC 20001-1564
tel. (202) 639-2100
fax (202) 639-5546

Association of Iron and Steel Engineers (AISE)
Three Gateway Center
Suite 2350
Pittsburgh, PA 15222
tel. (412) 281-6323
fax (412) 281-4657

Canadian Standards Association (CSA)
178 Rexdale Boulevard
Rexdale, Ontario
Canada M9W 1R3
tel. (416) 747-4311
fax (416) 747-4149

Canadian Welding Bureau (CWB)
254 Merton Street
Toronto, Ontario M4S 1A9
Canada
tel. (416) 487-5415

Compressed Gas Association (CGA)
1725 Jefferson Davis Highway
Suite 1004
Arlington VA 22202-4104
tel. (703) 412-0900
fax (703) 412-0128

Copper Development Association
260 Madison Avenue
New York, NY 10016-2401
tel. (212) 251-7200
fax (212) 251-7234

Edison Welding Institute (EWI)
1250 Arthur E. Adams Drive
Columbus, OH 43210
tel. (614) 688-5000
fax (614) 688-5001

Fabricators & Manufacturers' Association International (FMA)
833 Featherstone Road
Rockford, IL 61107-6302
tel. (815) 399-8700
fax (815) 399-7279

International Institute of Welding (IIW)
550 N.W. LeJeune Road
Miami, FL 33126
tel. (305) 443-9353
fax (305) 443-7559

International Organization for Standardization (ISO)
(See American National Standards Institute)

International Oxygen Manufacturers' Association (IOMA)
P.O. Box 16248
Cleveland, OH 44116-0248
tel. (216) 228-2166
fax (216) 228-5810

International Titanium Association
1871 Folsom Street, Suite 100
Boulder, CO 80302
tel. (303) 443-7515
fax (303) 443-4406

National Association of Corrosion Engineers (NACE)
Box 218340
Houston, TX 77218-8340
tel. (713) 492-0535
fax (713) 492-8254

National Board of Boiler and Pressure Vessel Inspectors (NBBPVI)
1055 Crupper Avenue
Columbus, OH 43229
tel. (614) 888-8320
fax (614) 888-0750

National Electrical Manufacturers' Association (NEMA)
2101 L Street, N.W.
Washington, DC 20037
tel. (202) 457-8400
fax (202) 457-8411

National Fire Protection Association (NFPA)
P.O. Box 9101
Batterymarch Park
Quincy, MA 02269-9101
tel. (617) 770-3000
fax (617) 770-0700

National Institute of Standards and Technology (NIST)
325 Broadway
Boulder, CO 80303
tel. (303) 497-3000

National Electrical Manufacturers Association (NEMA)
1300 N. 17th Street
Suite 1847
Rosslyn, VA 22209
tel. (703) 841-3200
fax (703) 841-5900

National Welding Supply Association (NWSA)
1900 Arch Street
Philadelphia, PA 19103
tel. (215) 564-3484
fax (215) 564-2175

Naval Publication and Forms Center
5801 Tabor Avenue
Philidelphia, PA 19120
tel. (215) 697-2000

Nickel Development Institute (NiDI)
214 King Street West
Suite 500
Toronto, Ontario
Canada M5H 356
tel. (416) 591-7999
fax (416) 591-7987

Resistance Welder Manufacturers Association (RWMA)
1900 Arch Street
Philadelphia, PA 19103
tel. (215) 564-3484
fax (215) 564-2175

Robotic Industries Association
900 Victors Way
Ann Arbor, MI 48106
tel. (313) 994-6088
fax (313) 994-3338

Society of Automotive Engineers (SAE)
400 Commonwealth Drive
Warrandale, PA 15096
tel. (412) 776-4841
fax (412) 776-5760

Society of Manufacturing Engineers (SME)
One SME Drive
P.O. Box 930
Dearborn, MI 48121
tel. (313) 271-1500
fax (313) 271-2861

Steel Tank Institute (STI)
570 Oakwood Road
Lake Zurich, IL 60047-1559
tel. (708) 438-8265
fax (708) 438-8766

Steel Tube Institute of North America
8500 Station Street
Suite 270
Mentor, OH 44060
tel. (216) 974-6990
fax (216) 974-6994

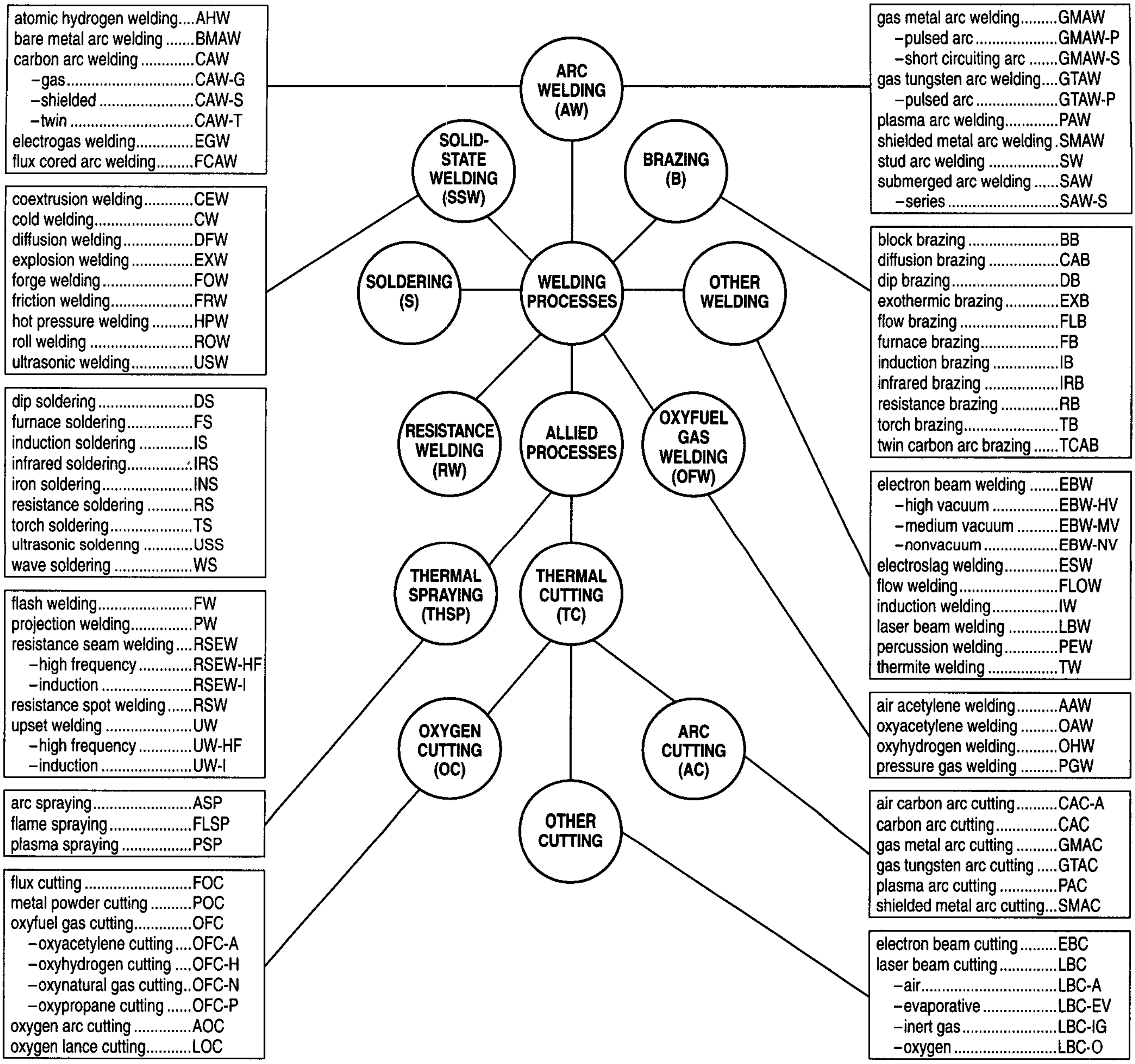
Ultrasonic Industry Association (UIA)
3738 Hilliard Cemetery Road
P.O. Box 628
Hilliard, OH 43026-8353
tel. (614) 771-1972
fax (614) 771-1984

Underwriters Laboratories, Inc. (UL)
333 Pfingsten Road
Northbrook, IL 60062
tel. (847) 272-8800
fax (847) 272-8129

Uniform Boiler and Pressure Vessel Laws Society (UBPVLS)
308 N. Evergreen Road
Suite 240
Louisville, KY 40243-1010
tel. (502) 244-6029
fax (502) 244-6030

Welding Research Council (WRC)
345 East 47th Street
Suite 1301
New York, NY 10017
tel. (212) 705-7956
fax (212) 371-9622

Appendix 3
Master Chart of Welding and Allied Processes



atomic hydrogen welding	AHW
bare metal arc welding	BMAW
carbon arc welding	CAW
–gas	CAW-G
–shielded	CAW-S
–twin	CAW-T
electrogas welding	EGW
flux cored arc welding	FCAW

coextrusion welding	CEW
cold welding	CW
diffusion welding	DFW
explosion welding	EXW
forge welding	FOW
friction welding	FRW
hot pressure welding	HPW
roll welding	ROW
ultrasonic welding	USW

dip soldering	DS
furnace soldering	FS
induction soldering	IS
infrared soldering	IRS
iron soldering	INS
resistance soldering	RS
torch soldering	TS
ultrasonic soldering	USS
wave soldering	WS

flash welding	FW
projection welding	PW
resistance seam welding	RSEW
–high frequency	RSEW-HF
–induction	RSEW-I
resistance spot welding	RSW
upset welding	UW
–high frequency	UW-HF
–induction	UW-I

arc spraying	ASP
flame spraying	FLSP
plasma spraying	PSP

flux cutting	FOC
metal powder cutting	POC
oxyfuel gas cutting	OFC
–oxyacetylene cutting	OFC-A
–oxyhydrogen cutting	OFC-H
–oxynatural gas cutting	OFC-N
–oxypropane cutting	OFC-P
oxygen arc cutting	AOC
oxygen lance cutting	LOC

gas metal arc welding	GMAW
–pulsed arc	GMAW-P
–short circuiting arc	GMAW-S
gas tungsten arc welding	GTAW
–pulsed arc	GTAW-P
plasma arc welding	PAW
shielded metal arc welding	SMAW
stud arc welding	SW
submerged arc welding	SAW
–series	SAW-S

block brazing	BB
diffusion brazing	CAB
dip brazing	DB
exothermic brazing	EXB
flow brazing	FLB
furnace brazing	FB
induction brazing	IB
infrared brazing	IRB
resistance brazing	RB
torch brazing	TB
twin carbon arc brazing	TCAB

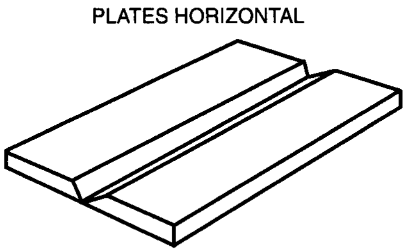
electron beam welding	EBW
–high vacuum	EBW-HV
–medium vacuum	EBW-MV
–nonvacuum	EBW-NV
electroslag welding	ESW
flow welding	FLOW
induction welding	IW
laser beam welding	LBW
percussion welding	PEW
thermite welding	TW

air acetylene welding	AAW
oxyacetylene welding	OAW
oxyhydrogen welding	OHW
pressure gas welding	PGW

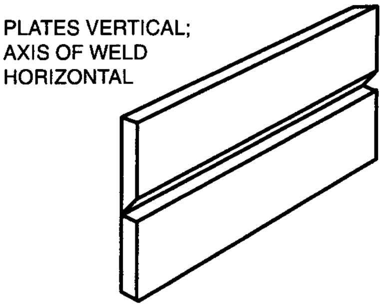
air carbon arc cutting	CAC-A
carbon arc cutting	CAC
gas metal arc cutting	GMAC
gas tungsten arc cutting	GTAC
plasma arc cutting	PAC
shielded metal arc cutting	SMAC

electron beam cutting	EBC
laser beam cutting	LBC
–air	LBC-A
–evaporative	LBC-EV
–inert gas	LBC-IG
–oxygen	LBC-O

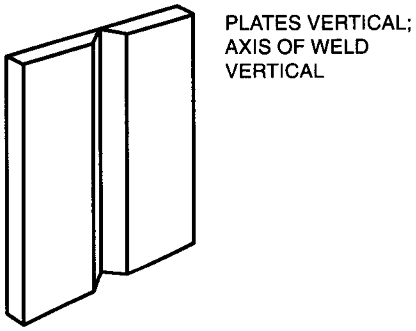
Appendix 4
Welding Test Positions



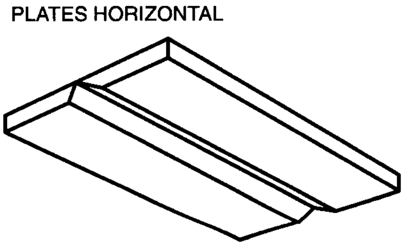
(A) TEST POSITION 1G



(B) TEST POSITION 2G

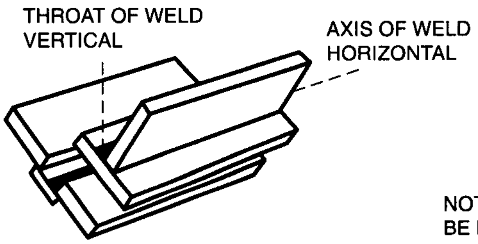


(C) TEST POSITION 3G

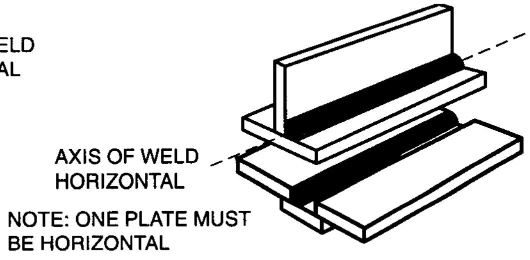


(D) TEST POSITION 4G

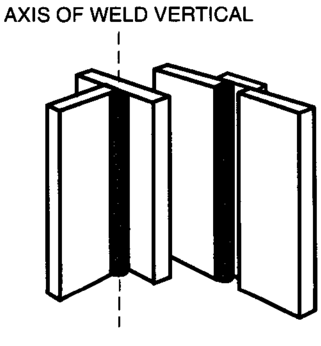
Positions for Test Plates for Groove Welds



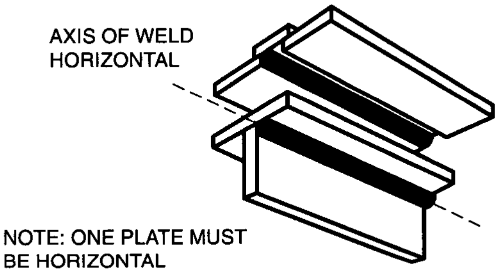
(A) FLAT POSITION 1F



(B) HORIZONTAL POSITION 2F

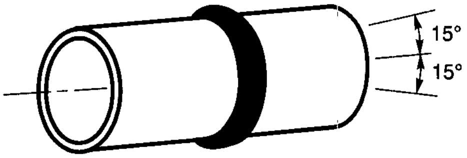


(C) VERTICAL POSITION 3F



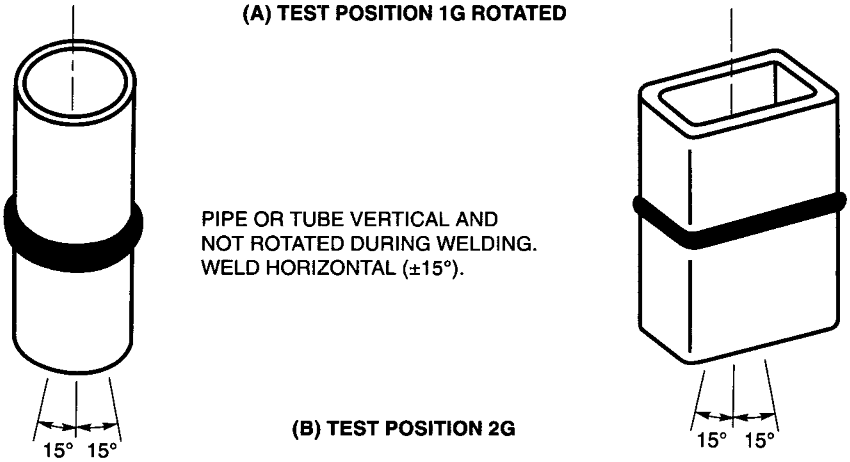
(D) OVERHEAD POSITION 4F

Positions of Test Plates for Fillet Welds



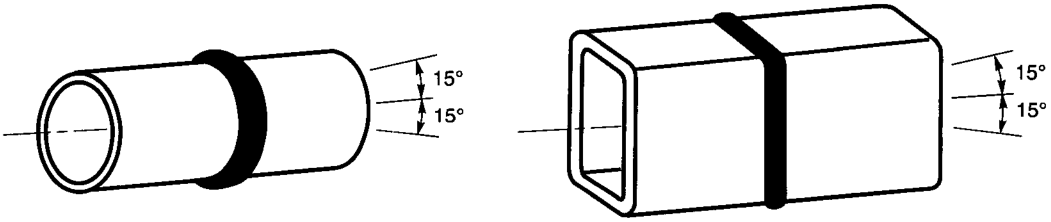
PIPE HORIZONTAL AND ROTATED.
WELD FLAT (±15°). DEPOSIT
FILLER METAL AT OR NEAR THE TOP.

(A) TEST POSITION 1G ROTATED



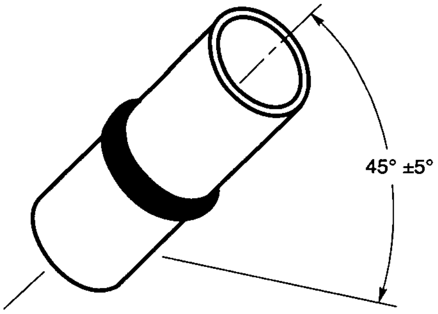
PIPE OR TUBE VERTICAL AND
NOT ROTATED DURING WELDING.
WELD HORIZONTAL (±15°).

(B) TEST POSITION 2G



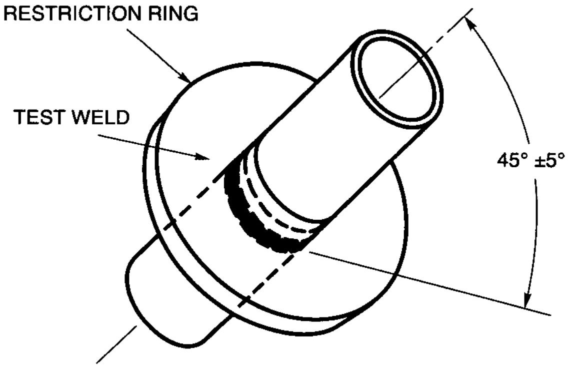
PIPE OR TUBE HORIZONTAL FIXED (±15°) AND NOT ROTATED DURING WELDING.
WELD FLAT, VERTICAL, OVERHEAD.

(C) TEST POSITION 5G



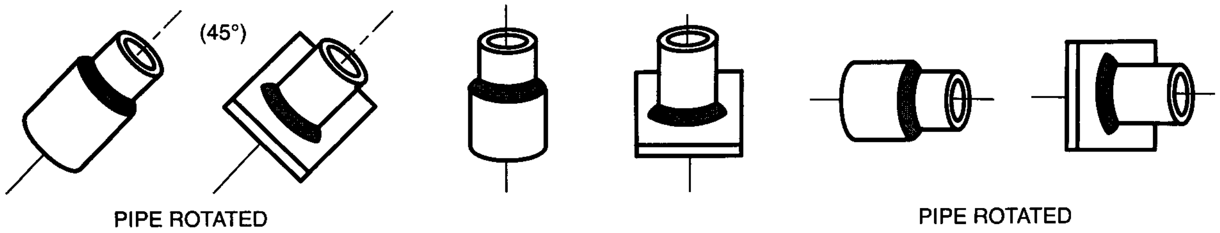
PIPE INCLINATION FIXED (45° ±5°) AND NOT
ROTATED DURING WELDING.

(D) TEST POSITION 6G



(E) TEST POSITION 6GR (T-, Y- OR K-CONNECTIONS)

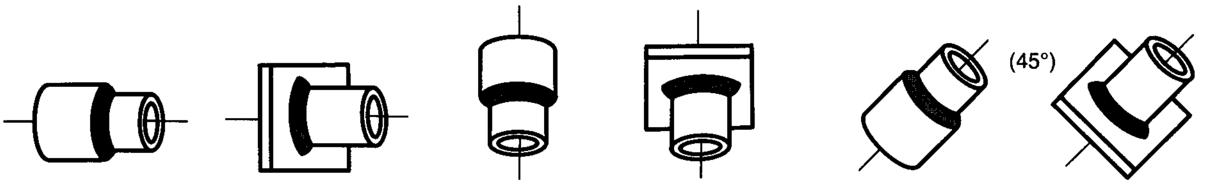
Positions of Test Pipe for Groove Welds



(A) FLAT WELDING TEST POSITION — 1F

(B) HORIZONTAL WELDING TEST POSITION — 2F

(C) HORIZONTAL WELDING TEST POSITION — 2FR



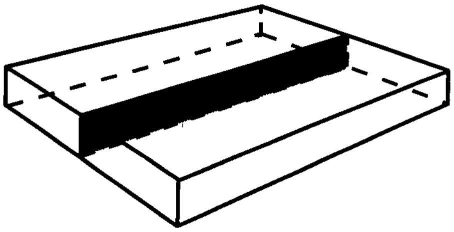
(D) OVERHEAD WELDING TEST POSITION — 4F

(E) MULTIPLE WELDING TEST POSITION — 5F

(F) MULTIPLE WELDING TEST POSITION — 6F

Positions of Test Pipes for Fillet Welds

Appendix 5
Types of Weld Joints

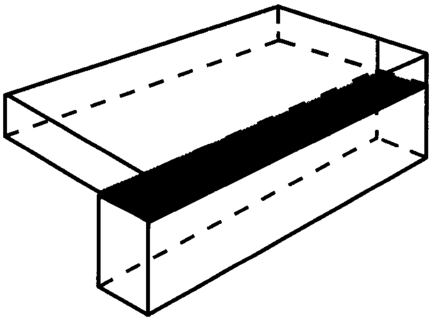


(A) BUTT JOINT

APPLICABLE WELDS

BEVEL-GROOVE
FLARE-BEVEL-GROOVE
FLARE-V-GROOVE
J-GROOVE
SQUARE-GROOVE

U-GROOVE
V-GROOVE
EDGE-FLANGE
BRAZE

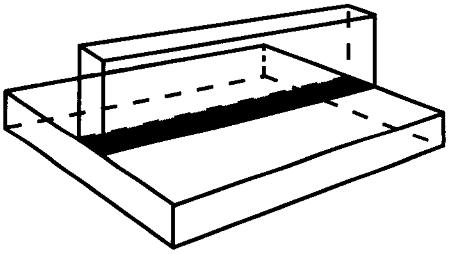


(B) CORNER JOINT

APPLICABLE WELDS

FILLET
BEVEL-GROOVE
FLARE-BEVEL-GROOVE
FLARE-V-GROOVE
J-GROOVE
SQUARE-GROOVE
U-GROOVE

V-GROOVE
PLUG
SLOT
SPOT
SEAM
PROJECTION
BRAZE

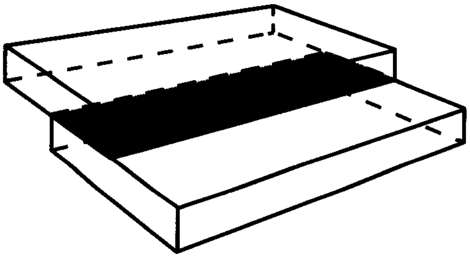


(C) T-JOINT

APPLICABLE WELDS

FILLET
BEVEL-GROOVE
FLARE-BEVEL-GROOVE
J-GROOVE
SQUARE-GROOVE
PLUG

SLOT
SPOT
SEAM
PROJECTION
BRAZE

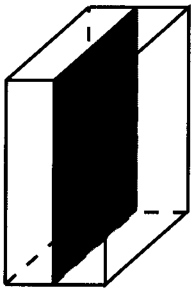


(D) LAP JOINT

APPLICABLE WELDS

FILLET
BEVEL-GROOVE
FLARE-BEVEL-GROOVE
J-GROOVE
PLUG

SLOT
SPOT
SEAM
PROJECTION
BRAZE



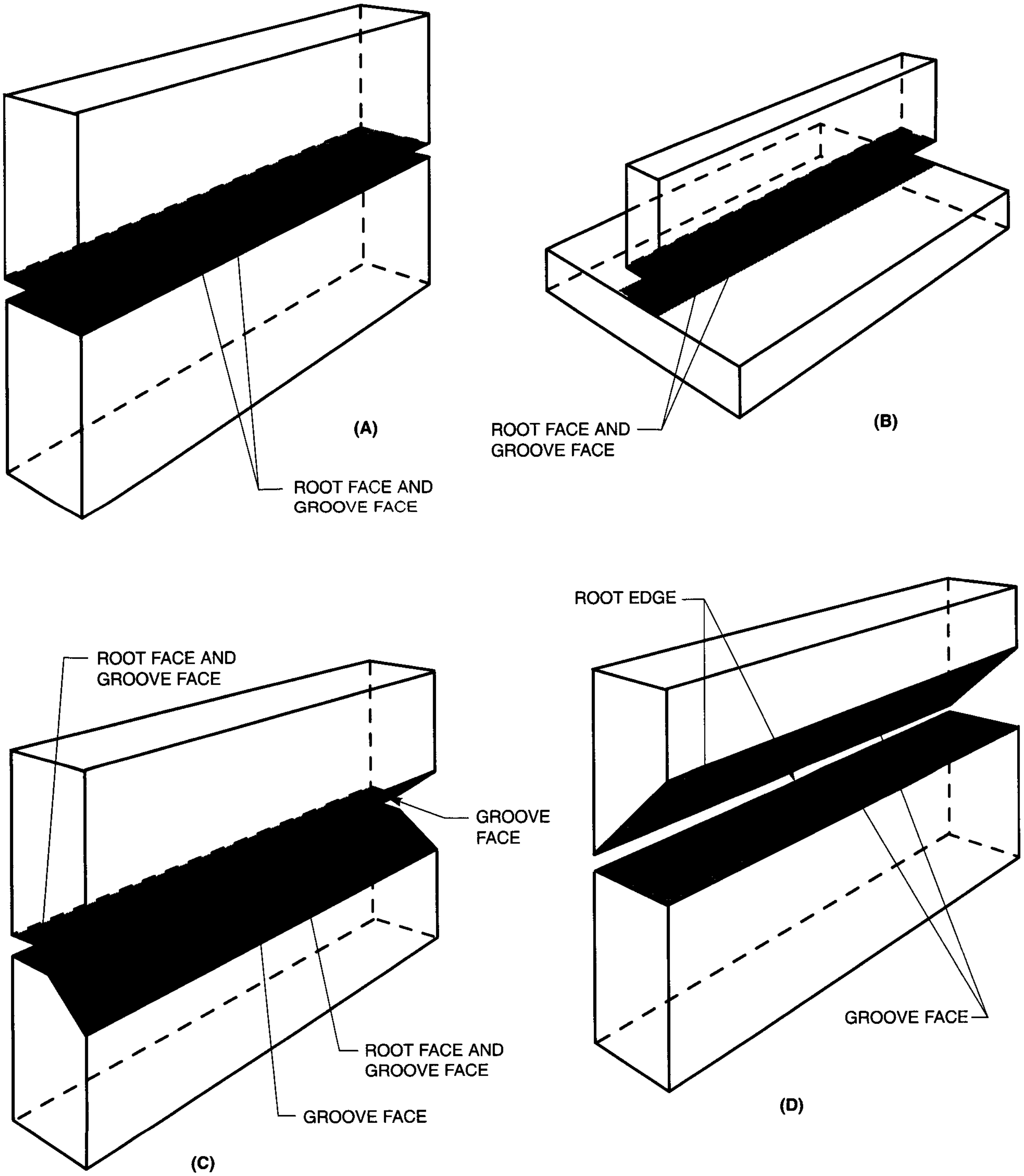
(E) EDGE JOINT

APPLICABLE WELDS

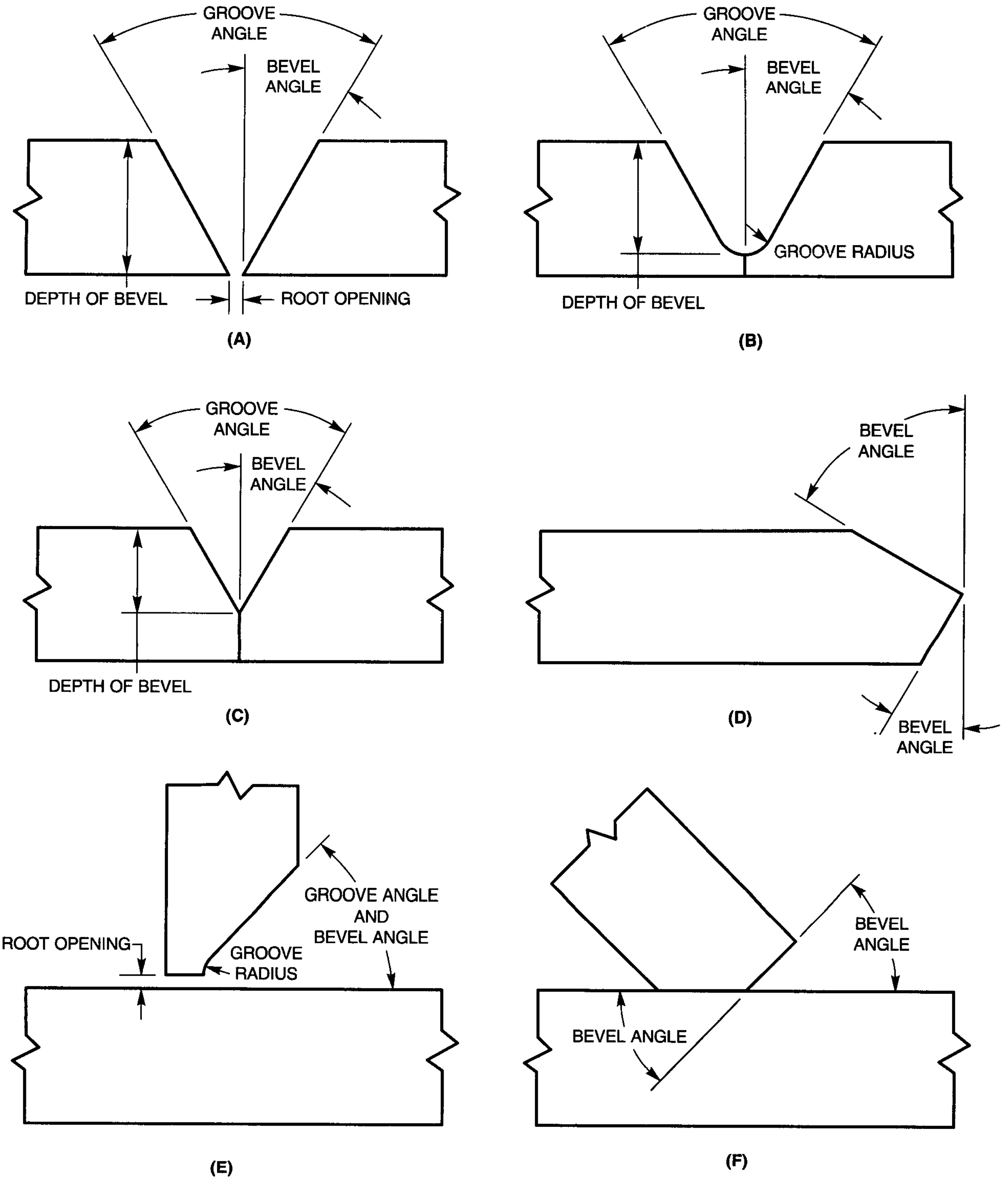
BEVEL-GROOVE
FLARE-BEVEL-GROOVE
FLARE-V-GROOVE
J-GROOVE
SQUARE-GROOVE

U-GROOVE
V-GROOVE
EDGE
SEAM

Appendix 6
Weld Joint Preparation



Section 1—Groove Face, Root Edge, and Root Face



Section 2—Bevel Angle, Depth of Bevel, Groove Angle, Groove Radius, and Root Opening

(A) SQUARE EDGE SHAPE

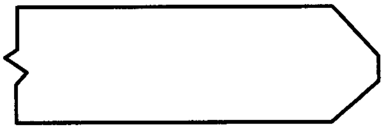
APPLICABLE WELDS

DOUBLE-BEVEL-GROOVE
DOUBLE-BEVEL-FLARE-GROOVE
DOUBLE-J-GROOVE
SINGLE-BEVEL-GROOVE
SINGLE-FLARE-BEVEL-GROOVE
SINGLE-J-GROOVE
SQUARE-GROOVE
EDGE
FILLET
BRAZE

(B) SINGLE-BEVEL EDGE SHAPE

APPLICABLE WELDS

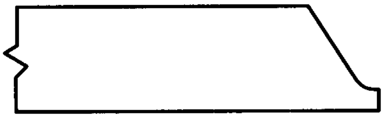
SINGLE-BEVEL-GROOVE
SINGLE-V-GROOVE
BRAZE



(C) DOUBLE-BEVEL EDGE SHAPE

APPLICABLE WELDS

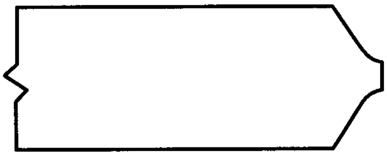
DOUBLE-BEVEL-GROOVE
DOUBLE-V-GROOVE



(D) SINGLE-J EDGE SHAPE

APPLICABLE WELDS

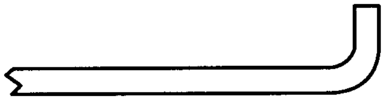
SINGLE-J-GROOVE
SINGLE-U-GROOVE



(E) DOUBLE-J EDGE SHAPE

APPLICABLE WELDS

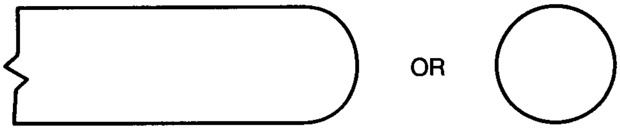
DOUBLE-J-GROOVE
DOUBLE-U-GROOVE



(F) FLANGED EDGE SHAPE

APPLICABLE WELDS

SINGLE-FLARE-BEVEL-GROOVE
SINGLE-FLARE-V-GROOVE
EDGE
FILLET
PROJECTION
SEAM
SPOT
BRAZE



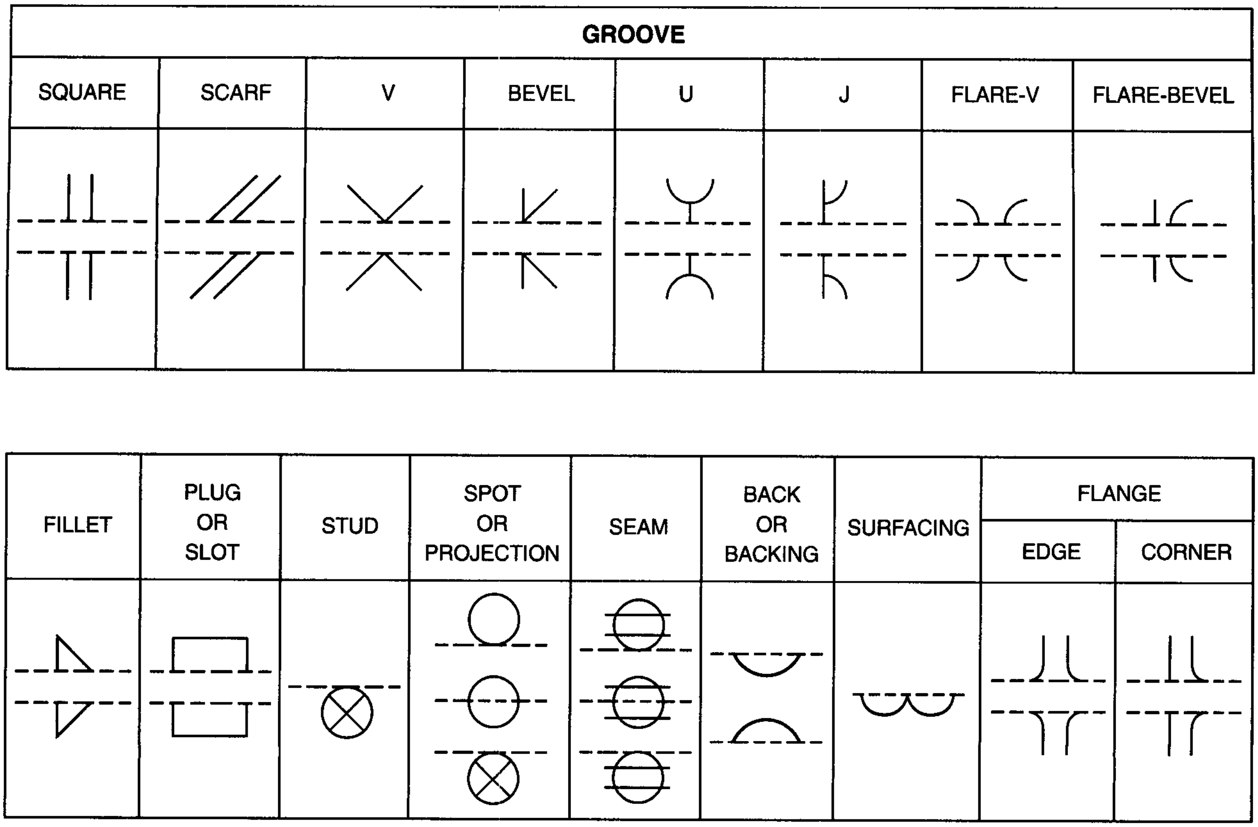
(G) ROUND EDGE SHAPE

APPLICABLE WELDS

DOUBLE-FLARE-BEVEL-GROOVE
DOUBLE-FLARE-V-GROOVE
BRAZE

Section 3—Edge Shapes

Appendix 7
Welding Symbols



NOTE: THE REFERENCE LINE IS SHOWN DASHED FOR ILLUSTRATIVE PURPOSES.

Figure 7-1—Weld Symbols

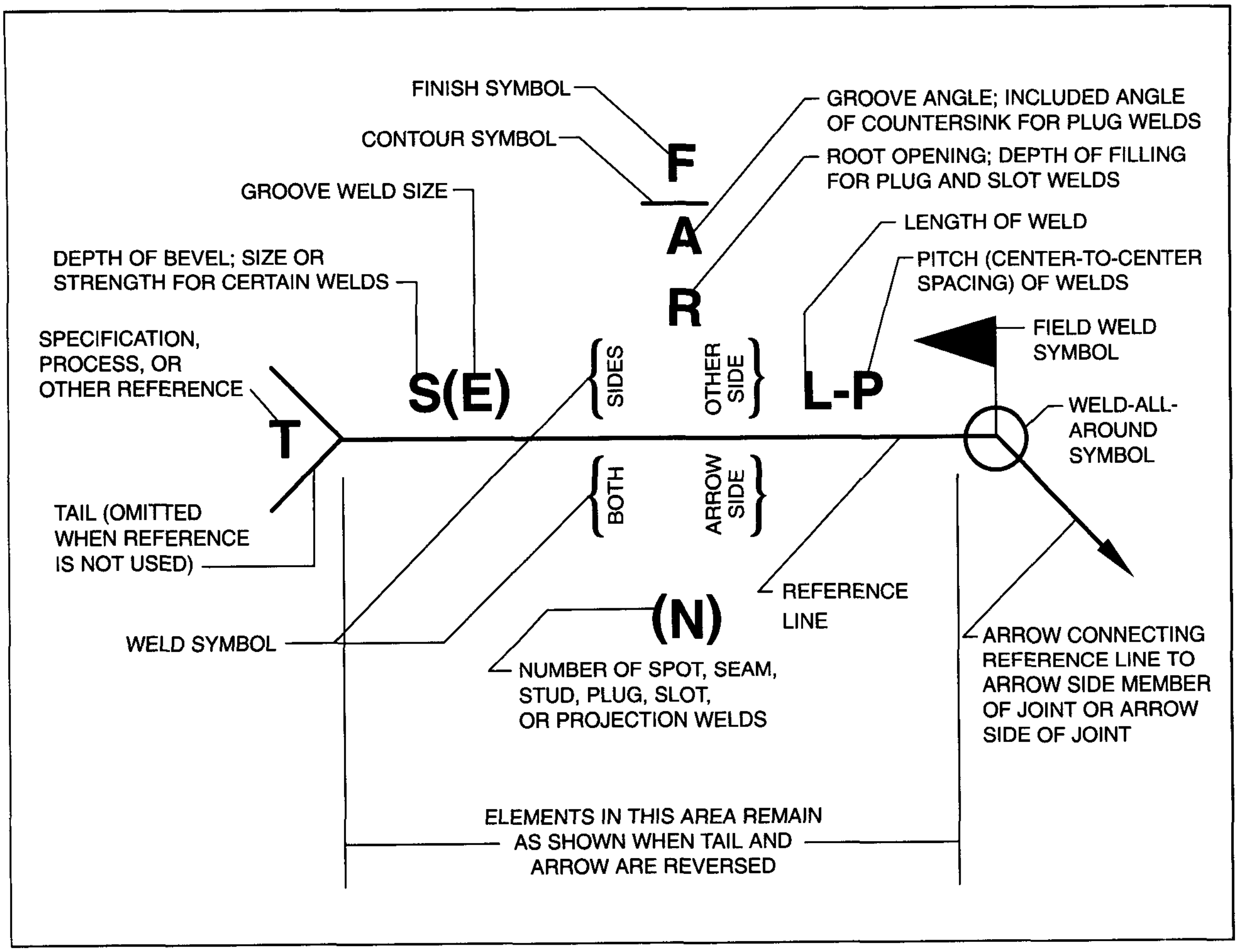


Figure 7-2—Standard Location of Elements of a Welding Symbol

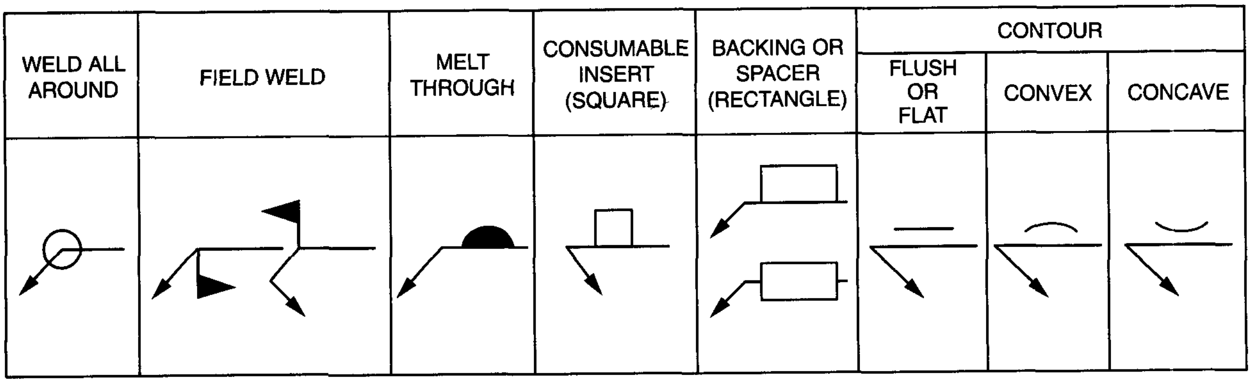
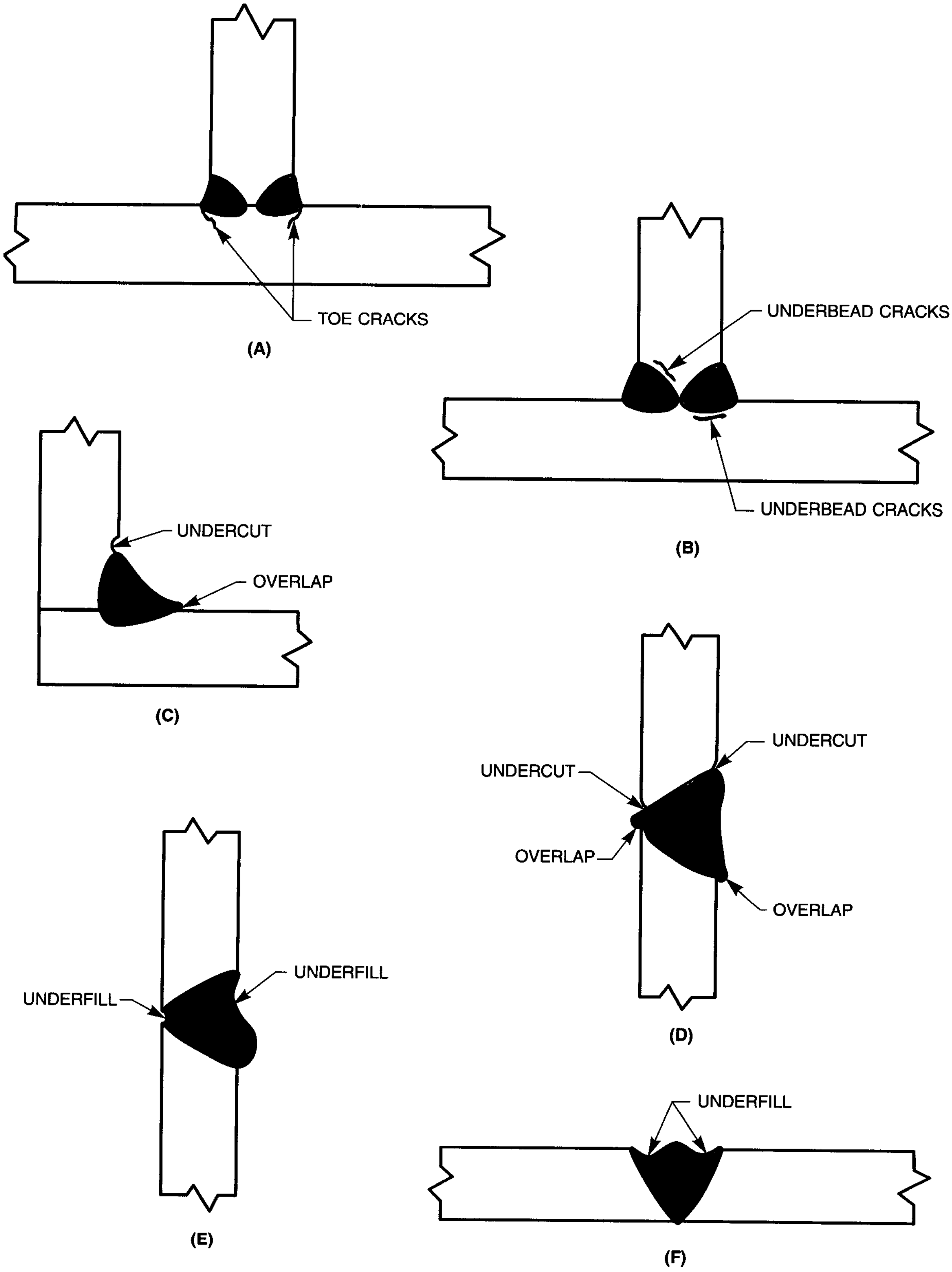
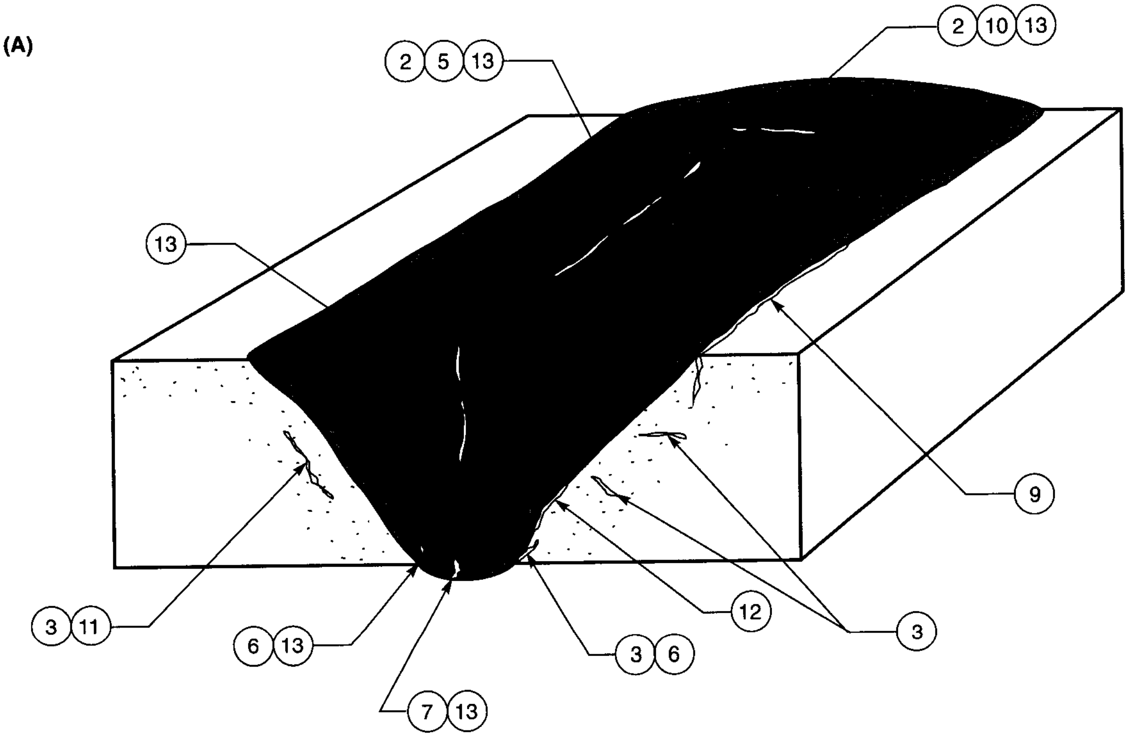


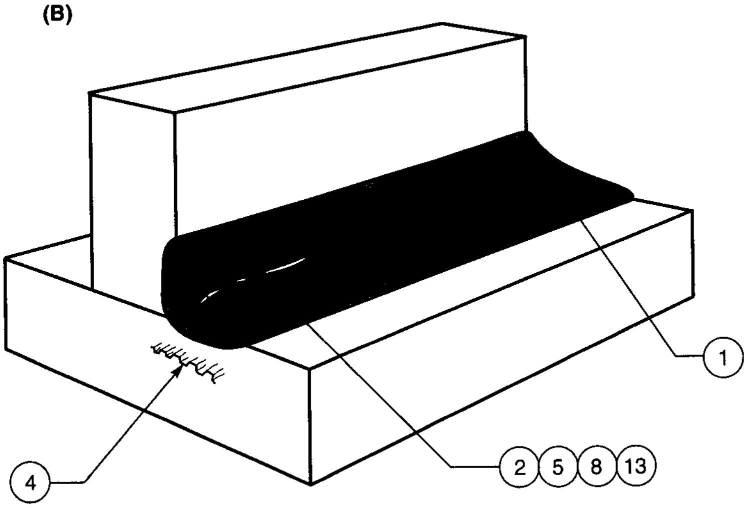
Figure 7-3—Supplementary Symbols

Appendix 8
Weld Discontinuities



Appendix 9
Types of Weld Cracks

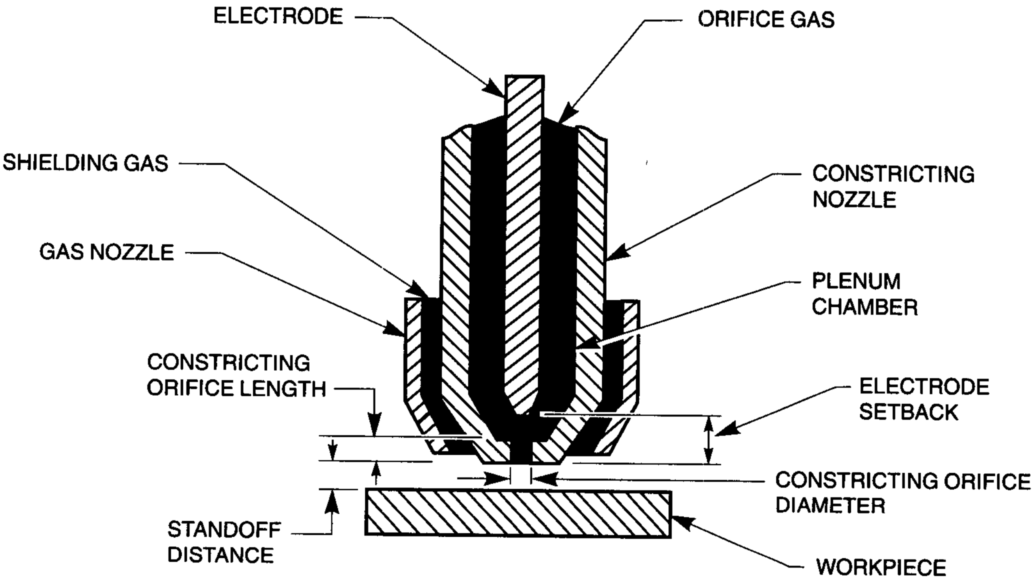




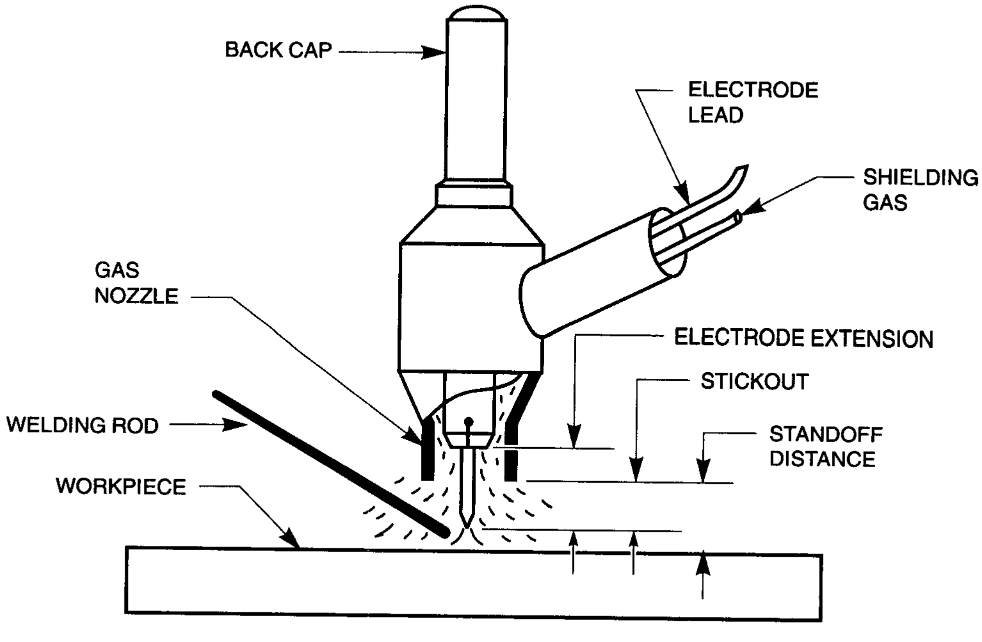
LEGEND:

1 CRATER CRACK
2 FACE CRACK
3 HEAT-AFFECTED ZONE CRACK
4 LAMELLAR TEAR
5 LONGITUDINAL CRACK
6 ROOT CRACK
7 ROOT SURFACE CRACK
8 THROAT CRACK
9 TOE CRACK
10 TRANSVERSE CRACK
11 UNDERBEAD CRACK
12 WELD INTERFACE CRACK
13 WELD METAL CRACK

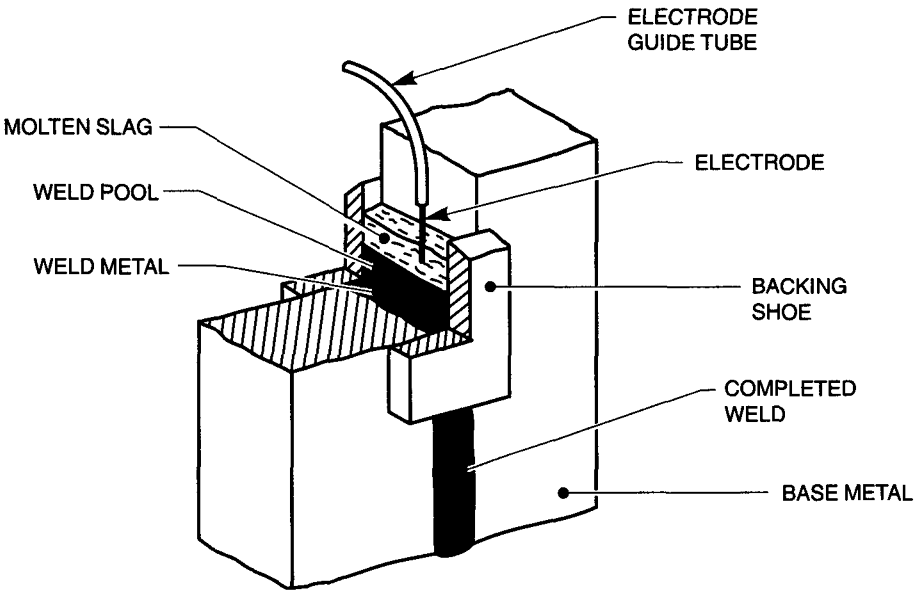
Appendix 10
Torch Nomenclature



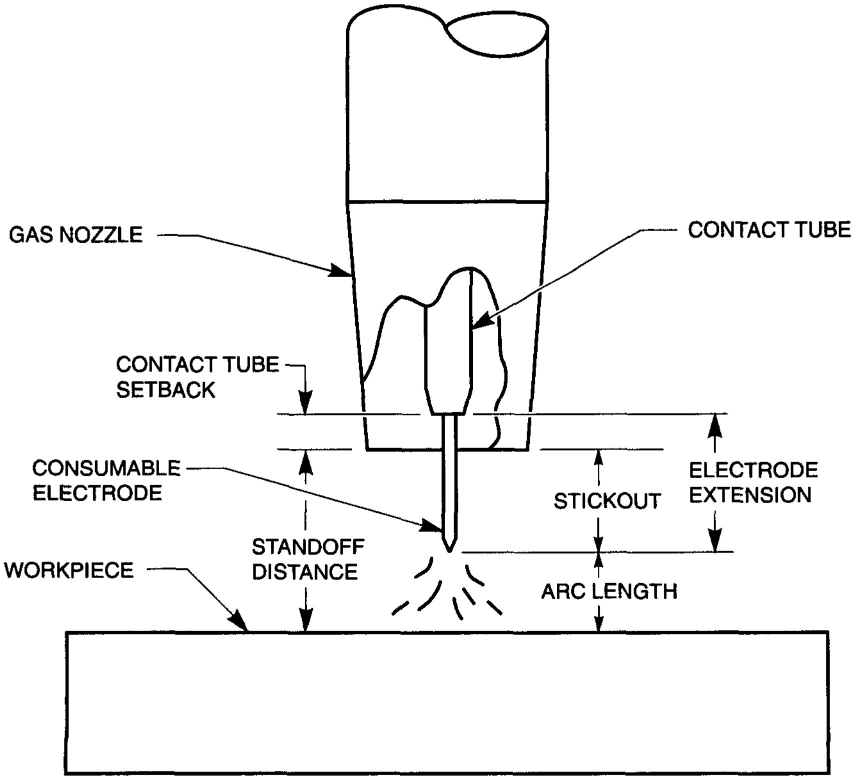
(A)
PLASMA ARC TORCH NOMENCLATURE



(B)
GAS TUNGSTEN ARC WELDING TORCH NOMENCLATURE

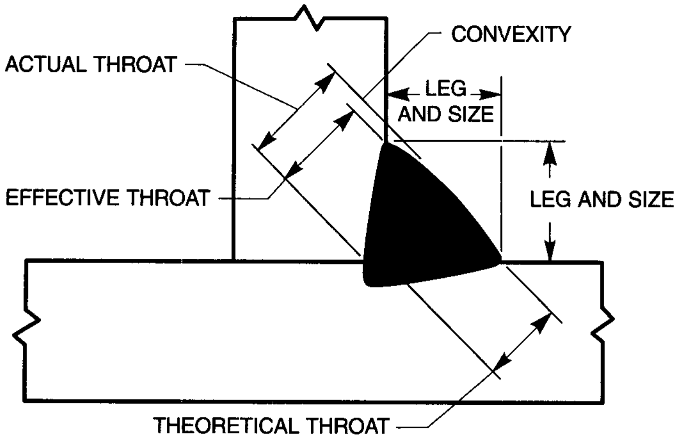


(C)
TYPICAL ARRANGEMENT FOR ELECTROSLAG WELDING PROCESS NOMENCLATURE

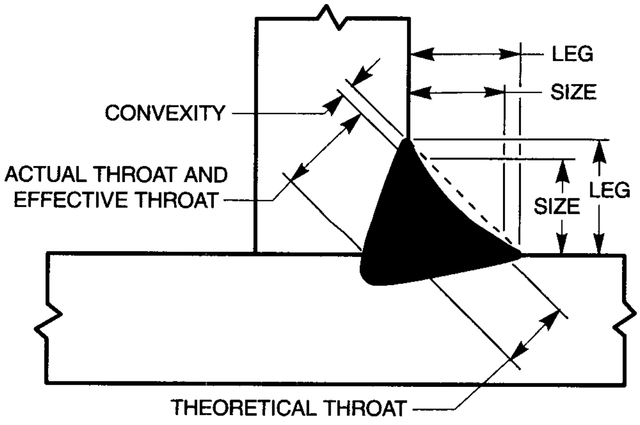


(D)
GAS METAL ARC WELDING GUN NOMENCLATURE

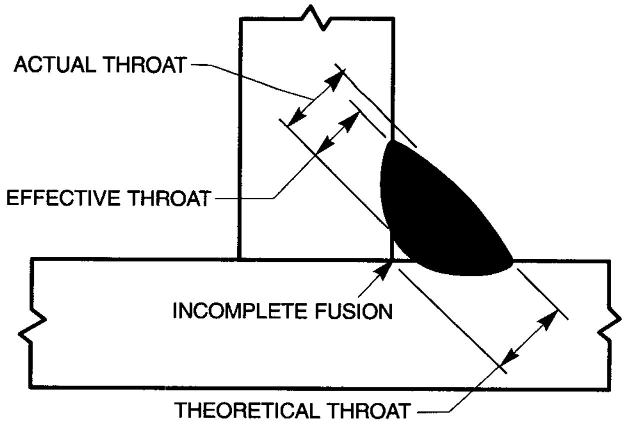
Appendix 11
Weld Sizes



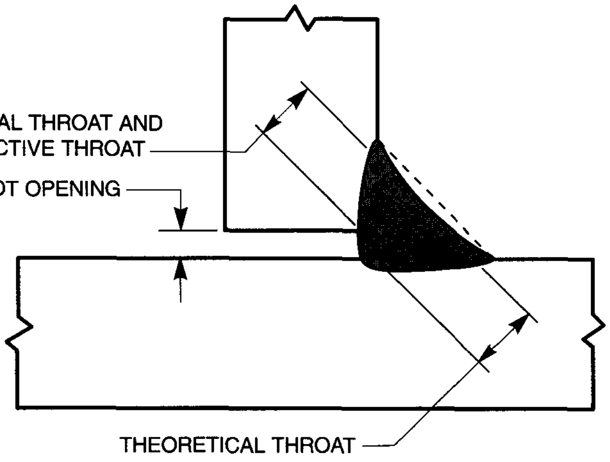
(A) CONVEX FILLET WELD



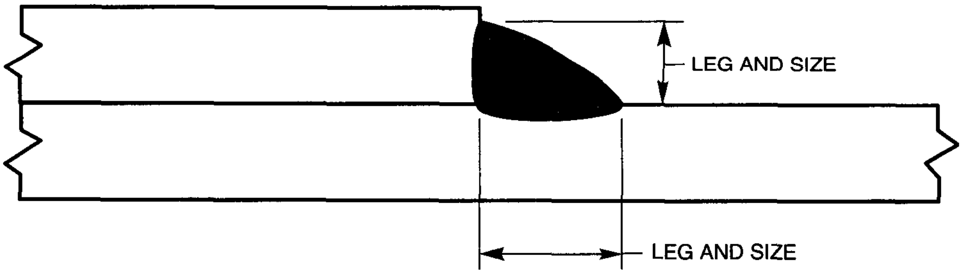
(B) CONCAVE FILLET WELD



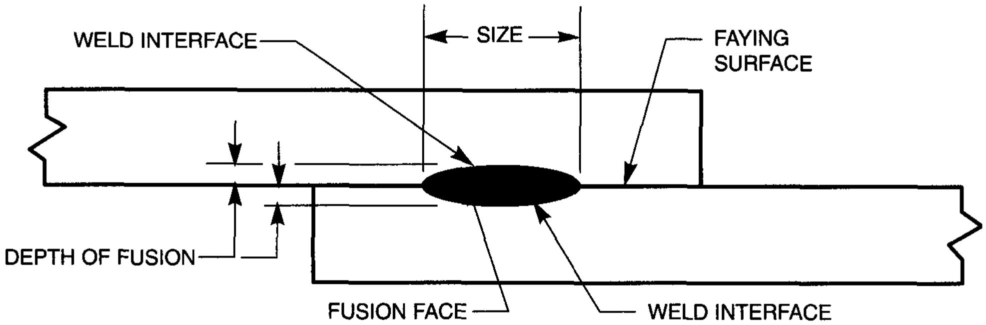
(C) FILLET WELD WITH INCOMPLETE FUSION



(D) T-JOINT WITH ROOT OPENING



(E) UNEQUAL LEG FILLET WELD



(F) RESISTANCE SPOT OR SEAM WELD

Appendix 12
Joint Penetration

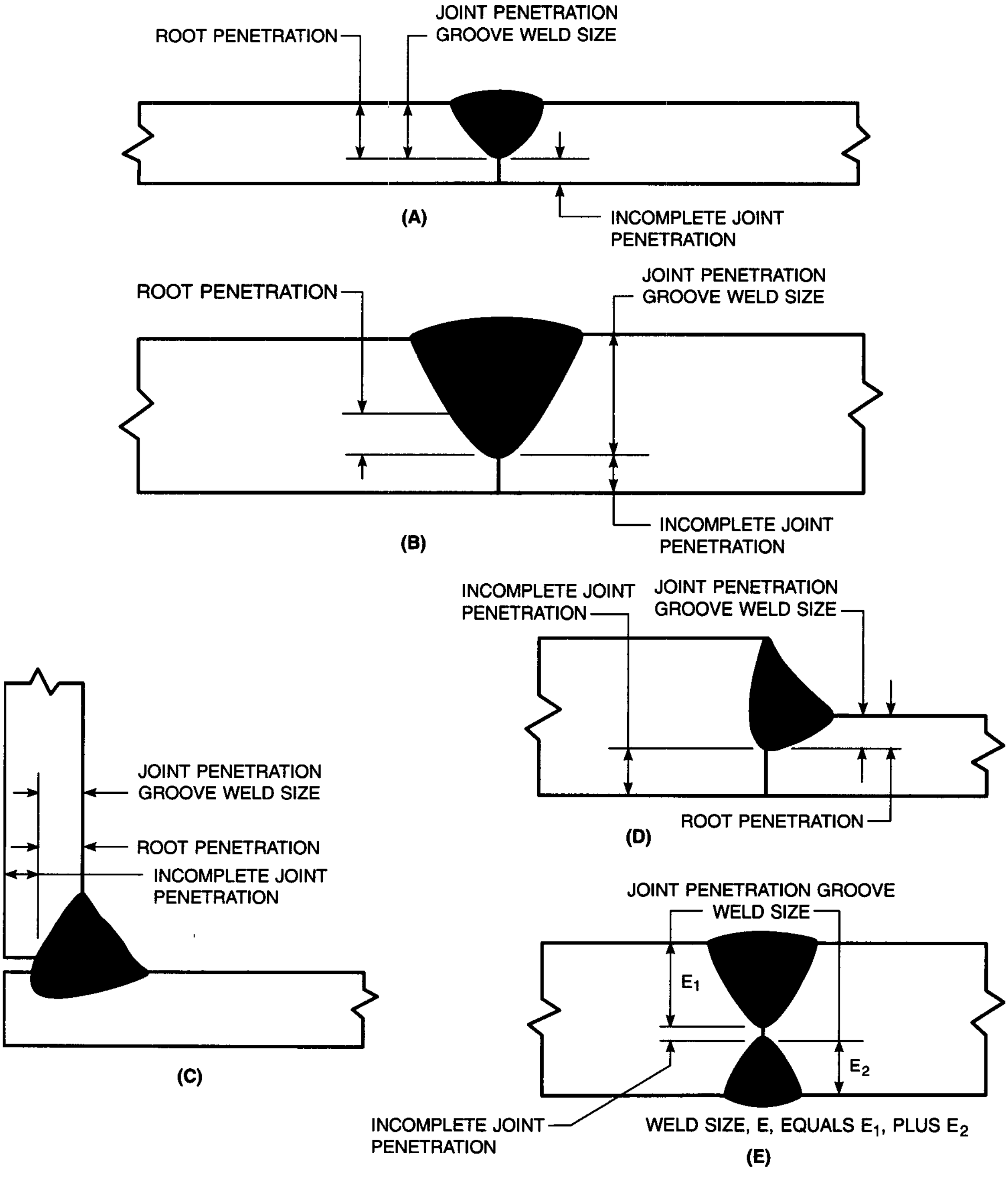


Figure 12-1—Joint Penetration, Root Penetration, and Incomplete Joint Penetration

Appendix 13
Safety

This Appendix covers the basic elements of safety general to all welding, cutting, thermal spraying, and related processes. It includes safety procedures common to a variety of applications. However, it does not cover all safety aspects of every process; especially not those involving sophisticated technology. For this reason, the manufacturers' literature should be referenced for additional important safety information.

Safety is an important consideration in all welding, cutting, and related work. No activity is satisfactorily completed if someone is injured. The hazards that may be encountered and the practices that will minimize personal injury and property damage are discussed.

Management Support. The most important components of an effective safety and health program are management support and direction. Management must clearly state objectives and demonstrate its commitment to safety and health by consistent execution of safe practices.

Management must designate approved areas where welding and cutting operations may be carried on safely. When these operations must be done in other than designated areas, management must assure that proper procedures are established and followed to protect personnel and property.

Management must be certain that only approved welding, cutting, and allied equipment is used. Such equipment includes torches, regulators, welding machines, electrode holders, and personal protective devices. Adequate supervision must be provided to assure that all equipment is properly used and maintained.

Training. Thorough and effective training is a key aspect of a safety program. Adequate training is mandated under provisions of the U.S. Occupational Safety and Health Act (OSHA), especially those of the Hazard Communication Standard (29 CFR 1910.1200). Welders and other equipment operators perform most safely when they are properly trained in the subject. (The term *welder* is intended to include all welding and cutting personnel, thermal sprayers, brazers, and solderers). Proper training includes instruction in the safe use of equipment and processes, and the safety rules that must be followed. Personnel need to know and understand the rules, and the consequences of disobeying them. For example, welders must be trained to position themselves while welding or cutting so that their heads are not in the gases or fume plume. (Fume plume is the smoke-like cloud containing minute solid particles arising directly from the area of melting metal). Distinct from gas, fumes are metallic vapors that have condensed to solids and are often associated with a chemical reaction, such as oxidation. Refer to American Welding Society, *Fumes and Gases in the Welding Environment*: Miami, Florida, 1979.

Certain American Welding Society (AWS) specifications call for precautionary labels on consumables and equipment. These labels concerning the safe use of the products should be read and followed. A typical label is illustrated in Figure 13-1.

WARNING: PROTECT yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health. ARC RAYS can injure eyes and burn. ELECTRIC SHOCK can KILL.

- **Read and understand the manufacturer's instructions and your employer's safety practices.**
- **Keep your head out of the fumes.**
- **Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases from your breather zone and the general area.**
- **Wear correct eye, ear, and body protection.**
- **Do not touch live electrical parts.**
- **See American National Standard Z49.1 "Safety in Welding and Cutting" published by the American Welding Society, 550 N.W. LeJeune Rd., Miami, Florida 33126; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.**

DO NOT REMOVE THIS LABEL

Figure 13-1—Minimum Warning Label for Arc Welding Processes and Equipment

Manufacturers of welding consumables must provide, on request, a *Material Safety Data Sheet* (MSDS) that identifies those materials present in their products that have hazardous physical or health properties. The MSDS provides the OSHA Permissible Exposure Limit (PEL), and any other exposure limit used or recommended by the manufacturer. Employers that use consumables must make the applicable MSDS readily available to their employees, as well as train them to read and understand the contents.

The MSDS contain important information about the ingredients contained in welding electrodes, rods, and fluxes, the composition of fumes which may be generated in their use, and the means to be followed to protect the welder and others from hazards which might be involved.

Under OSHA Hazard Communication Standard 29 CFR 1910.1200, employers are responsible for the training of employees with respect to hazardous materials used in their workplace. Many welding consumables are included in the definition of hazardous materials according to this standard. Welding employers must comply with the communication and training requirements of this standard.

The proper use and maintenance of the equipment must also be taught. For example, defective or worn electrical insulation cannot be tolerated in arc welding or cutting, nor can defective or worn hoses be used in oxyfuel gas welding and cutting, brazing, or soldering. Proper training in equipment operation is fundamental to safe operation.

General Housekeeping. Good housekeeping is essential to avoid injuries. A welder's vision is often restricted by necessary eye protection. Persons passing a welding station must shield their eyes from the flame or arc radiation. The limited vision of the welder and passers-by makes them vulnerable to tripping over objects on the floor. Therefore, welders and supervisors must always make sure that the area is clear of tripping hazards. Management must lay out the production area so that gas hoses, cables, mechanical assemblies, and other equipment do not cross walkways or interfere with routine tasks.

When work is above ground or floor level, safety rails or lines must be provided to prevent falls as a result of restricted vision from eye protection devices. Safety lines and harnesses can be helpful to restrict workers to safe areas, and to restrain them in case of a fall.

Unexpected events, such as fire and explosions, do occur in industrial environments. All escape routes must be identified and kept clear so that orderly, rapid, and safe evacuation of an area can take place.

Protection in the General Area. Equipment, machines, cables, hoses, and other apparatus should always be placed so that they do not present a hazard to personnel in passageways, on ladders, or on stairways. Warning signs should be posted to designate welding areas, and to specify that eye protection must be worn.

Protective screens. Persons in areas adjacent to welding and cutting must be protected from radiant energy and hot spatter by (1) flame-resistant screens or shields, or (2) suitable eye and face protection and protective clothing. Appropriate radiation protective, semi-transparent materials are permissible.

Wall Reflectivity. Where arc welding or cutting is regularly carried on adjacent to painted walls, the walls should be painted with a finish having low reflectivity of ultraviolet radiation. A reference is *Ultraviolet Reflectance of Paint*, American Welding Society, Miami, Florida: 1976.

Finishes formulated with certain pigments, such as titanium dioxide or zinc oxide, have low reflectivity to ultraviolet radiation. Color pigments may be added if they do not increase reflectivity. Pigments based on powdered or flaked metals are not recommended because they reflect ultraviolet radiation.

Public Demonstrations. Persons putting on public demonstrations involving observation of arc or oxyfuel gas welding or cutting processes are responsible for the safety of observers and the general public. Observers are not likely to have the necessary protective equipment to let them observe demonstrations safely. For exhibits involving observation of arc or oxyfuel gas welding and cutting processes, appropriate eye protection for both observers and passers-by is mandatory.

Fire. In most welding, cutting, and allied processes, a high-temperature heat source is present. Open flames, electric arcs, hot metal, sparks, and spatter are ready sources of ignition. Many fires are started by sparks, which can travel horizontally up to 11 m (35 ft) from their source and fall much greater distances. Sparks can pass through or lodge in cracks, holes, and other small openings in floors and walls.

The risk of fire is increased by combustibles in the work area, or by welding or cutting too close to combustibles that have not been shielded. Materials most commonly ignited are combustible floors, roofs, partitions, and building contents, including trash, wood, paper, textiles, plastics, chemicals, and flammable liquids and gases. Outdoors, the most common combustibles are dry grass and brush.

Hot Work Permit System. When welding, cutting, or similar hot working operations are to be performed in areas not normally assigned for such operations, a hot-work permit system should be used. The purpose of the hot-work permit system is to alert area supervisors to an extraordinary danger of fire that will exist at a particular time. The permit system should include a check list of safety precautions that includes an inspection for fire extinguishers, establishment of fire watches if necessary, search for combustible materials, and safety instructions for personnel in the area who are not involved in the hot work.

Explosion. Combustible gases, vapors, and dusts, when mixed with air or oxygen in certain proportions, present danger of explosion as well as fire. To prevent explosions, avoid all sources of ignition. Welding, brazing, soldering, cutting, or operating equipment that can produce heat or sparks must not be done in atmospheres containing combustible gases, vapors or dusts.

Hollow containers must be vented before applying heat. Heat must not be applied to a container that has held an unknown material, a combustible substance, or a substance that may form combustible vapors on heating. Additional information is given in AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping that Have Held Hazardous Substances*. Miami: American Welding Society (latest edition).

Burns. Burns of the eye or body are serious hazards of welding, brazing, soldering, thermal coating, and cutting. Eye, face, and body protection for the operator and others in the work area are required to prevent burns from ultraviolet and infrared radiation, sparks, and spatter.

Eye and Face Protection

Arc Welding and Cutting. Welding helmets or hand shields containing appropriate filter lenses and cover plates must be used by welders and welding operators and nearby personnel when viewing an arc. Standards for welding helmets, hand shields, face shields, goggles, and spectacles are given in ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection.* New York: American National Standards Institute (latest edition).

Oxyfuel Gas Welding and Cutting, Submerged Arc Welding. Safety goggles with filter lenses (*see* Appendix 18) and full conforming side shields must be worn while performing oxyfuel gas welding and cutting. During submerged arc welding, the arc is covered by flux and not readily visible; hence, an arc welding helmet is not needed. However, because the arc occasionally flashes through the flux burden, the operator should wear tinted safety glasses.

Protective Clothing. Sturdy shoes or boots, and heavy clothing similar to that in Figure 13-2 should be worn to protect the whole body from flying sparks, spatter, and radiation burns. Woolen clothing is preferable to cotton because it is not so readily ignited. Cotton clothing, if used, should be chemically treated to reduce its combustibility. Clothing treated with nondurable flame retardants must be retreated after each washing or cleaning. Clothing or shoes of synthetic or plastic materials which can melt and cause severe burns should not be worn. Outer clothing should be kept free of oil and grease, especially in an oxygen-rich atmosphere.

Figure 13-2—Personal Protective Equipment

Cuffless pants and covered pockets are recommended to avoid spatter or spark entrapment. Pockets should be emptied of combustible or readily ignitable materials before welding because they may be ignited by sparks or weld spatter and result in severe burns. Pants should be worn outside of shoes. Protection of the hair with a cap is recommended, especially if a hairpiece is worn. Flammable hair preparations should not be used.

Durable gloves of leather or other suitable material should always be worn. Gloves not only protect the hands from burns and abrasion, but also provide insulation from electrical shock. A variety of special protective clothing is also available for welders. Aprons, leggings, suits, capes, sleeves, and caps, all of durable materials, should be worn when welding overhead or when special circumstances warrant additional protection of the body. Sparks or hot spatter in the ears can be particularly painful and serious. Properly fitted, flame-resistant ear plugs should be worn whenever operations pose such risks.

Noise. Excessive noise, particularly continuous noise at high levels, can damage hearing. It may cause either temporary or permanent hearing loss. U.S. Department of Labor Occupational Safety and Health Administration regulations describe allowable noise exposure levels. Requirements of these regulations may be found in General Industry Standards, 29 CFR 1910.95.

In welding, cutting, and allied operations, noise may be generated by the process or the equipment, or both. Additional information is presented in *Arc Welding and Cutting Noise.* Miami: American Welding Society, latest edition. Processes that tend to have high noise levels are air carbon arc and plasma arc cutting. Engine-driven generators sometimes emit a high noise level, as do some high-frequency and induction welding power sources.

Machinery Guards. Welders and other workers must be protected from injury by machinery and equipment that they are operating, or by other machinery operating in the work area. Moving components and drive belts must be covered by guards to prevent physical contact. Workers must be protected against accidental entry into the working envelope of a robot.

Because welding helmets and dark filter lenses restrict the visibility of welders, they may be even more susceptible than ordinary workers to injury from unseen, unguarded machinery. Therefore, special attention is required to this hazard.

Fumes and Gases. Welders, welding operators, and other persons in the area must be protected from overexposure to fumes and gases produced during welding, brazing, soldering, and cutting. Overexposure is exposure that is hazardous to health, and exceeds the permissible limits specified by a government agency. Such recognized authorities are the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), Regulations 29 CFR 1910.1000; the American Conference of Governmental Industrial Hygienists (ACGIH) in its publications *Threshold Limit Values for Chemical Substances* and *Physical Agents in the Workroom Environment.* Persons with special health problems may have unusual sensitivity that requires even more stringent protection.

Fumes and gases are usually a greater concern in arc welding than in oxyfuel gas welding, cutting, or brazing because a welding arc may generate a larger volume of fume and gas, and greater varieties of materials are usually involved.

Protection from excess exposure is usually accomplished by ventilation. Where exposure would exceed permissible limits with available ventilation, respiratory protection must be used. Protection must be provided not only for the welding and cutting personnel but also for other persons in the area.

Refer to *Industrial Ventilation, A Manual of Recommended Practice*, Cincinnati: American Conference of Governmental Industrial Hygienists (latest edition).

Arc Welding. Fumes and gases from arc welding and cutting cannot be classified simply. Their composition and quantity depend on the base metal composition; the process and consumables used; coatings on the work, such as paint, galvanizing, or plating; contaminants in the atmosphere, such as halogenated hydrocarbon vapors from cleaning and degreasing activities; and other factors.

Various gases are generated during welding. Some are products of the decomposition of fluxes and electrode coatings. Others are formed by the action of arc heat or ultraviolet radiation emitted by the arc on atmospheric constituents and contaminants. Potentially hazardous gases include carbon monoxide, oxides of nitrogen, ozone, and phosgene or other decomposition products of chlorinated hydrocarbons, such as phosgene.

Helium and argon, although chemically inert and nontoxic, are simple asphyxiants, and can dilute the atmospheric oxygen concentration to potentially harmful low levels. Carbon dioxide (CO_2) and nitrogen can also cause asphyxiation.

Ozone may be generated by ultraviolet radiation from welding arcs. This is particularly true with gas shielded arcs, especially when argon is used. Photochemical reactions between ultraviolet radiation and chlorinated hydrocarbons result in the production of phosgene and other decomposition products.

Exposure Factors. The single most important factor influencing exposure to fume is the position of the welder's head with respect to the fume plume. When the head is in such a position that the fume envelops the face or helmet, exposure levels can be very high. Therefore, welders must be trained to keep their heads to one side of the fume plume. In some cases, the work can be positioned so the fume plume rises to one side.

Ventilation. Ventilation has a significant influence on the amount of fumes in the work area, and hence the welder's exposure. Ventilation may be local, where the fumes are extracted near the point of welding, or general, where the shop air is changed or filtered. The appropriate type will depend on the welding process, the material being welded, and other shop conditions. Adequate ventilation is necessary to keep the welder's exposure to fumes and gases within safe limits.

The bulk of fume generated during welding and cutting consists of small particles that remain suspended in the atmosphere for a considerable time. As a result, fume concentration in a closed area can build up over time, as can the concentration of any gases evolved or used in the process. The particles eventually settle on the walls and floor, but the settling rate is low compared to the generation rate of the welding or cutting processes. Therefore, fume concentration must be controlled by ventilation.

Adequate ventilation is the key to control of fumes and gases in the welding environments. Natural, mechanical, or respirator ventilation must be provided for all welding, cutting, brazing, and related operations. The ventilation must ensure that concentrations of hazardous airborne contaminants are maintained below recommended levels. These levels must be no higher than the allowable levels specified by the U.S. Occupational Safety and Health Administration or other appropriate authorities.

Respiratory Protective Equipment. Where natural or mechanical ventilation is not adequate or where toxic materials require a supplement to ventilation, respiratory protective equipment must be used. Respirators with air lines, or face masks that give protection against all contaminants are generally preferred. Air-supplied welding helmets are also available commercially. Filter-type respirators, approved by the U.S. Bureau of Mines for metal fume, give adequate protection against particulate contaminants that are less toxic than lead, provided they are used and maintained correctly. Their general use is not recommended, however, because of the difficulty in assuring proper use and maintenance. They will not protect against mercury vapor, carbon monoxide, or nitrogen dioxide. For these hazards an air line respirator, hose mask, or gas mask is required.

Special Ventilation Situations

Welding in Confined Spaces. Special consideration must be given to the safety and health of welders and other workers in confined places. Gas cylinders must be located outside of the confined space to avoid possible contamination of the space with leaking gases or volatile material. Welding power sources should also be located outside to reduce danger of engine exhaust and electric shock.

A means for removing persons quickly in case of emergency must be provided. Safety belts and lifelines, when used, should be attached to the worker's body in a manner that avoids the possibility of the person becoming jammed in the exit. A trained helper should be stationed outside the confined space with a preplanned rescue procedure to be put into effect in case of emergency.

Welding of Containers. Welding or cutting on the outside or inside of containers or vessels that have held dangerous substances presents special hazards. Flammable or toxic vapors may be present, or may be generated by the applied heat. The immediate area outside and inside the container should be cleared of all obstacles and hazardous materials.

When repairing a container in place, entry of hazardous substances released from the floor or the soil beneath the container must be prevented. The required air-supplied respirators or hose masks are those accepted by the U.S. Bureau of Mines or other recognized agency. For more complete procedures, refer to AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and* Cutting *Containers that Have Held Hazardous Substances.* Miami: American Welding Society (latest edition). When welding or cutting inside of vessels that have held dangerous materials, the precautions for confined spaces must also be observed.

Highly Toxic Materials. Certain materials which are sometimes present in consumables, base metals, coatings, or atmospheres for welding or cutting operations, have permissible exposure limits of 1.0 mg/m^3 or less. Among such materials are the following metals and their compounds:

(1) Antimony
(2) Arsenic
(3) Barium
(4) Beryllium

(5) Cadmium
(6) Chromium
(7) Cobalt
(8) Copper
(9) Lead
(10) Manganese
(11) Mercury
(12) Nickel
(13) Selenium
(14) Silver
(15) Vanadium

Base metals and filler metals that may release some of these materials as fume during welding or cutting are shown in Table 13-1.

Table 13-1
Possible Toxic Materials Evolved During Welding or Thermal Cutting

Base or Filler Metal	Evolved Metals or Their Compounds
Carbon and low alloy steels	Chromium, manganese, vanadium
Stainless steel	Chromium, manganese, nickel
Manganese steels and hardfacing materials	Chromium, cobalt, manganese, nickel, vanadium
High copper alloys	Beryllium, chromium, copper, lead, nickel
Coated or plated steel or copper	Cadmium*, chromium, copper, lead, nickel, silver

*When cadmium is a constituent in a filler metal, a warning label must be affixed to the container or coil. Refer to ANSI/ASC Z49.1, *Safety in Welding and Cutting*. New York: American National Standards Institute (latest edition).

Manufacturer's Material Safety Data Sheets should be consulted to determine if any of these highly toxic materials are present in welding filler metals and fluxes being used. Material Safety Data Sheets should be requested from suppliers. However, welding filler metals and fluxes are not the only source of these materials. They may also be present in base metals, coatings, or other sources in the work area. Radioactive materials under Nuclear Regulatory Commission jurisdiction require special considerations.

When toxic materials are encountered as designated constituents in welding, brazing or cutting operations, special ventilation precautions must be taken to assure that the levels of these contaminants in the atmosphere are at or below the limits allowed for human exposure. All persons in the immediate vicinity of welding or cutting operations involving toxic materials must be similarly protected. Unless atmospheric tests under the most adverse conditions establish that exposure is within acceptable concentrations, the following precautions must be observed.

Confined Spaces. Whenever any toxic materials are encountered in confined space operations, local exhaust ventilation and respiratory protection must be used.

Indoors. When any toxic materials are encountered in indoor operations, local exhaust (mechanical) ventilation must be used. When beryllium is encountered, respiratory protection in addition to local exhaust ventilation is essential.

Outdoors. When any toxic materials are encountered in outdoor operations, respiratory protection approved by the Mine Safety and Health Association (MSHA), the National Institute of Occupational Safety and Health (NIOSH), or other approving authority may be required.

Persons should not consume food in areas where fumes that contain materials with very low allowable exposure limits may be generated. They should also practice good personal hygiene, such as washing hands before touching food, to prevent ingestion of toxic contaminants.

Fluorine Compounds. Fumes and gases from fluorine compounds can be dangerous to health, and can burn the eyes and skin on contact. Local mechanical ventilation or respiratory protection must be provided when welding, brazing, cutting, or soldering in confined spaces involving fluxes, coatings, or other material containing fluorine compounds.

When such processes are employed in open spaces, the need for local exhaust ventilation or respiratory protection will depend upon the circumstances. Such protection is not necessary when air samples taken in breathing zones indicate that all fluorides are within allowable limits. However, local exhaust ventilation is always desirable for fixed-location production welding and for all production welding of stainless steels when filler metals or fluxes containing fluorides are used.

Fumes Containing Zinc. Compounds may produce symptoms of nausea, dizziness, or fever (sometimes called "metal fume fever"). Welding or cutting where zinc may be present in consumables, base metals, or coatings should be done as described for fluorine compounds.

Measurement of Exposure

The American Conference of Governmental Industrial Hygienists (ACGIH) and the U.S. Department of Labor, Occupational Health and Safety Administration (OSHA) have established allowable limits of airborne contaminants. They are called *threshold limit values* (TLVs), or permissible exposure limits (PELs).

The TLV (a registered trade mark of the ACGIH) is the concentration of an airborne substance to which most workers may be repeatedly exposed, day after day, without adverse effect. In adapting these to the working environment, a TLV-TWA (Threshold Limit Value-Time Weighted Average) quantity is defined. TLV-TWA is the time weighted average concentration for a normal 8-hour workday or 40-hour workweek to which nearly all workers may be repeatedly exposed without adverse effect. TLV-TWA values should be used as guides in the control of health hazards, and should not be interpreted as sharp lines between safe and dangerous concentrations.

TLVs are revised annually as necessary. They may or may not correspond to OSHA permissible exposure limits (PEL) for the same materials. In many cases, current ACGIH values for welding materials are more stringent than OSHA levels.

The only way to assure that airborne contaminant levels are within the allowable limits is to take air samples at the breathing zones of the personnel involved. An operator's actual on-the-job exposure to welding fume should be measured following the guidelines provided in ANSI/AWS F1.1, *Method for Sampling Airborne Particulates Generated by Welding and Allied Processes*. This document describes how to obtain an accurate breathing zone sample of welding fume for a particular welding operation. Both the amount of the fume and the composition of the fume can be determined in a single test using this method. Multiple samples are recommended for increased accuracy. When a helmet is worn, the sample should be collected inside the helmet in the welder's breathing zone.

Regulators. A pressure-reducing regulator should always be used when withdrawing gas from gas cylinders for welding or cutting operations. Gas regulators should meet the requirements of E-4, *Standard for Gas Regulators for Welding and Cutting*; New York: Compressed Gas Association, and other code regulations.

Pressure reducing regulators must be used only for the gas and pressure stated on the label. They should not be used with other gases, or at other pressures, even though the cylinder valve outlet threads may be the same. The threaded connections to the regulator must not be forced. Improper fit of threads between a gas cylinder and regulator or between the regulator and hose indicates that an improper combination of devices is being used. Refer to ANSI/CGA V-1, *Compressed Gas Cylinder Valve Outlet and Inlet Connections*. New York: Compressed Gas Association.

Oxygen. Oxygen is nonflammable but it supports the combustion of flammable materials. It can initiate combustion and vigorously accelerate it. Therefore, oxygen cylinders and liquid oxygen containers should not be stored in the vicinity of combustibles or with cylinders of fuel gas. Oxygen should never be used as a substitute for compressed air. Pure oxygen supports combustion more vigorously than air, which contains only 20% oxygen. Therefore, the identification of oxygen and air should be differentiated.

Oil, grease, and combustible dusts may spontaneously ignite on contact with oxygen. Hence, all systems and apparatus for oxygen service must be kept free of any combustibles. Valves, piping, or system components that have not been expressly manufactured for oxygen service must be cleaned and approved for this service before use. Refer to G4.1, *Cleaning Equipment for Oxygen Service*; New York: Compressed Gas Association.

Apparatus that has been manufactured expressly for oxygen service, and is usually so labeled, must be kept in the clean condition as originally received.

Oxygen valves, regulators, and apparatus should never be lubricated with oil. If lubrication is required, the type of lubricant and the method of applying the lubricant should be specified in the manufacturer's literature. If it is not, then the device should be returned to the manufacturer or authorized representative for service. Oxygen must never be used to power compressed air tools. These are almost always lubricated with oil. Similarly, oxygen must not be used to blow dirt from work and clothing because they are often contaminated with oil, grease, or combustible dust.

Only clean clothing should be worn when working with oxygen systems. Oxygen must not be used to ventilate confined spaces. Severe bums may result from ignition of clothing or the hair in an oxygen-rich atmosphere.

Fuel Gases. Fuel gases commonly used in oxyfuel gas welding (OFW) and cutting (OFC) are acetylene, methyl-acetylene-propadiene (MPS), natural gas, propane, and propylene. Hydrogen is used in a few applications. Gasoline is sometimes used as fuel for oxygen cutting. It vaporizes in the torch. These gases should always be referred to by name.

Acetylene in cylinders is dissolved in a solvent so that it can be safely stored under pressure. In the free state, acetylene should never be used at pressures over 103 kPa (15 psig) because it can dissociate with explosive violence at higher pressures.

Acetylene and MPS should never be used in contact with silver, mercury, or alloys containing 70% or more copper. These gases react with these metals to form unstable compounds that may detonate under shock or heat.

Valves on fuel gas cylinders should never be opened to clean the valve outlet, especially not near possible sources of flame ignition or in confined spaces.

Shielding Gases. Argon, helium, nitrogen, and carbon dioxide (CO_2) are used for shielding with some welding processes. All, except carbon dioxide, are used as brazing atmospheres. These gases are odorless and colorless and can displace air needed for breathing.

Confined spaces filled with these gases must be well ventilated before personnel enter them. If there is any question, the space should be checked first with an oxygen analyzer for adequate oxygen concentration. If an analyzer is not available, an air-supplied respirator should be worn by anyone entering the space. Containers of these gases should not be placed in confined spaces.

Electrical Safety

Electric Shock. Electric shock can cause sudden death. Injuries and fatalities from electric shock in welding and cutting operations can occur if proper precautionary measures are not followed. Most welding and cutting operations employ some type of electrical equipment. For example, automatic oxyfuel gas cutting machines use electric motor drives, controls, and systems.

Some electrical accidents may not be avoidable, such as those caused by lightning. However, the majority are avoidable, including those caused by lack of proper training.

A good safety training program is essential. Before being allowed to commence operations, welding operators must be fully instructed in electrical safety by a competent person. As a minimum, the training should include the points covered in ANSI/ASC Z49.1, *Safety in Welding and Cutting* (published by the American Welding Society).

Equipment Selection. Electric shock hazards are minimized by proper equipment installation and maintenance, good operator practice, proper operator clothing and body protection, and the use of equipment designed for the job and situation. Equipment should meet applicable National Electrical Manufacturers Association (NEMA) or American National Standards Institute (ANSI) standards, such as ANSI/UL 551, *Safety Standard for Transformer Type Arc Welding Machines*, latest edition.

When special welding and cutting processes require open circuit voltages higher than those specified in ANSI/NEMA Publication EW-1, *Electrical Arc Welding Apparatus*, insulation and operating procedures must be provided that are adequate to protect the welder from these higher voltages.

Installation. Equipment should be installed in a clean, dry area. When this is not possible, it should be adequately guarded from dirt and moisture. Installation must be done to the requirements of ANSI/NFPA 70, *National Electric Code*, and local codes. This includes necessary disconnects, fusing, and type of incoming power lines.

Terminals for welding leads and power cables must be shielded from accidental contact by personnel or by metal objects, such as vehicles and cranes. Connections between welding leads and power supples may be guarded using (1) dead front construction and receptacles for plug connections, (2) terminals located in a cover, (3) insulating sleeves, or (4) other equivalent mechanical means.

Wearers of Pacemakers. The technology of heart pacemakers and the extent to which they are influenced by other electrical devices is constantly changing. It is impossible to make a general statement concerning the possible effects of welding operations on such devices. Wearers of pacemakers or other electronic equipment vital to life should check with the device manufacturer or their doctor to determine whether any hazard exists.

Grounding. The workpiece being welded and the frame or chassis of all electrically powered machines must be connected to a good electrical ground. Grounding can be done by locating the workpiece or machine on a grounded metal floor or platen, or by connecting it to a properly grounded building frame or other satisfactory ground. Chains, wire ropes, cranes, hoists, and elevators must not be used as grounding connectors or to carry welding current.

The workpiece lead is not the grounding lead. The workpiece lead connects the work terminal on the power source to the workpiece. A separate lead is required to ground the workpiece or power source work terminal.

Care should be taken when connecting the grounding circuit. Otherwise, the welding current may flow through a connection intended only for grounding, and may be of higher magnitude than the grounding conductor can safely carry. Special radio-frequency grounding may be necessary for arc welding machines equipped with high-frequency arc initiating devices. Refer to EW-1, *Electric Arc Welding Power Sources*, Section 10.5.6, National Electrical Manufacturers Association.

Brazing and Soldering

Hazards encountered in brazing and soldering operations are similar to those associated with welding and cutting processes. Brazing and soldering operations may be done at temperatures where some elements in the filler metal will vaporize. Personnel and property must be projected against hot materials, gases, fumes, electrical shock, radiation, and chemicals.

It is essential that adequate ventilation be provided so that personnel do not inhale gases and fumes generated during brazing or soldering. Some filler metals and base metals contain toxic materials such as cadmium, beryllium, zinc, mercury, or lead that vaporize during brazing. Fluxes contain chemical compounds of fluorine, chlorine, and boron that are harmful if they are inhaled or contact the eyes or skin. Suitable ventilation must be provided to avoid these hazards.

High-Frequency Welding. High-frequency generators are electrical devices and require all usual safety precautions when handling and repairing such equipment. Voltages are in the range from 400 to 20 000 V and are lethal. These voltages may be either low or high frequency. Proper care and safety precautions should be taken while working on high-frequency generators and their control systems. Units must be equipped with safety interlocks on access doors and with automatic safety grounding devices to prevent operation of the equipment when access doors are open. The equipment should not be operated with panels or high voltage covers removed or with interlocks and grounding devices blocked. This equipment should not be confused with high-frequency arc stabilization equipment used in gas tungsten arc welding (GTAW).

Laser Beam Welding and Cutting. The basic hazards associated with laser operation are:

(1) Eye damage from the beam, including burns of the cornea or retina, or both

(2) Skin burns from the beam

(3) Respiratory system damage from hazardous materials evolved during operation

(4) Electrical shock

(5) Chemical hazards

(6) Contact with cryogenic coolants

Laser manufacturers are required to qualify their equipment with the U.S. Bureau of Radiological Health (BRH). Electrical components should be in compliance with NEMA standards. User action is governed by OSHA requirements. In all cases, American National Standard Z136.1, *Safe Use of Lasers* (latest edition), should be followed.

Friction Welding. Friction welding machines are similar to machine tool lathes in that one workpiece is rotated by a drive system. They are also similar to hydraulic presses in that one workpiece is forced against the other. Therefore, safe practices for lathes and power presses should be used as guides for the design and operation of friction welding machines.

Explosion Welding. Explosives and explosive devices are a part of explosion welding. Such materials and devices are inherently dangerous, but there are safe methods for handling them. However, if the materials are misused, they can kill or injure operators or persons in the vicinity, and destroy or damage property. Explosive materials should be handled and used only by trained personnel who are experienced in that field. Handling and safety procedures must comply with all applicable federal, state, and local regulations. Refer to ANSI/NFPA 495, *Manufacture, Transportation, Storage and Use of Explosive Materials*; New York: American National Standards Institute, latest edition.

Ultrasonic Welding. With high-power ultrasonic equipment, high voltages are present in the frequency converter, the welding head, and the coaxial cable connecting these components. Consequently, the equipment should not be operated with the panel doors open or housing covers removed. Door interlocks are usually installed to prevent introduction of power to the equipment when the high-voltage circuitry is exposed.

The cables are fully shielded and present no hazard when properly connected and maintained.

Because of hazards associated with the application of clamping force, the operator should not place hands or arms in the vicinity of the welding tip when the equipment is energized. For manual operation, the equipment should be activated by dual palm buttons that meet the requirements of OSHA.

Thermite Welding. Thermite mix, in the crucible or on the workpieces, can lead to rapid formation of steam when the chemical reaction for thermite welding takes place. This may cause ejection of molten metal from the crucible. Therefore, the thermite mix should be stored in a dry place, the crucible should be dry, and moisture should not be allowed to enter the system before or during welding.

The work area should be free of combustible materials that may be ignited by sparks or small particles of molten metal. The area should be well ventilated to avoid the buildup of fumes and gases from the reaction. Starting powders and rods should be protected against accidental ignition.

Personnel should wear appropriate protection against hot particles or sparks. This includes full face shields with filter lenses for eye protection and headgear. Safety boots are recommended to protect the feet from hot sparks. Clothing should not have pockets or cuffs that might catch hot particles.

Thermal Spraying. The potential hazards to the health and safety of personnel involved in thermal spraying operations and to persons in the immediate vicinity are as follows:

(1) Electrical shock
(2) Fire
(3) Fumes and gases
(4) Dust
(5) Arc radiation
(6) Noise.

These hazards are not unique to thermal spraying methods. For example, flame spraying has hazards similar to those associated with the oxyfuel gas welding and cutting processes. Likewise, arc spraying and plasma spraying are similar in many respects to gas metal arc and plasma arc welding, respectively. Safe practices for these processes should be followed when thermal spraying with similar equipment. However, thermal spraying does generate dust and fumes to a greater degree. Refer to *Thermal Spraying: Practice, Theory, and Application*; Miami, Florida: American Welding Society, latest edition.

Adhesive Bonding. Adequate safety precautions must be observed with adhesives. Corrosive materials, flammable liquids, and toxic substances are commonly used in adhesive bonding. Therefore, manufacturing operations should be carefully supervised to ensure that proper safety procedures, protective devices, and protective clothing are being used. Operations should comply with all federal, state, and local regulations, including OSHA Regulation 29CRF 1900.1000, *Air Contaminants.*

Severe allergic reactions can result from direct contact, inhalation, or ingestion of toxic materials such as phenolics and epoxies as well as most catalysts and accelerators. The eyes or skin may become sensitized over a long period of time even though no signs of irritation are visible. Once workers are sensitized to a particular type of adhesive, they may no longer be able to work near it because of allergic reactions. Careless handling of adhesives by production workers may expose others to toxic materials if proper safety rules are not observed. For example, coworkers may touch tools, door knobs, light switches, or other objects contaminated by careless workers.

For the normal individual, proper handling methods that eliminate skin contact with an adhesive should be sufficient. It is mandatory that protective equipment, barrier creams, or both be used to avoid skin contact with certain types of formulations.

Source: American Welding Society, *Welding Handbook*, Vol. 1, 8th Edition. Miami, Florida: American Welding Society, 1987.

Additional Safety Resources

American National Standards Institute (ANSI)/ National Fire Protection Association (NFPA). ANSI/NFPA 51B, *Cutting and Welding Processes,* Quincy, MA: National Fire Protection Association.

ANSI/NFPA S1, *Oxygen-Fuel Gas Systems for Welding, Cutting and Allied Processes*, Quincy, MA: National Fire Protection Association.

American Society for Metals, *Metals Handbook*, Vol. 4. Heat Treating. Metals Park, OH: American Society for Metals (latest edition).

American Welding Society. ANSI/ASC Z49.1, *Safety in Welding and Cutting.* Miami, Florida: American Welding Society.

___. *Arc Welding and Cutting Noise.* Miami, FL: American Welding Society.

___. *Arc Welding Safely.* Miami, FL: American Welding Society.

___. *Characterization of Arc Welding Fumes.* Miami, FL: American Welding Society.

___. *Effects of Welding on Health I, II, III, IV, and V.* Miami, FL: American Welding Society.

——. *Fumes and Gases in the Welding Environment.* Miami, FL: American Welding Society.

——. *Oxyfuel Gas Welding, Cutting, and Heating Safely.* Miami, FL: American Welding Society.

——. AWS F2.1, *Recommended Safe Practices for Electron Beam Welding and Cutting.* Miami, FL: American Welding Society.

——. AWS F4. 1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers that Have Held Hazardous Substances.* Miami, FL: American Welding Society.

——. AWS C2.1, *Recommended Safe Practices for Thermal Spraying.* Miami, FL: American Welding Society.

——. *The Welding Environment.* Miami, FL: American Welding Society.

——. *Ultraviolet Reflectance of Paint.* Miami, FL: American Welding Society.

——. *Welding Fume Control, a Demonstration Project.* Miami, FL: American Welding Society.

Balchin, N. C. *Health and Safety in Welding and Allied Processes*, 3rd Ed., England: The Welding Institute.

Compressed Gas Association, Incorporated. *Handbook of Compressed Gases*, 2nd Ed., New York, NY: Van Nostrand Reinhold Co.

——. *Handling Acetylene Cylinders in Fire Situations,* SB-4. New York, NY: Compressed Gas Association.

——. *Safe Handling of Compressed Gases in Containers,* P-1, New York, NY: Compressed Gas Association.

Fireman's Fund Insurance Companies. *Welding Fume Control with Mechanical Ventilation,* 2nd Ed., San Francisco, CA: Fireman's Fund Insurance Companies.

The Welding Institute. *The Facts about Fume.* England: The Welding Institute.

Appendix 14
Metric Conversions

Table 14-1
Metric Conversion Factors for Common Engineering Terms

Property	To Convert From	To	Multiply By
acceleration (angular)	revolution per minute squared	rad/s^2	$1.745\ 329 \times 10^{-3}$
acceleration (linear)	in./min^2	m/s^2	$7.055\ 556 \times 10^{-6}$
	ft/min^2	m/s^2	$8.466\ 667 \times 10^{-5}$
	ft/s^2	m/s^2	$3.048\ 000 \times 10^{-1}$
area	in.^{2}	m^2	$6.451\ 600 \times 10^{-4}$
	ft^2	m^2	$9.290\ 304 \times 10^{-2}$
	yd^2	m^2	$8.361\ 274 \times 10^{-1}$
	acre (U.S. Survey)	m^2	$4.046\ 873 \times 10^{3}$
density	pound mass per cubic inch	kg/m^3	$2.767\ 990 \times 10^{4}$
energy, work, heat, and impact energy	foot pound force	J	1.355 818
	Btu	J	$1.054\ 350 \times 10^{3}$
	calorie	J	4.184 000
	watt hour	J	$3.600\ 000 \times 10^{3}$
force	kilogram-force	N	9.806 650
	pound-force	N	4.448 222
length	in.	m	$2.540\ 000 \times 10^{-2}$
	ft	m	$3.048\ 000 \times 10^{-1}$
	yd	m	$9.144\ 000 \times 10^{-1}$
	mile (U.S. Survey)	km	1.609 347
mass	pound mass (avdp)	kg	$4.535\ 924 \times 10^{-1}$
	metric ton	kg	$1.000\ 000 \times 10^{3}$
	ton (short 2000 lbm)	kg	$9.071\ 847 \times 10^{2}$
power	horsepower (550 ft lbf/s)	W	$7.456\ 999 \times 10^{2}$
	horsepower (electric)	W	$7.460\ 000 \times 10^{2}$
	Btu/min	W	$1.757\ 250 \times 10$
	calorie per minute	W	$6.973\ 333 \times 10^{-2}$
	foot pound-force per minute	W	$2.259\ 697 \times 10^{-2}$
pressure	pound force per square inch	kPa	6.894 757
	bar	kPa	$1.000\ 000 \times 10^{2}$
	atmosphere	kPa	$1.013\ 250 \times 10^{2}$
tensile strength (stress)	ksi	MPa	6.894 757
torque	inch pound force	N · m	$1.129\ 848 \times 10^{-1}$
	foot pound force	N · m	1.355 818
velocity (angular)	revolution per minute	rad/s	$1.047\ 198 \times 10^{-1}$
	degree per minute	rad/s	$2.908\ 882 \times 10^{-4}$
	revolution per minute	deg/min	$3.600\ 000 \times 10^{2}$
velocity (linear)	in./min	m/s	$4.233\ 333 \times 10^{-4}$
	ft/min	m/s	$5.080\ 000 \times 10^{-3}$
	mile/hour	km/h	1.609 344
volume	in.^{3}	m^3	$1.638\ 706 \times 10^{-5}$
	ft^3	m^3	$2.831\ 685 \times 10^{-2}$
	yd^3	m^3	$7.645\ 549 \times 10^{-1}$
	in.^{3}	L	$1.638\ 706 \times 10^{-2}$
	ft^3	L	$2.831\ 685 \times 10$
	gallon	L	3.785 412

Table 14-2
Metric Conversion Factors for Common Welding Terms

Property	To Convert From	To	Multiply By
area dimensions (mm^2)	in.^{2}	mm^2	6.451 600 × 10^2
	mm^2	in.^{2}	1.550 003 × 10^{-3}
current density	A/in.^{2}	A/mm^2	1.550 003 × 10^{-3}
	A/mm^2	A/in.^{2}	6.451 600 × 10^2
deposition rate*	lb/h	kg/h	0.45
electrode force	pound-force	N	4.448 222
	kilogram-force	N	9.806 650
	N	lbf	2.248 089 × 10^{-1}
flow rate (L/min)	ft^3/h	L/min	4.719 475 × 10^{-1}
	gallon per hour	L/min	6.309 020 × 10^{-2}
	gallon per minute	L/min	3.785 412
	L/min	ft^3/h	2.118 880
heat input	J/in.	J/m	3.937 008 × 10
	J/m	J/in.	2.540 000 × 10^{-2}
impact energy	foot pound force	J	1.355 818
linear measurements	in.	mm	2.540 000 × 10
	ft	mm	3.048 000 × 10^2
	mm	in.	3.937 008 × 10^{-2}
	mm	ft	3.280 840 × 10^{-3}
power density	W/in.^{2}	W/m^2	1.550 003 × 10^3
pressure (gas and liquid)	W/mm^2	W/m^2	6.451 600 × 10^{-4}
	psi	Pa	6.894 757 × 10^{-3}
	lb/ft^2	Pa	4.788 026 × 10
	N/mm^2	Pa	1.000 000 × 10^6
	kPa	psi	1.450 377 × 10^{-1}
	kPa	lb/ft^2	2.088 543 × 10
	kPa	N/mm^2	1.000 000 × 10^{-3}
	torr (mm Hg at 0°C)	kPa	1.333 22 × 10^{-1}
	micron (µm Hg at 0°C)	kPa	1.333 22 × 10^{-4}
	kPa	torr	7.500 64 × 10
	kPa	micron	7.500 64 × 10^3
tensile strength (MPa)	psi	kPa	6.894 757
	lb/ft^2	kPa	4.788 026 × 10^{-2}
	N/mm^2	MPa	1.000 000
	MPa	psi	1.450 377 × 10^2
	MPa	lb/ft^2	2.088 543 × 10^4
	MPa	N/mm^2	1.000 000
thermal conductivity (W/(m · K)	cal/(cm · s · °C)	W/(m · K)	4.184 000 × 10^2
travel speed, wire feed speed (mm/s)	in./min	mm/s	4.233 333 × 10^{-1}
	mm/s	in./min	2.362 205

*Approximate conversion

Table 14-3
Temperature Conversion: SI Units ↔ U.S. Customary

Degrees Celsius ⇔ Degrees Farhenheit

Despite international acceptance and usage of the Kelvin and the Celsius temperature scales, the Fahrenheit scale continues to be widely used in the USA, hence the conversion table for °C to °F herewith. The term *centigrade* should not be used for temperature because in metric countries this means one hundredth part of the unit of plane angle; i.e., the grade. Between the temperatures of melting ice and boiling water, there are 180° on the Fahrenheit and Rankine scales as compared with 100° on the Celsius and Kelvin scales. The ration of these numbers is 9:5, therefore, the following equations apply:

$$°C = 5/9\ (°F - 32),\ \text{and},\ °F = 9/5\ °C = 32°$$

To use the tables below, enter the central (bold-face) columns with the number to be converted. If converting Fahrenheit degrees, read the Celsius equivalent in column headed "C" to the left. If converting Celsius degrees, read the Fahrenheit equivalent in the column headed "F" to the right.

C		F	C		F	C		F	C		F
–273	**–459**		–40.0	**–40**	–40.0	24.4	**76**	168.8	199	**390**	734
–268	**–450**		–34.0	**–30**	–22.0	25.6	**78**	172.4	204	**400**	752
–262	**–440**		–29.0	**–20**	–4.0	26.7	**80**	176.0	210	**410**	770
–257	**–430**		–23.0	**–10**	14.0	27.8	**82**	179.6	216	**420**	788
–251	**–420**		–17.8	**0**	32.0	28.9	**84**	183.2	221	**430**	806
–246	**–410**		–16.7	**2**	35.6	30.0	**86**	186.8	227	**440**	824
–240	**–400**		–15.6	**4**	39.2	31.1	**88**	190.4	232	**450**	842
–234	**–390**		–14.4	**6**	42.8	32.2	**90**	194.0	238	**460**	860
–229	**–380**		–13.3	**8**	46.4	33.3	**92**	197.6	243	**470**	878
–223	**–370**		–12.2	**10**	50.0	34.4	**94**	201.2	249	**480**	896
–218	**–360**		–11.1	**12**	53.6	35.6	**96**	204.8	254	**490**	914
–212	**–350**		–10.0	**14**	57.2	36.7	**98**	208.4	260	**500**	932
–207	**–340**		–8.9	**16**	60.8	37.8	**100**	212.0	266	**510**	960
–201	**–330**		–7.8	**18**	64.4	43.0	**110**	230.0	271	**520**	968
–196	**–320**		–6.7	**20**	68.0	49.0	**120**	248.0	277	**530**	986
–190	**–310**		–5.6	**22**	71.6	54.0	**130**	266.0	282	**540**	1004
–184	**–300**		–4.4	**24**	75.2	60.0	**140**	284.0	288	**550**	1022
–179	**–290**		–3.3	**26**	78.8	66.0	**150**	302.0	293	**560**	1040
–173	**–280**		–2.2	**28**	82.4	71.0	**160**	320.0	299	**570**	1058
–168	**–270**	–454	–1.1	**30**	86.0	77.0	**170**	338.0	304	**580**	1076
–162	**–260**	–436	0.0	**32**	89.6	82.0	**180**	356.0	310	**590**	1094
–157	**–250**	–418	1.1	**34**	93.2	88.0	**190**	374.0	316	**600**	1112
–151	**–240**	–400	2.2	**36**	96.8	93.0	**200**	392.0	321	**610**	1130
–146	**–230**	–382	3.3	**38**	100.4	99.0	**210**	410.0	327	**620**	1148
–140	**–220**	–364	4.4	**40**	104.0	100.0	**212**	414.0	332	**630**	1166
–134	**–210**	–346	5.6	**42**	107.6	104.0	**220**	428.0	338	**640**	1184
–129	**–200**	–328	6.7	**44**	111.2	110.0	**230**	446.0	343	**650**	1202
–123	**–190**	–310	7.8	**46**	114.8	116.0	**240**	464.0	349	**660**	1220
–118	**–180**	–292	8.9	**48**	118.4	121.0	**250**	482.0	354	**670**	1238
–112	**–170**	–274	10.0	**50**	122.0	127.0	**260**	500.0	360	**680**	1256
–107	**–160**	–256	11.1	**52**	125.6	132.0	**270**	518.0	366	**690**	1274
–101	**–150**	–238	12.2	**54**	129.2	138.0	**280**	536.0	371	**700**	1292
–96	**–140**	–220	13.3	**56**	132.8	143.0	**290**	554.0	377	**710**	1310
–90	**–130**	–202	14.4	**58**	136.4	149.0	**300**	572.0	382	**720**	1328
–84	**–120**	–184	15.6	**60**	140.0	154.0	**310**	590.0	388	**730**	1346
–79	**–110**	–166	16.7	**62**	143.6	160.0	**320**	608.0	393	**740**	1364
–73	**–100**	–148	17.8	**64**	147.2	166.0	**330**	626.0	399	**750**	1382
–68	**–90**	–130	18.9	**66**	150.8	171.0	**340**	644.0	404	**760**	1400
–62	**–80**	–112	20.0	**68**	154.4	177.0	**350**	662.0	410	**770**	1418
–57	**–70**	–94	21.1	**70**	158.0	182.0	**360**	680.0	416	**780**	1436
–51	**–60**	–76	22.2	**72**	161.6	186.0	**370**	698.0	421	**790**	1454
–46	**–50**	–58	23.3	**74**	165.2	193.0	**380**	716.0	427	**800**	1472

Table 14-3
Temperature Conversion: SI Units ↔ U.S. Customary (Continued)

C		F	C		F	C		F	C		F
432	**810**	1490	738	**1360**	2480	1043	**1910**	3470	1349	**2460**	4460
438	**820**	1508	743	**1370**	2498	1049	**1920**	3488	1354	**2470**	4478
443	**830**	1526	749	**1380**	2516	1054	**1930**	3506	1360	**2480**	4496
449	**840**	1544	754	**1390**	2534	1060	**1940**	3524	1366	**2490**	4514
454	**850**	1562	760	**1400**	2552	1066	**1950**	3542	1371	**2500**	4532
460	**860**	1580	766	**1410**	2570	1071	**1960**	3560	1377	**2510**	4550
466	**870**	1598	771	**1420**	2888	1077	**1970**	3578	1382	**2520**	4568
471	**880**	1616	777	**1430**	2606	1082	**1980**	3596	1388	**2530**	4586
477	**890**	1634	782	**1440**	2624	1088	**1990**	3614	1383	**2540**	4604
482	**900**	1652	788	**1450**	2642	1093	**2000**	3632	1399	**2550**	4622
488	**910**	1670	793	**1460**	2660	1099	**2010**	3650	1404	**2560**	4640
493	**920**	1688	799	**1470**	2678	1104	**2020**	3668	1410	**2570**	4658
499	**930**	1706	804	**1480**	2696	1110	**2030**	3686	1416	**2580**	4676
504	**940**	1724	810	**1490**	2714	1116	**2040**	3704	1421	**2590**	4694
510	**950**	1742	816	**1500**	2732	1121	**2050**	3722	1427	**2600**	4712
516	**960**	1760	821	**1510**	2750	1127	**2060**	3740	1432	**2610**	4730
521	**970**	1778	827	**1520**	2768	1132	**2070**	3758	1438	**2620**	4748
527	**980**	1796	832	**1530**	2786	1138	**2080**	3776	1443	**2630**	4766
532	**990**	1814	838	**1540**	2804	1143	**2090**	3794	1449	**2640**	4784
538	**1000**	1832	843	**1550**	2822	1149	**2100**	3812	1454	**2650**	4802
543	**1010**	1850	849	**1560**	2840	1154	**2110**	3830	1460	**2660**	4820
549	**1020**	1868	854	**1570**	2858	1160	**2120**	3848	1466	**2670**	4838
554	**1030**	1886	860	**1580**	2876	1166	**2130**	3866	1471	**2680**	4856
560	**1040**	1904	866	**1590**	2894	1171	**2140**	3884	1477	**2690**	4874
566	**1050**	1922	871	**1600**	2912	1177	**2150**	3902	1482	**2700**	4892
571	**1060**	1940	877	**1610**	2930	1182	**2160**	3920	1488	**2710**	4910
577	**1070**	1958	882	**1620**	2948	1188	**2170**	3938	1493	**2720**	4928
582	**1080**	1976	888	**1630**	2966	1193	**2180**	3956	1499	**2730**	4946
588	**1090**	1994	893	**1640**	2984	1199	**2190**	3974	1504	**2740**	4964
593	**1100**	2012	899	**1650**	3002	1204	**2200**	3992	1510	**2750**	4982
599	**1110**	2030	904	**1660**	3020	1210	**2210**	4010	1516	**2760**	5000
604	**1120**	2048	910	**1670**	3038	1216	**2220**	4028	1521	**2770**	5018
610	**1130**	2066	916	**1680**	3056	1221	**2230**	4046	1527	**2780**	5036
616	**1140**	2084	921	**1690**	3074	1227	**2240**	4064	1532	**2790**	5054
621	**1150**	2102	927	**1700**	3092	1232	**2250**	4082	1538	**2800**	5072
627	**1160**	2120	932	**1710**	3110	1238	**2260**	4100	1543	**2810**	5090
632	**1170**	2138	938	**1720**	3128	1243	**2270**	4118	1549	**2820**	5108
638	**1180**	2156	943	**1730**	3146	1249	**2280**	4136	1554	**2830**	5126
643	**1190**	2174	949	**1740**	3164	1254	**2290**	4154	1560	**2840**	5144
649	**1200**	2192	954	**1750**	3182	1260	**2300**	4172	1566	**2850**	5162
654	**1210**	2210	960	**1760**	3200	1266	**2310**	4190	1571	**2860**	5180
660	**1220**	2228	966	**1770**	3218	1271	**2320**	4208	1577	**2870**	5198
666	**1230**	2246	971	**1780**	3236	1277	**2330**	4226	1582	**2880**	5216
671	**1240**	2264	977	**1790**	3254	1282	**2340**	4244	1588	**2890**	5234
677	**1250**	2282	982	**1800**	3272	1288	**2350**	4262	1593	**2900**	5252
682	**1260**	2300	988	**1810**	3290	1293	**2360**	4280	1599	**2910**	5270
688	**1270**	2318	993	**1820**	3308	1299	**2370**	4298	1604	**2920**	5288
693	**1280**	2336	999	**1830**	3326	1304	**2380**	4316	1610	**2930**	5306
699	**1290**	2354	1004	**1840**	3344	1310	**2390**	4334	1616	**2940**	5324
704	**1300**	2372	1010	**1850**	3362	1316	**2400**	4352	1621	**2950**	5342
710	**1310**	2390	1016	**1860**	3380	1321	**2410**	4370	1627	**2960**	5360
716	**1320**	2408	1021	**1870**	3398	1327	**2420**	4388	1632	**2970**	5378
721	**1330**	2426	1027	**1880**	3416	1332	**2430**	4406	1638	**2980**	5396
727	**1340**	2444	1032	**1890**	3434	1338	**2440**	4424	1643	**2990**	5414
732	**1350**	2462	1038	**1900**	3452	1343	**2450**	4442	1649	**3000**	5432

Appendix 15
Elements—Chemical Symbols and Atomic Numbers

Element	Atomic No.	Element	Atomic No.	Element	Atomic No.
Actinium (Ac)	89	Hafnium (Hf)	72	Promethium (Pm)	61
Aluminum (Al)	13	Helium (He)	2	Protactinium (Pa)	91
Americium (Am)	95	Holmium (Ho)	67	Radium (Ra)	88
Antimony (Sb)	51	Hydrogen (H)	1	Radon (Rn)	86
Argon (A)	18	Indium (In)	49	Rhenium (Re)	75
Arsenic (As)	33	Iodine (I)	53	Rhodium (Rh)	45
Astatine (At)	85	Iridium (Ir)	77	Rubidium (Rb)	37
Barium (Ba)	56	Iron (Fe)	26	Ruthenium (Ru)	44
Berkelium (Bk)	97	Krypton (Kr)	36	Samarium (Sm)	62
Beryllium (Be)	4	Lanthanum (La)	57	Scandium (Sc)	21
Bismuth (Bi)	83	Lawrencium (Lw)	103	Selenium (Se)	34
Boron (B)	5	Lead (Pb)	82	Silicon (Si)	14
Bromine (Br)	35	Lithium (Li)	3	Silver (Ag)	47
Cadmium (Cd)	48	Lutetium (Lu)	71	Sodium (Na)	11
Calcium (Ca)	20	Magnesium (Mg)	12	Strontium (Sr)	38
Californium (Cf)	98	Manganese (Mn)	25	Sulfur, yellow (S)	16
Carbon, graphite (C)	6	Mendelevium (Mv)	101	Tantalum (Ta)	73
Cerium (Ce)	58	Mercury (Hg)	80	Technetium (Tc)	43
Cesium (Cs)	55	Molybdenum (Mo)	42	Tellurium (Te)	52
Chlorine (Cl)	17	Neodymium (Nd)	60	Terbium (Tb)	65
Chromium (Cr)	24	Neon (Ne)	10	Thallium (Tl)	81
Cobalt (Co)	27	Neptunium (Np)	93	Thorium (Th)	90
Copper (Cu)	29	Nickel (Ni)	28	Thulium (Tm)	69
Curium (Cm)	96	Niobium (Nb)	41	Tin (Sn)	50
Dysprosium (Dy)	66	Nitrogen (N)	7	Titanium (Ti)	22
Einsteinium (E)	99	Nobelium (No)	102	Tungsten (W)	74
Erbium (Er)	68	Osmium (Os)	76	Uranium (U)	92
Europium (Eu)	63	Oxygen (O)	8	Vanadium (V)	23
Fermium (Fm)	100	Palladium (Pd)	46	Xenon (Xe)	54
Fluorine (F)	9	Phosphorus, white (P)	15	Ytterbium (Yb)	70
Francium (Fr)	87	Platinum (Pt)	78	Yttrium (Y)	39
Gadolinium (Gd)	64	Plutonium (Pu)	94	Zinc (Zn)	30
Gallium (Ga)	31	Polonium (Po)	84	Zirconium (Zr)	40
Germanium (Ge)	32	Potassium (K)	19		
Gold (Au)	79	Praseodymium (Pr)	59		

Appendix 16
Standards for Welding, Cutting, and Allied Processes

Definitions. The American Welding Society uses the general term *standards* to refer to documents that govern and guide welding activities. Standards describe the technical requirements for a material, process, product, system, or service. They also indicate the procedures, methods, equipment, or tests used to determine that the requirements have been met.

Standards include codes, specifications, recommended practices, classifications, methods, and guides. These documents have many similarities, and the terms are often used interchangeably, but sometimes incorrectly. Each term has a specific definition.

Codes and *specifications* are similar types of standards that use the words *shall* and *will* to indicate the mandatory use of certain materials or actions, or both. Codes differ from specifications in that their use is generally applicable to a process. Specifications are generally associated with a product. Both become mandatory when specified by one or more governmental jurisdictions or when they are referenced by contractual or other procurement documents.

Recommended practices and *guides* are standards that are offered primarily as aids to the user. They use words such as *should* and *may* because their use is usually optional. However, if these documents are referenced by codes or contractual agreements, their use may become mandatory. If the codes or agreements contain non-mandatory sections or appendixes, the use of referenced guides or recommended practices is at the user's discretion.

Classifications and *methods* generally provide lists of established practices or categories for processes or products. The most common example is a standard testing method.

The user of a standard should become acquainted with its scope and intended use, both of which are usually included within the *Scope* or *Introduction* section of the standard. It is equally important, but often more difficult, to recognize subjects that are not covered by the document. These omissions may require additional technical consideration. A document may cover the details of the product form without considering special conditions under which it will be used. Examples of special conditions would be corrosive atmospheres, elevated temperatures, and dynamic rather than static loading.

Methods of achieving compliance vary with the standards. Some have specific requirements that do not allow for alternative actions. Others permit alternative actions or procedures, as long as they result in properties that meet specified criteria. These criteria are often given as minimum requirements; for example, the ultimate tensile strength of a welded specimen must meet or exceed the minimum tensile strength specified for the base material.

Sources. Private and governmental organizations develop, issue, and update standards that apply to their particular areas of interest. The following sources of standards are of interest to the welding industry:

American Association of State Highway and Transportation Officials
American Bureau of Shipping (ABS)
American Institute of Steel Construction (AISI)
American National Standards Institute (ANSI)
American Petroleum Institute (API)
American Railway Engineering Association (AREA)
American Society of Mechanical Engineers (ASME)
American Water Works Association (AWWA)
American Welding Society (AWS)
Association of American Railroads (AAR)
ASTM
Canadian Standards Association (CSA)
Compressed Gas Association (CGA)
International Organization for Standardization (ISO)
National Board of Boiler and Pressure Vessel Inspectors (NBBPVI)
National Fire Protection Association (NFPA)
Naval Publication and Forms Center (Military Specifications)
Pipe Fabrication Institute (PFI)
SAE
Superintendent of Documents (Federal Specifications)
Underwriters Laboratories, Inc.
Uniform Boiler and Pressure Vessel Laws Society (UBPVLS)

The welding interests of many of these groups overlap, and some agreements have been made to reduce duplication of effort. Many standards that are concerned with welding, brazing, and allied processes are prepared by the American Welding Society

(AWS) because these subjects are of primary interest to the members. Standards that apply to a particular product are usually prepared by the group that has overall responsibility. For example, those for railroad freight cars are published by the Association of American Railroads (AAR). However, freight cars are basically structures, and the applicable AAR specification currently refers to ANSI/AWS D1.1, *Structural Welding Code—Steel,* for the qualification of welding procedures, welders, and welding operators. In 1986, the American Welding Society published ANSI/AWS D15.1, *Railroad Welding Specification.* Revisions to the AAR standards will reference ANSI/AWS D15.1.

Each organization that prepares consensus standards has committees or task groups to perform this function. Members of these committees or task groups are specialists in their fields. They prepare drafts of standards that are reviewed and approved by a larger group. Each main committee is selected to include persons with diverse interests balanced equally among producers, users, and government representatives. To avoid control or undue influence by one interest group, consensus must be achieved by a high percentage of all members.

The federal government develops or adopts standards for items and services that are in the public rather than the private domain. The mechanisms for developing federal or military documents are similar to those of private organizations. Standard-writing committees usually exist within a federal department or agency that has responsibility for a particular item or service.

The American National Standards Institute (ANSI) is a private organization responsible for coordinating national standards for use within the United States. ANSI does not actually prepare standards. Instead, it forms national interest review groups to determine whether proposed standards are in the public interest. Each group is composed of persons from various organizations concerned with the scope and provisions of a particular document. If there is consensus regarding the general value of a particular standard, then it may be adopted as an American National Standard. Adoption of a standard by ANSI does not, of itself, give it mandatory status. However, if the standard is cited by a governmental rule or regulation, it may then be backed by force of law.

Other industrialized countries also develop and issue standards on the subject of welding. The following are examples of other national standards designations and the bodies responsible for them:

BS — British Standard issued by the British Standards Association

CSA — Canadian Standard issued by the Canadian Standards Association

DIN — West German Standard issued by the Deutsches Institute fuer Normung

JIS — Japanese Industrial Standard issued by the Japanese Standards Association

NF — French Standard issued by the Association Française de Normalisation

Of these, the Canadian Standards Association is discussed in a following section. There is also an International Organization for Standardization (ISO). Its goal is the establishment of uniform standards for use in international trade. This organization is discussed in a following section.

Applications. The minimum requirements of a particular standard may not satisfy the special needs of every user. Therefore, a user may find it necessary to invoke additional requirements to achieve the desired quality.

Most standards may be revised by using one of several procedures. These are used when a standard is found to be in error, unreasonably restrictive, or not applicable with respect to new technological developments. Some standards are updated on a regular basis; others are revised as needed. The revisions may be in the form of addenda, or they may be incorporated in superseding documents.

If there is a question about a particular standard involving either an interpretation or a possible error, the user should contact the responsible organization. When the use of a standard is mandatory, whether as a result of a government regulation or a legal contract, it is essential to know the specific edition of the document to be used. If there is a question concerning which edition or revision of a document is to be used, it should be resolved before commencement of work. It is unfortunate, but not uncommon, to find that an outdated edition of a referenced document has been specified, and must be followed to be in compliance.

Organizations responsible for preparing standards that relate to welding are discussed in the following sections. The publications are listed without reference to date of publication, latest revision, or amendment. New publications relating to welding may be issued, and current ones may be withdrawn or revised. The responsible organization should be contacted for current information on the standards it publishes.

Some organizations cover many product categories while others may cover only one. Table 16-1 lists the organizations and the product categories covered by their documents. The National Fire Protection Association is not listed in Table 16-1 because its standards are concerned with safe practices rather than with products. The American Welding Society and the American Petroleum Institute also publish standards concerned with welding safety.

American Association of State Highway and Transportation Officials

The member agencies of the American Association of State Highway and Transportation Officials (AASHTO) are the U.S. Department of Transportation, and the Departments of Transportation and Highways of the fifty states, Washington DC, and Puerto Rico. The AASHTO specifications are prepared by committees made up of employees of the member agencies. These documents are the minimum rules to be followed by all member agencies or others in the design and construction of highway bridges.

Standard Specifications for Highway Bridges. This AASHTO specification covers the design and construction requirements for all types of highway bridges. It refers to the welding fabrication requirements in the AASHTO standard, *Specifications for Welding of Structural Steel—Highway Bridges* and the ANSI/AWS D1.1, *Structural Welding Code—Steel.*

Standard Specifications for Welding of Structural Steel Highway Bridges. This AASHTO specification provides modifications to the ANSI/AWS D1.1, *Structural Welding Code—Steel,* which are deemed necessary for use by member agencies. These are referenced to the applicable sections of the AWS Code.

Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members. Fracture-critical members or components of a bridge are tension members or components, the failure of which would likely result in collapse of the structure. This document assigns the responsibility for specifying those bridge members or components, if any, that fall into the fracture-critical category. It requires that such members or components be fabricated to the required workmanship standards only by organizations having the proper personnel, experience, procedures, knowledge and

Table 16-1
Products Covered by Standards of Various Organizations

Product	AAR	AASHTO	ABS	AISC	API	AREA	ASME	NBBPVI UBPVLS	ASTM	AWS	AWWA	FED	PFI	SAE	UL
Base metals			X		X		X		X			X		X	
Bridges		X		X		X				X		X			
Buildings				X						X					
Construction equipment										X		X		X	
Cranes, hoists							X			X					
Elevators, escalators							X								
Filler metals			X				X			X		X		X	
Food, drug equipment							X								
Machine tools										X					
Military equipment												X			
Power generation equipment			X				X	X				X			
Piping			X		X		X			X	X	X	X		
Presses										X					
Pressure vessels, boilers			X		X		X	X							
Railway equipment	X					X				X					
Sheet metal fabrication										X					
Ships			X							X		X			
Storage tanks					X					X	X				X
Structures, general				X						X					
Vehicles										X		X		X	

equipment. For example, all welding inspectors and nondestructive testing personnel must have demonstrated competency for assuring quality in compliance with the governing specifications. The document also contains requirements additional to those in the *Standard Specifications for Welding of Structural Steel—Highway Bridges.*

American Bureau of Shipping

The function of the American Bureau of Shipping (ABS) is to control the quality of ship construction. Each year, ABS reissues the *Rules for Building and Classing Steel Vessels.* These rules are applicable to ships that are intended to have American registration.

To obtain American registration and insurance, a ship must be classed (approved) by ABS after inspections and reviews by its surveyors (inspectors). The surveys begin with a review of the proposed design. Reviews are also made during and after construction to verify that construction complies with the ABS rules. The process is completed with the assignment and registration of a class (numerical identification) for the ship.

One section of the ABS Rules addresses welding and is divided into the following parts:

Part 1 — Hull Construction

Part 2 — Boilers, Unfired Pressure Vessels, Piping, and Engineering Structures

Part 3 — Weld Tests

The section addresses such topics as weld design, welding procedures, qualification testing, preparation for welding, production welding, workmanship, and inspection.

ABS also publishes a list of welding consumables, entitled *Approved Welding Electrodes, Wire-Flux, and Wire-Gas Combinations.* These consumables are produced by various manufacturers around the world. They are tested under ABS supervision and approved for use under the ABS rules.

American Institute of Steel Construction

The American Institute of Steel Construction (AISC) is a non-profit trade organization for the fabricated structural steel industry in the United States. The Institute's objectives are to improve and advance the use of fabricated structural steel through research and engineering studies, and to develop the most efficient and economical design of structures. The organization also conducts programs to improve and control product quality.

Manual of Steel Construction. The first four parts of the manual cover such topics as (1) the dimensions and properties of rolled structural steel shapes, (2) beam, girder, and column design, and (3) welded connection design. Part 5 of the manual is the "Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings." This part includes certain aspects of structural steel design that are not included in other parts of the manual.

Specification for the Design, Fabrication, and Erection of Structural Steel For Buildings. This document specifies, in detail, all principal steps required for the construction of structural steel buildings. It references the AWS filler metal specifications, and specifies the particular filler metal classification to be used with a welding process for each type of structural steel. Requirements for the types and details of fillet, plug, and slot welds are also included. The specification refers to ANSI/AWS D1.1, *Structural Welding Code—Steel,* for welding procedure and welder performance qualifications.

Quality Criteria and Inspection Standards. This document covers such subjects as preparation of materials, fitting and fastening, dimensional tolerances, welding, surface preparation, and painting. It discusses the practical implementation of some of the requirements of other AISC specifications. Typical problems that may be encountered in steel construction and recommended solutions are presented. The welding section provides interpretations regarding AISC requirements or prequalification of welding procedures, preheating, control of distortion, and tack welding.

American National Standards Institute

The American National Standards Institute (ANSI) is the coordinating organization for the United States voluntary standards system; it does not develop standards directly. The Institute provides the means for determining the need for standards, and ensures that organizations competent to fill these needs undertake the development work. The approval procedures of ANSI ensure that all interested persons have an opportunity to participate in the development of a standard or to comment on provisions of the standard prior to publication. ANSI is the U.S. member of non-treaty international standards organizations, such as the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC).

The American National Standards Institute provides a common language that can be used confidently by industry, suppliers, customers, business, the public, government, and labor. Each of these interests has either participated in the development of the standards or has been given the opportunity to comment on their provisions. However, these standards are developed and used voluntarily. They become mandatory only when they are adopted or referenced by a governmental body.

American Petroleum Institute

The American Petroleum Institute (API) publishes documents in all areas related to petroleum production. Those documents that include welding requirements are related to pipelines and refinery equipment, storage tanks for refinery service, and safety and fire protection.

Pipelines and Refinery Equipment. The appendix entitled "Inspection of Welding" in *The Guide for Inspection of Refinery Equipment* is the only part that applies specifically to welding. Its objective is to guide the user in determining whether welded joints are of acceptable quality and comply with both the requirements of the contract or job specifications and the prescribed welding procedure specifications.

Recommended Pipeline Maintenance Welding Practices, RP 1107. The primary purpose of this recommended practice is safety. It prohibits practices that are known to be unsafe, and warns against practices for which caution is necessary. It also includes 18methods for the inspection of repair welds, and for installing appurtenances on loaded piping systems being used for the transmission of natural gas, crude petroleum, and petroleum products.

The legal authority for RP 1107 comes from reference to it in ASME B31.4, *Liquefied Petroleum Transportation Piping Systems* (described under the American Society of Mechanical Engineers). The latter publication, like API Std 1104, *Standard for Welding Pipelines and Related Facilities,* is also referenced by Title 49, Part 195, *Transportation of Liquids by Pipeline,* of the United States Code of Federal Regulations.

Recommended Practice for Welded, Plain Carbon Steel Refinery Equipment for Environmental Cracking Service, Publ 942. This publication proposes actions for protection against hydrogen stress cracking of welds in plain carbon steel that are exposed, under stress, to certain aqueous-phase acidic environments, such as moist hydrogen sulfide.

Standard for Welding Pipelines and Related Facilities, API Std 1104. This standard applies to arc and oxyfuel gas welding of piping used in the compression, pumping, and transmission of crude petroleum, petroleum products, and fuel gases, and also to the distribution systems when applicable. It presents methods for the production of acceptable welds by qualified welders using approved welding procedures, materials, and equipment. It also presents methods for the production of suitable radiographs by qualified technicians using approved procedures and equipment, to ensure proper analysis of weld quality. Standards of acceptability and repair of weld defects are also included.

The legal authority for the use of API Std 1104 comes from Title 49, Part 195, *Transportation of Liquids by Pipeline,* of the United States Code of Federal Regulations.

Storage Tanks for Refinery Service

Inspection, Rating and Repair of Pressure Vessels in Petroleum Refinery Service, RP 510. This recommended practice covers the inspection, repair, evaluation for continued use, and methods for computing the maximum allowable working pressure of existing pressure vessels. The vessels include those constructed in accordance with Section VIII of the *ASME Boiler and Pressure Vessel Code* or other pressure vessel codes.

Recommended Rules for Design and Construction of Large, Welded, Low-Pressure Storage Tanks, Std 620. These rules cover the design and construction of large, field-welded tanks that are used for storage of petroleum intermediates and finished products under pressure of 103 kPa (15 psig) and less.

Welded Steel Tanks for Oil Storage, Std 650. This standard covers the material, design, fabrication, erection, and testing requirements for vertical, cylindrical, welded steel storage tanks that are above ground and not subject to internal pressure.

Safety and Fire Protection

Repairs to Crude Oil, Liquefied Petroleum Gas, and Products Pipelines, PSD 2200. This petroleum safety data sheet is a guide to safe practices for the repair of pipelines for crude oil, liquefied petroleum gas, and petroleum products.

Safe Practices in Gas and Electric Cutting and Welding in Refineries, Gasoline Plants, Cycling Plants, and Petrochemical Plants, Publ 2009. This publication outlines precautions for protecting persons from injury and property from damage by fire that might result during the operation of oxyfuel gas and electric cutting and welding equipment in and around petroleum operations.

Welding or Hot Tapping on Equipment Containing Flammables, PSD 2201. This petroleum safety data sheet lists procedures for welding, as well as for making hot taps (connections while in operation), on pipelines, vessels, or tanks containing flammables. This data sheet and PSD 2200 are also requirements of ASME B31.4, *Liquefied Petroleum Transportation Piping Systems.*

American Railway Engineering Association

The American Railway Engineering Association (AREA) publishes the *Manual for Railway Engineering.* This manual contains specifications, rules, plans, and instructions that constitute the recommended practices of railway engineering. Two chapters specifically cover steel construction. One of these covers the design, fabrication, and erection of buildings for railway purposes. The other addresses the same topics for railway bridges and miscellaneous steel structures.

American Society of Mechanical Engineers

Two standing committees of the American Society of Mechanical Engineers (ASME) are actively involved in the formulation, revision, and interpretation of standards covering products that may be fabricated by welding. These committees are responsible for preparing the ASME *Boiler and Pressure Vessel Code* and the *Code for Pressure Piping,* which are American National Standards.

Boiler and Pressure Vessel Code. The *ASME Boiler and Pressure Vessel Code* (PVC) contains eleven sections. Sections I, III, IV, VIII, E, and X cover the design, construction, and inspection of boilers and pressure vessels. Sections VI, VII, and XI cover the maintenance and operation of boilers or nuclear power plant components. The remaining Sections II, V, and IX cover material specifications, nondestructive examination, and welding and brazing qualifications, respectively.

Section I, *Power Boilers*, covers power, electric, and miniature boilers; high temperature boilers used in stationary service; and power boilers used in locomotive, portable, and traction service. Section III, *Nuclear Power Plant Components*, addresses the various components required by the nuclear power industry. Section IV, *Heating Boilers*, applies to steam heat and hot water supply boilers that are directly fired by oil, gas, electricity, or coal. Section VIII, *Pressure Vessels*, covers unfired pressure vessels. Unfired pressure vessels are containers for the containment of pressure either internal or external. All Code vessels not covered by Sections I, III, and IV are covered by Section VIII. These include towers, reactors and other oil and chemical refining vessels, heat exchangers for refineries, paper mills, and other process industries, as well as storage tanks for large and small air and gas compressors.

Section II, *Material Specifications*, contains the specifications for acceptable ferrous and nonferrous base metals, and for acceptable welding and brazing filler metals and fluxes. Many of these specifications are identical to and have the same numerical designation as ASTM and AWS specifications for base metals and welding consumables, respectively. Section V, *Nondestructive Examination*, covers methods and standards for nondestructive examination of boilers and pressure vessels. Section IX, *Welding and Brazing Qualifications*, covers the qualification of (1) welders, welding operators, brazers, and brazing operators, and (2) the welding and brazing procedures that are to be employed for welding or brazing of boilers or pressure vessels. This section of the Code is often cited by other standards and regulatory bodies as the welding and brazing qualification standard for other types of welded or brazed products.

The ASME *Boiler and Pressure Vessel Code* is referenced in the safety regulations of most states and major cities of the United States, and also the provinces of Canada. A number of federal agencies include the Code as part of their regulations.

The Uniform Boiler and Pressure Vessel Laws Society (UBPVLS) has, as its objective, uniformity of laws, rules, and regulations that affect boiler and pressure vessel fabricators, inspection agencies, and users. The Society believes that such laws, rules, and regulations should follow nationally accepted standards. It recommends the ASME *Boiler and Pressure Vessel Code* as the standard for construction and the *Inspection Code* of the National Board of Boiler and Pressure Inspectors (NBBPVI), discussed in a following section, as the standard for inspection and repair.

The ASME *Boiler and Pressure Vessel Code* is unique in that it requires third-party inspection independent of it the fabricator and the user. The NBBPVI commissions inspectors by examination. These inspectors are employed either by authorized inspection agencies (usually insurance companies) or by jurisdictional authorities.

Prior to building a boiler or pressure vessel, a company must have a quality control system and a manual that describes it. The system must be acceptable to the authorized inspection agency and either the jurisdictional authority or the NBBPVI. Based on the results of an audit of the fabricator's quality system, ASME may issue the fabricator a Certificate of Authorization and a code symbol stamp. The authorized inspection agency is also involved in monitoring the fabrication and field erection of boilers and pressure vessels. An authorized inspector must be satisfied that all applicable provisions of the ASME *Boiler and Pressure Vessel Code* have been followed before allowing the fabricator to apply its code symbol stamp to the vessel name plate.

Code for Pressure Piping

The ASME B31, *Code for Pressure Piping,* presently consists of seven sections. Each section prescribes the minimum requirements for the design, materials, fabrication, erection, testing, and inspection of a particular type of piping system.

B31.1, *Power Piping,* covers power and auxiliary service systems for electric generation stations; industrial and institutional plants; central and district heating plants; and district heating systems.

This section excludes boiler external piping which is defined by Section I of the ASME *Boiler and Pressure Vessel Code.* Boiler piping requires a quality control system and third-party inspection similar to those required for boiler fabrication. Otherwise, the materials, design, fabrication, installation, and testing for boiler external piping must meet the requirements of section B31.1. A fabricator is not required to provide a quality control system and third-party inspection for the other piping systems covered by B31.

B31.2, *Fuel Gas Piping,* covers piping systems for fuel gases including natural gas, manufactured gas, liquefied petroleum gas (LPG) and air mixtures above the upper combustible limits, LPG in the gaseous phase, or mixtures of these gases. These piping systems, both in and between buildings, extend from the outlet of the consumer's meter set assembly (or point of delivery) to and including the first pressure-containing valve upstream of the gas utilization device.

B31.3, *Chemical Plant and Petroleum Refinery Piping,* covers all piping within the property limits of facilities engaged in processing or handling of chemical, petroleum, or related products. Examples are chemical plants, petroleum refineries, loading terminals, natural gas processing plants (including liquefied natural gas facilities), bulk plants, compounding plants, and tank farms. This section applies to piping systems that handle all fluids, including fluidized solids, and to all types of service including raw, intermediate, and finished chemicals; oil and other petroleum products; gas, steam, air, water, and refrigerants, except as specifically excluded.

Piping for air and other gases, which is not now within the scope of existing sections of this code, may be designed, fabricated, inspected, and tested in accordance with the requirements of this section of the Code. The piping must be in plants, buildings, and similar facilities that are not otherwise within the scope of this section.

B31.4, *Liquid Petroleum Transportation Piping Systems,* covers piping for transporting liquid petroleum products between producers' lease facilities, tank farms, natural gas processing plants, refineries, stations, terminals, and other delivery and receiving points. Examples of such products are crude oil, condensate, gasoline, natural gas liquids, and liquefied petroleum gas.

B31. 5, *Refrigeration Piping,* applies to refrigerant and brine piping for use at temperatures as low as –196°C, (–320°F) whether erected on the premises or assembled in a factory. It does not include (1) self-contained or unit refrigeration systems subject to the requirements of Underwriters Laboratories or any other nationally recognized testing laboratory, (2) water piping, or (3) piping designed for external or internal pressure not exceeding 103 kPa (15 psig), regardless of size. Other sections of the Code may provide requirements for refrigeration piping in their respective scopes.

B31.8, *Gas Transmission and Distribution Piping Systems,* addresses gas compressor stations, gas metering and regulating stations, gas mains, and service lines up to the outlet of the customer's meter set assembly. Gas storage lines and gas storage equipment of the closed-pipe type that are either fabricated or forged from pipe or fabricated from pipe and fittings are also included.

B31.9, *Building Services Piping,* applies to piping systems for services in industrial, commercial, public, institutional and multi-unit residential buildings. It includes only those piping systems within the buildings or property limit.

All sections of the *Code for Pressure Piping* require qualification of the welding procedures and performance of welders and welding operators to be used in construction. Some sections require these qualifications to be performed in accordance with Section IX of the ASME *Boiler and Pressure Vessel Code,* while in others it is optional. The use of API Std 1104, *Standard for Welding Pipelines and Related Facilities* or AWS D10. 9, *Specification for Qualification of Weld-*

ing Procedures and Welders for Piping and Tubing is permitted in some sections as an alternative to Section IX. Each section of the Code should be consulted for the applicable qualification documents.

ASTM

ASTM (formerly the American Society for Testing and Materials) develops and publishes specifications for use in the production and testing of materials. The committees that develop the specifications are comprised of producers and users, as well as others who have an interest in the subject materials. The specifications cover virtually all materials used in industry and commerce with the exception of welding consumables, which are covered by AWS specifications.

ASTM publishes the *Annual Book of ASTM Standards* that incorporates new and revised standards. It is currently composed of 15 sections comprising 65 volumes and an index. Specifications for the metal products, test methods, and analytical procedures of interest to the welding industry are found in the first three sections, comprising 17 volumes. Section 1 covers iron and steel products; Section 2, nonferrous metal products; and Section 3, metal test methods and analytical procedures. Copies of single specifications are also available from ASTM.

Prefix letters, which are part of each specification's alpha-numeric designation, provide a general idea of the specification content. They include A for ferrous metals, B for nonferrous metals, and E for miscellaneous subjects including examination and testing. When ASME adopts an ASTM specification for certain applications, either in its entirety or in a revised form, it adds an "S" in front of the ASTM letter prefix.

Many ASTM specifications include supplementary requirements that must be specified by the purchaser if they are desired. These may include vacuum treatment, additional tension tests, impact tests, or ultrasonic examination.

The producer of a material or product is responsible for compliance with all mandatory and specified supplementary requirements of the appropriate ASTM specification. The user of the material is responsible for verifying that the producer has complied with all requirements.

Some codes permit the user to perform the tests required by ASTM or other specification to verify that a material meets requirements. If the results of the tests conform to the requirements of the designated specification, the material can be used for the application.

Some products covered by ASTM specifications are fabricated by welding. The largest group is steel pipe and tubing. Some types of pipe are produced from strip by rolling and arc welding the longitudinal seam. The welding procedures generally must be qualified to the requirements of the ASME *Boiler and Pressure Vessel Code* or another code.

Other types of pipe and tubing are produced with resistance welded seams. There are generally no specific welding requirements in the applicable ASTM specification. The finished pipe and tubing must pass specific tests that should result in failure at the welded seam if the welding operation is out of control.

Two ASTM specifications cover joints in piping systems. These are ASTM A422, *Standard Specification for Butt Welds in Still Tubes for Refinery Service* and ASTM F722, *Standard Specification for Welded Joints for Ship-board Piping Systems.* ASTM E190, *Guided Bend Test for Ductility of Welds,* is presently the only ASTM testing specification that is solely intended for welds.

American Water Works Association

The American Water Works Association (AWWA) currently has two standards that pertain to the welding of water storage and transmission systems. One of these standards was developed jointly with and adopted by the American Welding Society.

Standard for Field Welding of Steel Water Pipe Joints C206. This standard covers field welding of steel water pipe. It includes the welding of circumferential pipe joints as well as other welding required in the fabrication and installation of specials and accessories. The maximum wall thickness of pipe covered by this standard is 31.8 mm (1.25 in.).

Standard for Welded Steel Elevated Tanks, Standpipes, and Reservoirs for Water Storage, D100 (AWS D5.2). This standard covers the fabrication of water storage tanks. An elevated tank is one supported on a tower. A standpipe is a flat-bottomed cylindrical tank having a shell height greater than its diameter. A reservoir is a flat-bottomed cylindrical tank having a shell height equal to or smaller than its diameter. In addition to welding details, this standard specifies the responsibilities of the purchaser and the contractor for such items as the foundation plans, the foundation itself, water for pressure testing, and a suitable right-of-way from the nearest public road for on-site erection.

American Welding Society

The American Welding Society (AWS) publishes numerous documents covering the use and quality control of welding. These documents include codes, specifications, recommended practices, classifications, methods, and guides. The general subject areas covered are:

(1) Definitions and symbols
(2) Filler metals
(3) Qualification and testing
(4) Welding processes
(5) Welding applications
(6) Safety

Definitions and Symbols

ANSI/AWS A2.4 Symbols for Welding, Brazing, and Nondestructive Examination. This publication describes the standard symbols used to convey welding, brazing, and nondestructive testing requirements on drawings. Symbols in this publication are intended to facilitate communications between designers and fabrication personnel. Typical information that can be conveyed with welding symbols includes type of weld, joint geometry, weld size or effective throat, extent of welding, and contour and surface finish of the weld.

ANSI/AWS A3.0, Standard Welding Terms and Definitions. This publication lists and defines the standard terms that should be used in oral and written communications conveying welding, brazing, soldering, thermal spraying, and thermal cutting information. Nonstandard terms are also included; these are defined by reference to the standard terms.

Filler Metals

A listing of AWS specifications for filler metals is shown in Appendix 17.

Qualification and Testing

AWS C2.16, Guide for Thermal Spray Operator and Equipment Qualification. This guide provides for the qualification of operators and equipment for applying thermal sprayed coatings. It recommends procedural guidelines for qualification testing. The criteria used to judge acceptability are determined by the certifying agent alone or together with the purchaser.

AWS D10.9, Specification for Qualification of Welding Procedures and Welders for Piping and Tubing. This standard applies specifically to qualifications for tubular products. It covers circumferential groove and fillet welds but excludes welded longitudinal seams involved in pipe and tube manufacture. An organization may make this specification the governing document for qualifying welding procedures and welders by referencing it in the contract and by specifying one of the two levels of acceptance requirements. One level applies to systems that require a high degree of weld quality. Examples are lines in nuclear, chemical, cryogenic, gas, or steam systems. The other level applies to systems requiring an average degree of weld quality, such as low-pressure heating, air-conditioning, sanitary water, and some gas or chemical systems.

AWS B2.2, Standard for Brazing Procedure and Performance Qualification. The requirements for qualification of brazing procedures, brazers, and brazing operators for furnace, machine, and automatic brazing are covered by this publication. It is to be used when required by other documents, such as codes, specifications, or contracts. Those documents must specify certain requirements applicable to the production brazement. Applicable base metals are carbon and alloy steels, cast iron, aluminum, copper, nickel, titanium, zirconium, magnesium, and cobalt alloys.

AWS B2.1, Standard for Welding Procedure and Performance Qualification. This standard provides requirements for qualification of welding procedures, welders, and welding operators. It may be referenced in a product code, specification, or contract documents. If a contract document is not specific, certain additional requirements must also be specified, as listed in this standard. Applicable base metals are carbon and alloy steels, cast irons, aluminum, copper, nickel, and titanium alloys.

ANSI/AWS C3.2, Standard Method for Evaluating the Strength of Brazed Joints in Shear. This standard describes a test method used to obtain reliable shear strengths of brazed joints. For comparison purposes, specimen preparation, brazing practices, and testing, procedures must be consistent. Production brazed joint strength may not be the same as test joint strength if the brazing practices are different. With furnace brazing, for example, the actual part temperature or time at temperature, or both, during production may vary from those used to determine joint strength.

ANSI/AWS B4.0 Standard Methods for Mechanical Testing of Welds. This document describes the basic mechanical tests used for evaluation of welded joints, weldability, and hot cracking. The tests applicable to welded butt joints are tension, Charpy impact, drop-weight, dynamic-tear, and bend tests. Tests of fillet welds are limited to break and shear tests.

For welding materials and procedure qualifications, the most commonly used tests are round-tension, reduced-section tension, face-, root-, and side-bend, and Charpy V-notch impact. Fillet weld tests are employed to determine proper welding techniques and conditions, and the shear strength of welded joints for design purposes.

AWS B1.10, Guide for the Nondestructive Inspection of Welds. This standard describes the common nondestructive methods for examining welds. The methods included are visual, penetrant, magnetic particle, radiography, ultrasonic and eddy current inspection.

Welding Processes

AWS publishes recommended practices and guides for arc and oxyfuel gas welding and cutting; brazing; resistance welding; and thermal spraying. The following is a list of processes and applicable documents.

Arc and Gas Welding and Cutting

Air Carbon-Arc Gouging and Cutting, Recommended Practices for, ANSI/AWS C5.3

Electrogas Welding, Recommended Practices for, AWS C5.7

Gas Metal Arc Welding, Recommended Practices for, AWS C5.6

Gas Tungsten Arc Welding, Recommended Practices for, AWS C5.5

Oxyfuel Gas Cutting, Operator's Manual for, AWS C4.2

Plasma Arc Cutting, Recommended Practices for, AWS C5.2

Plasma Arc Welding, Recommended Practices for, AWS C5.1

Stud Welding, Recommended Practices for, ANSI/AWS C5.4

Brazing

Design, Manufacture, and Inspection of Critical Brazed Components, Recommended Practices for, AWS C3.3

Resistance Welding

Resistance Welding, Recommended Practices for, AWS C1.1

Resistance Welding Coated Low Carbon Steels, Recommended Practices for, AWS C1.3

Thermal Spraying

Thermal Spraying: Practice, Theory, and Application

Metallizing with Aluminum and Zinc for Protection of Iron and Steel, Recommended Practices for, AWS C2.2

Welding Applications

AWS publishes standards that cover various applications of welding. The subjects and appropriate documents are listed below.

Automotive

Automotive Portable Gun Resistance-Spot Welding, Recommended Practices for, AWS D8.5

Automotive Resistance Spot Welding Electrodes, Standard for, AWS D8. 6

Automotive Welding Design, Recommended Practices for, AWS D8.4

Automotive Weld Quality-Resistance Spot Welding, Specification for, AWS D8.7

Machinery and Equipment

Earthmoving and Construction Equipment, Specification for Welding, AWS D14.3

Industrial and Mill Crane and Other Material Handling Equipment, Specification for Welding, ANSI/AWS D14.1

Machinery and Equipment, Classification and Application of Welded Joints for, AWS D14.4

Metal Cutting Machine Tool Weldments, Specification for, ANSI/AWS D14.2

Presses and Press Components, Specification for Welding of, AWS D14.5

Railroad Welding Specification, ANSI/AWS D15.1

Rotating Elements of Equipment, Specification for, AWS D14.6

Marine

Aluminum Hull Welding, Guide for, ANSI/AWS D3.7

Steel Hull Welding, Guide for, ANSI/AWS D3.5

Underwater Welding, Specification for, ANSI/AWS D3.6

Piping and Tubing

Aluminum and Aluminum Alloy Pipe, Recommended Practices for Gas Shielded Arc Welding of, ANSI/AWS D10.7

Austenitic Chromium Nickel Stainless Steel Piping and Tubing, Recommended Practices for Welding, ANSI/AWS D10.4

Chromium-Molybdenum Steel Piping and Tubing, Recommended Practices for Welding of, ANSI/AWS D10.8

Local Heat Treatment of Welds in Piping and Tubing, AWS D10.10

Plain Carbon Steel Pipe, Recommended Practices and Procedures for Welding, AWS D10.12

Root Pass Welding and Gas Purging, Recommended Practices for, ANSI/AWS D10.11

Titanium Piping and Tubing, Recommended Practices for Gas Tungsten Arc Welding of, ANSI/AWS D10.6

Sheet Metal

ANSI/AWS D9.1, *Specification for Welding of Sheet Metal* covers non-structural fabrication and erection of sheet metal by welding for heating, ventilating, and air conditioning systems; architectural usages, food-processing equipment, and similar applications. Where differential pressures of more than 30 kPa (120 in. of water) or structural requirements are involved, other standards are to be used.

Structural Welding

ANSI/AWS D1.2, *Structural Welding Code—Aluminum,* addresses welding requirements for aluminum alloy structures. It is used in conjunction with appropriate complementary codes or specifications for materials, design, and construction. The structures covered are tubular designs and static and dynamic nontubular designs.

ANSI/AWS D1.4, *Structural Welding Code—Reinforcing Steel,* applies to the welding of concrete reinforcing steel for splices (prestressing steel excepted), steel connection devices, inserts, anchors, anchorage details, and other welding in reinforced concrete construction. Welding may be done in a fabrication shop or in the field. When welding reinforcing steel to primary structural members, the provisions of ANSI/AWS D1.1, *Structural Welding Code—Steel,* also apply.

ANSI/AWS D1.3, *Structural Welding Code—Sheet Steel,* applies to the arc welding of sheet and strip steel, including cold-formed members, that are 5 mm (0.18 in.) or less in thickness. The welding may involve connections of sheet or strip steel to thicker supporting structural members. When sheet steel is welded to primary structural members, the provisions of ANSI/AWS D1.1, *Structural Welding Code*—Steel, also apply.

ANSI/AWS D1.1, *Structural Welding Code—Steel,* covers welding requirements applicable to welded structures of carbon- and low-alloy steels. It is to be used in conjunction with any complementary code or specification for the design and construction of steel structures. It is not intended to apply to pressure vessels, pressure piping, or base metals less than 3 mm (1/8 in.) thick. There are sections devoted exclusively to buildings (static loading), bridges (dynamic loading), and tubular structures.

Safety

ANSI/ASC Z49.1, *Safety in Welding and Cutting,* was developed by the ANSI Accredited Standards Committee Z49, Safety in Welding and Cutting, and then published by AWS. The purpose of the Standard is the protection of persons from injury and illness, and the protection of property from damage by fire and explosions arising from welding, cutting, and allied processes.

It specifically covers arc, oxyfuel gas, and resistance welding, and thermal cutting, but the requirements are generally applicable to other welding processes as well.

The provisions of this standard are backed by the force of law since they are included in the *General Industry Standards* of the U.S. Department of Labor, Occupational Safety and Health Administration.

Other safety and health standards published by AWS include the following:

Electron Beam Welding and Cutting, Recommended Safe Practices for, AWS F2.1

Evaluating Contaminants in the Welding Environment, A Sampling Strategy Guide, AWS F1.3

Measuring Fume Generation Rates and Total Fume Emission for Welding and Allied Processes, Laboratory Method for, ANSI/AWS F1.2

Preparation for Welding and Cutting Containers and Piping That Have Held Hazardous Substances, Recommended Safe Practices for the, AWS F4.1

Sampling Airborne Particulates Generated by Welding and Allied Processes, Method for, ANSI/AWS F1.1

Sound Level Measurement of Manual Arc Welding and Cutting Processes, Method for, AWS F6.1

Thermal Spraying, Recommended Safe Practices for, AWS C2.1

Association of American Railroads

Manual of Standards and Recommended Practices. The primary source of welding information relating to the construction of new railway equipment is the *Manual of Standards and Recommended Practices* prepared by the Mechanical Division, Association of American Railroads (AAR). This manual includes specifications, standards, and recommended practices adopted by the Mechanical Division. Several sections of the manual relate to welding, and the requirements are similar to those of ANSI/AWS D1.1, *Structural Welding Code—Steel.* This Code is frequently referenced, particularly with regard to weld procedure and performance qualification.

The American Welding Society publishes AWS D15.1, *Railroad Welding Specification.* AWS D15.1 is written by the Committee on Railroad Welding, which is made up of representatives of AAR and AWS. ANSI/AWS D15.1, *Railroad Welding Specification,* has been endorsed by the AAR. Revisions of the *Manual of Standards and Recommended Practices* refer to AWS D15.1 for all welding requirements on construction and maintenance of steel and aluminum railcars.

The sections of the current *Manual of Standards and Recommended Practices* that relate to welding are summarized below.

Section C, Part II, Specifications for Design, Fabrication and Construction of Freight Cars. This specification covers the general welding practices for freight car construction. Welding processes and procedures other than those listed in the document may be used. However, they must conform to established welding standards or proprietary car builder's specifications, and produce welds of quality consistent with design requirements and good manufacturing techniques. The welding requirements are similar to, though not as detailed as those in ANSI/AWS D1.1, *Structural Welding Code—Steel.* The qualification of welders and welding operators must be done in accordance with the AWS Code.

Section C, Part III, Specification for Tank Cars. This specification covers the construction of railroad car tanks used for the transportation of hazardous and non-hazardous materials. The requirements for fusion welding of the tanks, and for qualifying welders and welding procedures to be used are described in an appendix. A second appendix describes the requirements for repairs, alterations, or conversions of car tanks. If welding is required, it must be performed by facilities certified by AAR in accordance with a third appendix. The rules for welding on the tanks are covered by the ASME *Boiler and Pressure Vessel Code.*

The U.S. Department of Transportation (DOT) issues regulations covering the transportation of explosives, radioactive materials, and other dangerous articles. Requirements for tank cars are set forth in the *United States Code of Federal Regulations,* Title 49, Sections 173.314, 173.316, and 179, which are included at the end of the AAR specifications.

Section D, Trucks and Truck Details. The procedures, workmanship, and qualification of welders employed in the fabrication of steel railroad truck frames are required to be in accordance with (1) the latest recommendations of the American Welding Society, (2) The Specifications for Design, Fabrication, and Construction of Freight Cars, and (3) the welding requirements of the Specifications for Tank Cars.

Field Manual of Association of American Railroads Interchange Rules. This manual covers the repair of existing railway equipment. The U.S. railway network is made up of numerous interconnecting systems, and it is often necessary for one system to make repairs on equipment of another system. The repair methods are detailed and specific so that they may be used as the basis for standard charges between the various railroad companies.

Canadian Standards Association

The Canadian Standards Association (CSA) is a voluntary membership organization engaged in standards development and also testing and certification. The CSA is similar to ANSI in the United States, but ANSI does not test and certify products. A CSA Certification Mark assures buyers that a product conforms to acceptable standards.

Examples of CSA welding documents are the following:

Aluminum Welding Qualification Code, CSA W47.2

Certification of Companies for Fusion Welding of Steel Structures, CSA W47. 1

Code for Safety in Welding and Cutting (Requirements for Welding Operators), CSA W117.2

Qualification Code for Welding Inspection Organizations, CSA W178

Resistance Welding Qualification Code for Fabricators of Structural Members Used in Buildings, CSA W55.3

Welded Aluminum Design and Workmanship (Inert Gas Shielded Arc Processes), CSA S244

Welded Steel Construction (Metal Arc Welding), CSA W59

Welding Electrodes, CSA W48 Series

Welding of Reinforcing Bars in Reinforced Concrete Construction, CSA W186

Compressed Gas Association

The Compressed Gas Association (CGA) promotes, develops, represents, and coordinates technical and standardization activities in the compressed gas industries, including end uses of products.

The Handbook of Compressed Gases, published by CGA, is a source of basic information about compressed gases, including transportation, uses, and safety considerations, and also the rules and regulations pertaining to them.

Standards for Welding and Brazing on Thin Walled Containers, CGA C-3, is directly related to the use of welding and brazing in the manufacture of DOT-regulated compressed gas cylinders. It covers procedure and operator qualification, inspection, and container repair.

The following CGA publications contain information on the properties, manufacture, transportation, storage, handling, and use of gases commonly used in welding operations:

Acetylene, G-1
Commodity Specification for Acetylene, G-1.1
Carbon Dioxide, G-6
Commodity Specification for Carbon Dioxide, G-6.2
Hydrogen, G-5
Commodity Specification for Hydrogen, G-5.3
Oxygen, G-4
Commodity Specification for Oxygen, G-4.3
The Inert Gases Argon, Nitrogen, and Helium, P-9
Commodity Specification for Argon, G-11.1
Commodity Specification for Helium, G-9.1
Commodity Specification for Nitrogen, G-10.1

Safety considerations related to the gases commonly used in welding operations are discussed in the following CGA pamphlets:

Handling Acetylene Cylinders in Fire Situations, SB-4
Oxygen-Deficient Atmospheres, SB-2
Safe Handling of Compressed Gases in Containers, P-1

Federal Government

Several departments of the federal government, including the General Services Administration, are responsible for developing welding standards or adopting existing standards, or both. More than 48 000 standards have been adopted by the federal government.

Consensus Standards. The U.S. Departments of Labor, Transportation, and Energy are primarily concerned with adopting existing national consensus standards, but they also make amendments to these standards or create separate standards, as necessary. For example, the Occupational Safety and Health Administration (OSHA) of the Department of Labor issues regulations covering occupational safety and health protection. The welding portions of standards adopted or established by OSHA are published under Title 29 of the *United States Code of Federal Regulations*. Part 1910 covers general industry; Part 1926 covers the construction industry. These regulations were derived primarily from national consensus standards of ANSI and the NFPA.

Similarly, the U.S. Department of Transportation is responsible for regulating the transportation of hazardous materials, petroleum, and petroleum products by pipeline in interstate commerce. Its rules are published under Title 49 of the *United Sates Code of Federal Regulations, Part 195.* Typical of the many national consensus standards incorporated by reference in these regulations are API Standard 1104 and ASME B31.4.

The U. S. Department of Transportation is also responsible for regulating merchant ships of American registry. It is empowered to control the design, fabrication, and inspection of these ships by Title 46 of the *United States Code of Federal Regulations.*

The U.S. Coast Guard is responsible for performing the inspections of merchant ships. The *Marine Engineering Regulations* incorporate references to national consensus standards, such as those published by ASME, ANSI, and ASTM. These rules cover repairs and alterations that must be performed with the cognizance of the local Coast Guard Marine Inspection Officer.

The U.S. Department of Energy is responsible for the development and use of standards by government and industry for the design, construction, and operation of safe, reliable, and economic nuclear energy facilities. National consensus standards, such as the ASME *Boiler and Pressure Vessel Code,* Sections III and IX, and ANSI/AWS D1.1, *Structural Welding Code—Steel,* are referred to in full or in part. These standards are supplemented by separate program standards, known as *RDT Standards.*

Military and Federal Specifications. Military specifications are prepared by the Department of Defense. They cover materials, products, or services specifically for military use, and commercial items modified to meet military requirements. Military specifications have document designations beginning with the prefix *MIL.* They are issued as either coordinated or limited-coordination documents. Coordinated documents cover items or services required by more than one branch of the military. Limited coordination documents cover items or services of interest to a single branch. If a document is of limited coordination, the branch of the military which uses the document will appear in parentheses in the document designation. The Department of Defense has begun to replace military specifications with consensus standards in the interest of economy.

Two current military specifications cover the qualification of welding procedures or welder performance, or both. One is MIL-STD-1595, *Qualification of Aircraft, Missile, and Aerospace Fusion Welders.* The other, MIL-STD-248, *Welding and Brazing Procedure and Performance Qualification,* covers the requirements for the qualification of welding and brazing procedures, welders, brazers, and welding and brazing operators. It allows the fabricator to submit for approval certified records of qualification tests prepared in conformance with the standards of other government agencies, ABS, ASME, or other organizations. Its use is mandatory when referenced by other specifications or contractual documents.

MIL-STD-1595 establishes the procedure for qualifying welders and welding operators engaged in the fabrication of components for aircraft, missiles, and other aerospace equipment by fusion welding processes. This standard is applicable when required in the contracting documents, or when invoked in the absence of a specified welder qualification document.

MIL-STD-1595 superseded MIL-T-5021, *Tests; Aircraft and Missile Welding Operator's Qualification,* which is obsolete. However, MIL-T-5021 is still referenced by other current government specifications and contract documents. When so referenced, a contractor has to perform the technically obsolete tests required by this standard.

Federal specifications are developed for materials, products, and services that are used by two or more Federal agencies, one of which is not a defense agency. Federal specifications are classified into broad categories. The *QQ* group, for example, covers metals and most welding specifications. Soldering and brazing fluxes are in the *O-F* group.

Some military and federal specifications include requirements for testing and approval of a material, process, or piece of equipment before its submission for use under the specification. If the acceptance tests pass the specification requirements, the material or equipment will be included in the applicable *Qualified Products List (QPL).* In other specifications, the supplier is responsible for product conformance. This is often the case for welded fabrications. The supplier must show evidence that the welding procedures and the welders are qualified in accordance with the requirements of the specification, and must certify the test report.

For a listing of military and federal specifications that pertain to welding, brazing, and soldering, refer to American Welding Society, *Welding Handbook,* Vol. 1, 8th Edition, Miami, Florida: American Welding Society, 1987.

International Organization for Standardization

The International Organization for Standardization (ISO) promotes the development of standards to facilitate the international exchange of goods and services. It is comprised of the standards-writing bodies of more than 80 countries and has adopted or developed over 4000 standards.

ANSI is the designated U.S. representative to ISO. ISO standards and publications are available from ANSI.

The ISO standards that relate to welding have been categorized into six groups: (1) General, (2) Arc and Gas Welding and Cutting Processes, (3) Resistance Welding Processes, (4) Filler Metals and Electrodes, (5) Design, and (6) Testing and Evaluation. For a listing of ISO standards, refer to American Welding Society, *Welding Handbook,* Vol. 1, 8th Edition, Miami, Florida: American Welding Society, 1987.

National Board of Boiler and Pressure Vessel Inspectors

The National Board of Boiler and Pressure Vessels (NBBPVI), often referred to as the National Board, represents the enforcement agencies empowered to assure adherence to the *ASME Boiler and Pressure Vessel Code.* Its members are the chief inspectors or other jurisdictional authorities who administer the boiler and pressure vessel safety laws in the various jurisdictions of the United States and provinces of Canada.

The National Board is involved in the inspection of new boilers and pressure vessels.It maintains a registration system for use by manufacturers who desire or are required by law to register the boilers or pressure vessels that they have constructed. The National Board is also responsible for investigating possible violations of the *ASME Boiler and Pressure Vessel Code* by either commissioned inspectors or manufacturers.

The National Board publishes a number of pamphlets and forms concerning the manufacture and inspection of boilers, pressure vessels, and safety valves. It also publishes the *National Board Inspection Code* for the guidance of its members, commissioned inspectors, and others. The purpose of this code is to maintain the integrity of boilers and pressure vessels after they have been placed in service by providing rules and guidelines for inspection after installation, repair, alteration, or re-rating. In addition, it provides inspection guidelines for authorized inspectors during fabrication of boilers and pressure vessels.

In some states, organizations that desire to repair boilers and pressure vessels must obtain the National Board Repair (R) stamp by application to the National Board. The firm must qualify all welding procedures and welders in accordance with the *ASME Boiler and Pressure Vessel Code, Section IX*, and the results must be accepted by the inspection agency. The firm must also have and demonstrate a quality control system similar to, but not as comprehensive as that required for an ASME code symbol stamp.

National Fire Protection Association

The mission of the National Fire Protection Association (NFPA) is the safeguarding of people and their environment from destructive fire through the use of scientific and engineering techniques and education. The NFPA standards are widely used as the basis of legislation and regulation at all levels of government. Many are referenced in the regulations of OSHA. The standards are also used by insurance authorities for risk evaluation and premium rating.

Installation of Gas Systems. NFPA publishes several standards that present general principles for the installation of gas supply systems and the storage and handling of gases commonly used in welding and cutting:

Bulk Oxygen Systems at Consumer Sites, NFPA 50

Design and installation of Oxygen-Fuel Gas Systems for Welding and Cutting and Allied Processes, NFPA 51

Gaseous Hydrogen Systems at Consumer Sites, NFPA 50A

National Fuel Gas Code, NFPA 54

Storage and Handling of Liquefied Petroleum Gases, NFPA 58

Users should check each standard to see if it applies to their particular situation. For example, NFPA 51 does not apply to a system comprised of a torch, regulators, hoses, and single cylinders of oxygen and fuel gas. Such a system is covered by ANSI/AWS Z49.1, *Safety in Welding and Cutting.*

Safety

NFPA publishes several standards which relate to the safe use of welding and cutting processes:

Cleaning Small Tanks and Containers, NFPA 327

Control of Gas Hazards on Vessels to be Repaired, NFPA 306

Fire Protection in Use of Cutting and Welding Processes, NFPA 51B

Installation of Blower and Exhaust Systems for Dust, Stock, and Vapor Removal or Conveying, NFPA 91

Standard on Aircraft Maintenance, NFPA 410

Again, the user should check the standards to determine those that apply to the particular situation.

Pipe Fabrication Institute

The Pipe Fabricating Institute (PFI) publishes numerous documents for use by the piping industry. Some of the standards have mandatory status because they are referenced in one or more piping codes. The purpose of PFI standards is to promote uniformity of piping fabrication in areas not specifically covered by codes. Other PFI documents, such as technical bulletins, are not mandatory, but they aid the piping fabricator in meeting the requirements of codes. The following PFI standards relate directly to welding.

End Preparation and Machined Backing Rings for Butt Welds, ES1

Manual Gas Tungsten Arc Root Pass Welding End Preparation and Fit up Tolerances, ES21

Minimum Length and Spacing for Welded Nozzles, ES7

Preheat and Postheat Treatment of Welds, ES19

Recommended Practice for Welding of Transition Joints Between Dissimilar Steel Combinations, ES28

Welded Load Bearing Attachments to Pressure Retaining Piping Materials, ES26

Visual Examination—The Purpose, Meaning, and Limitation of the Term, ES27

SAE

SAE (formerly the Society of Automotive Engineers) is concerned with the research, development, design, manufacture, and operation of all types of self-propelled machinery. Such machinery includes automobiles, trucks, buses, farm machines, construction equipment, airplanes, helicopters, and space vehicles. Related areas of interest to SAE are fuels, lubricants, and engineering materials.

Automotive Standards. Several SAE welding-related automotive standards are written in cooperation with AWS. These are:

Automotive Resistance Spot Welding Electrodes, Standard for, HS J1156 (AWS D8.6)

Automotive Weld Quality—Resistance Spot Welding, Specification for, HS J1188 (AWS D8.7)

Automotive Frame Weld Quality—Arc Welding, Specification for, HS J1196 (AWS D8.8)

Aerospace Material Specifications. Material specifications are published by SAE for use by the aerospace industry. The Aerospace Material Specifications (AMS) cover fabricated parts, tolerances, quality control procedures, and processes.

For a listing of welding-related AMS specifications, refer to American Welding Society, *Welding Handbook*, Vol. 1, 8th Edition, Miami, Florida: American Welding Society, 1987.

Unified Numbering System

The Unified Numbering System (UNS) provides a method for cross referencing the different numbering systems used to identify metals, alloys, and welding filler metals. With UNS, it is possible to correlate over 4400 metals and alloys used in a variety of specifications, regardless of the identifying number used by a society, trade association, producer, or user.

UNS is produced jointly by SAE and ASTM, and designated SAE HSJ1086/ASTM DS56. It cross references the numbered metal and alloy designations of the following organizations and systems:

AA (Aluminum Association)
ACI (Steel Founders Society of America)
AISI (American Iron and Steel Institute)
ASME (American Society of Mechanical Engineers)
ASTM (Formerly American Society for Testing and Materials
AWS (American Welding Society)
CDA (Copper Development Association)
Federal Specifications
MIL (Military Specifications)
SAE (Formerly Society of Automotive Engineers)
AMS (SAE Aerospace Materials Specifications)

Over 500 of the listed numbers are for welding and brazing filler metals. Numbers with the prefix W are assigned to welding filler metals that are classified by deposited metal composition.

Underwriter's Laboratories, Inc.

Underwriter's Laboratories, Inc., (UL) is a not-for-profit organization which operates laboratories for the examination and testing of devices, systems, and materials to determine their relation to hazards to life and property. *UL Standards for Safety* are developed under a procedure which provides for participation and comment from the affected public as well as industry. This procedure takes into consideration a survey of known existing standards, and the needs and opinions of a wide variety of interests concerned with the subject matter of a given standard. These interests include manufacturers, consumers, individuals associated with consumer-oriented organizations, academicians, government officials, industrial and commercial users, inspection authorities, insurance interests, and others. Examples of standards which contain welding requirements are the following:

Tanks, Steel Aboveground, for Flammable and Combustible Liquids, UL 58

Tanks, Steel Underground, for Flammable and Combustible Liquids, UL 142

Both of these standards include details relating to the types of welded joints that are allowed to be used and how they are to be tested.

UL should be contacted if no standard can be found for a particular product. The UL *Standards for Safety* pertain to more than 11 000 product types in over 500 generic product categories.

Source: American Welding Society, *Welding Handbook*, Vol. 1, 8th Edition. Miami, Florida: American Welding Society, 1987.

Appendix 17
Filler Metal Specifications

The AWS filler metal specifications cover most types of consumables used with the various welding and brazing processes. The specifications include both mandatory and nonmandatory provisions. The mandatory provisions cover such subjects as chemical or mechanical properties, or both, manufacture, testing, and packaging. The nonmandatory provisions, included in an appendix, are provided as a source of information for the user on the classification, description, and intended use of the filler metals covered.

Following is a current listing of AWS filler metal specifications.

Aluminum and Aluminum Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.10

Aluminum and Aluminum Alloy Covered Arc Welding Electrodes, Specification for, ANSI/AWS A5.3

Brazing Filler Metal, Specification for, ANSI/AWS A5.8

Composite Surfacing Welding Rods and Electrodes, Specification for, ANSI/AWS A5.21

Carbon Steel Electrodes for Flux Cored Arc Welding, Specification for, ANSI/AWS A5.20

Carbon Steel Electrodes and Fluxes for Submerged Arc Welding, Specification for, ANSI/AWS A5.17

Carbon Steel Filler Metals for Gas Shielded Arc Welding, Specification for, ANSI/AWS A5.18

Consumable Inserts, Specification for, ANSI/AWS A5.30

Consumables Used for Electrogas Welding of Carbon and High Strength Low Alloy Steels, Specification for, ANSI/AWS A5.26

Consumables Used for Electroslag Welding of Carbon and High Strength Low Alloy Steels, Specification for, ANSI/AWS A5.25

Copper and Copper Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.7

Copper and Copper Alloy Rods for Oxyfuel Gas Welding, Specification for, ANSI/AWS A5.27

Corrosion-Resisting Chromium and Chromium-Nickel Steel Bare and Composite Metal Cored and Stranded Arc Welding Electrodes and Welding Rods, Specification for, ANSI/AWS A5.9

Covered Carbon Steel Arc Welding Electrodes, Specification for, ANSI/AWS A5.1

Covered Copper and Copper Alloy Arc Welding Electrodes, Specification for, ANSI/AWS A5.6

Covered Corrosion-Resisting Chromium and Chromium-Nickel Steel Welding Electrodes, Specification for, ANSI/AWS A5.4

Flux-Cored Corrosion-Resisting Chromium and Chromium-Nickel Steel Electrodes, Specification for, ANSI/AWS A5.22

Iron and Steel Oxyfuel Gas Welding Rods, Specification for, ANSI/AWS A5.2

Low Alloy Steel Covered Arc Welding Electrodes, Specification for, ANSI/AWS A5.5

Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding, Specification for, ANSI/AWS A5.23

Low Alloy Steel Electrodes for Flux Cored Arc Welding, Specification for, ANSI/AWS A5.29

Low Alloy Steel Filler Metals for Gas Shielded Arc Welding, Specification for, ANSI/AWS A5.28

Magnesium Alloy Welding Rods and Bare Electrodes, Specification for, ANSI/AWS A5.19

Nickel and Nickel Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.14

Nickel and Nickel Alloy Covered Welding Electrodes, Specification for, ANSI/AWS A5.11

Solid Surfacing Welding Rods and Electrodes, Specification for, ANSI/AWS A5.13

Titanium and Titanium Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.16

Tungsten Arc Welding Electrodes, Specification for, ANSI/AWS A5.12

Welding Rods and Covered Electrodes for Cast Iron, Specification for, ANSI/AWS A5.15

Zirconium and Zirconium Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.24

Most AWS filler metal specifications have been approved by ANSI as American National Standards and are adopted by ASME. When ASME adopts an AWS filler metal specification, either in its entirety or with revisions, it adds the letters "SF" to the AWS alphanumeric designation. Thus, ASME SFA-5.4 specification would be similar, if not identical, to the AWS A5.4 specification.

AWS also publishes the following documents to aid users with the purchase of filler metals:

AWS A5.01, *Filler Metal Procurement Guidelines,* provides methods for identification of filler metal components, lot classification of filler metals, and specification of the testing schedule in procurement documents.

The *Filler Metal Comparison Charts* provide lists of manufacturers that supply filler metals in accordance with the various AWS specifications and provides the brand names. Conversely, the AWS specification, classification, and manufacturer of a filler metal can be determined from the brand name.

The *AWS User's Guide to Filler Metals* is a collection of commentary information selected from the 30 technical standards written by the AWS Committee on Filler Metal. The User's Guide provides descriptions of specific filler metals and their intended usage, as well as methods for classification, welding procedures, and safety considerations. Although reasonable care has been taken in the compilation and publication of the User's Guide to insure authenticity of the contents, no representation is made as to the accuracy or reliability of this information. The User's Guide is intended solely as a supplement to the AWS *Filler Metal Comparison Charts*, and should not be regarded as a substitute for the various AWS specifications to which it refers. This publication is subject to revision at any time.

Appendix 18
Recommended Eye Protection

Arc Welding and Cutting. Welding helmets or hand shields containing appropriate filter lenses and cover plates must be used by welders, welding operators and nearby personnel when viewing an arc. Suggested shade numbers for filter plates for various arc welding and cutting processes are shown in Table 18-1.

During submerged arc welding, the arc is covered by flux and is not readily visible; therefore a welding helmet is not needed. However, because the arc sometimes flashes through the flux burden, the operator should wear tinted safety glasses.

Oxyfuel Gas Welding, Cutting, Brazing and Soldering. Safety goggles with filter lenses (see Table 18-2) and full conforming side shields must be worn when performing oxyfuel gas welding and cutting. For torch brazing and soldering, safety spectacles with or without side shields are recommended. As with oxyfuel gas welding and cutting, a bright yellow flame may be visible during torch brazing. A filter similar to that used for oxyfuel gas welding and cutting should be used for torch brazing.

Thermal Spraying. The general requirements for the protection of thermal spray operators are the same as for welders. Table 18-3 is a guide for the selection of the proper filter shade number for viewing a specific spraying operation.

Laser Beam Welding and Cutting. Eye injury is readily caused by laser beams. Safety glasses are available that are substantially transparent to visible light but are opaque to specific laser beam outputs. Selective filters for ruby, Nd-YAG, and other laser systems are available. Glasses appropriate to the specific laser system must be used.

Table 18-1
Suggested Viewing Filter Plates—Arc Processes

Operation	Welding Current, A	Lowest Shade Number	Comfort Shade Number[a]
Shielded metal arc welding	Under 60	7	—
	60–160	7	10
	160–250	10	12
	250–550	11	14
Gas metal arc and flux cored arc welding	Under 60	7	—
	60–160	10	11
	160–250	10	12
	250–500	10	14
Gas tungsten arc welding	Under 50	8	10
	50–150	8	12
	150–550	10	14
Plasma arc welding	Under 20	6	6–8
	20–100	8	10
	100–400	10	12
	400–800	11	14
Plasma arc cutting[b]	Under 300	8	9
	300–400	9	12
	400–800	10	14
Air-carbon arc cutting	Under 500	10	12
	500–1000	11	14

a. To select the best shade for the application, first select a dark shade. If it is difficult to see the operation properly, select successively lighter shades until the operation is sufficiently visible for good control. However, do not go below the lowest recommended number, where given.

b. The suggested filters are for applications where the arc is clearly visible. Lighter shades may be used where the arc is hidden by the work or submerged in water.

Table 18-2
Suggested Viewing Filter Plates—Oxyfuel Gas Processes

Operation	Plate Thickness		Comfort Shade Number[a]
	mm	in.	
Oxyfuel gas welding (steel)[b]	3.2	Under 1/8	4, 5
	3.2–12.7	1/8–1/2	5, 6
	12.7	Over 1/2	6, 8
Oxyfuel cutting (steel)[b]	25	Under 1	3, 4
	25–125	1–6	4, 5
	150	Over 6	5, 6
Torch brazing	—	—	3, 4
Torch soldering	—	—	2

a. To select the best shade for the application, first select a dark shade. If it is difficult to see the operation properly, select successively lighter shades until the operation is sufficiently visible for good control. However, do not go below the lowest recommended number, where given.

b. With oxyfuel gas welding or cutting, the flame emits strong yellow light. A filter plate that absorbs yellow or sodium wave lengths of visible light should be used for good visibility.

Table 18-3
Recommended Eye Filter Plates for Thermal Spraying Operations

Operation	Filter Shade Numbers
Wire flame spraying (except molybdenum)	2 to 4
Wire flame spraying of molybdenum	3 to 6
Flame spraying of metal powder	3 to 6
Flame spraying of exothermics or ceramics	4 to 8
Plasma and arc spraying	9 to 12
Fusing operations	4 to 8

Appendix 19
Automatic Welding Programs

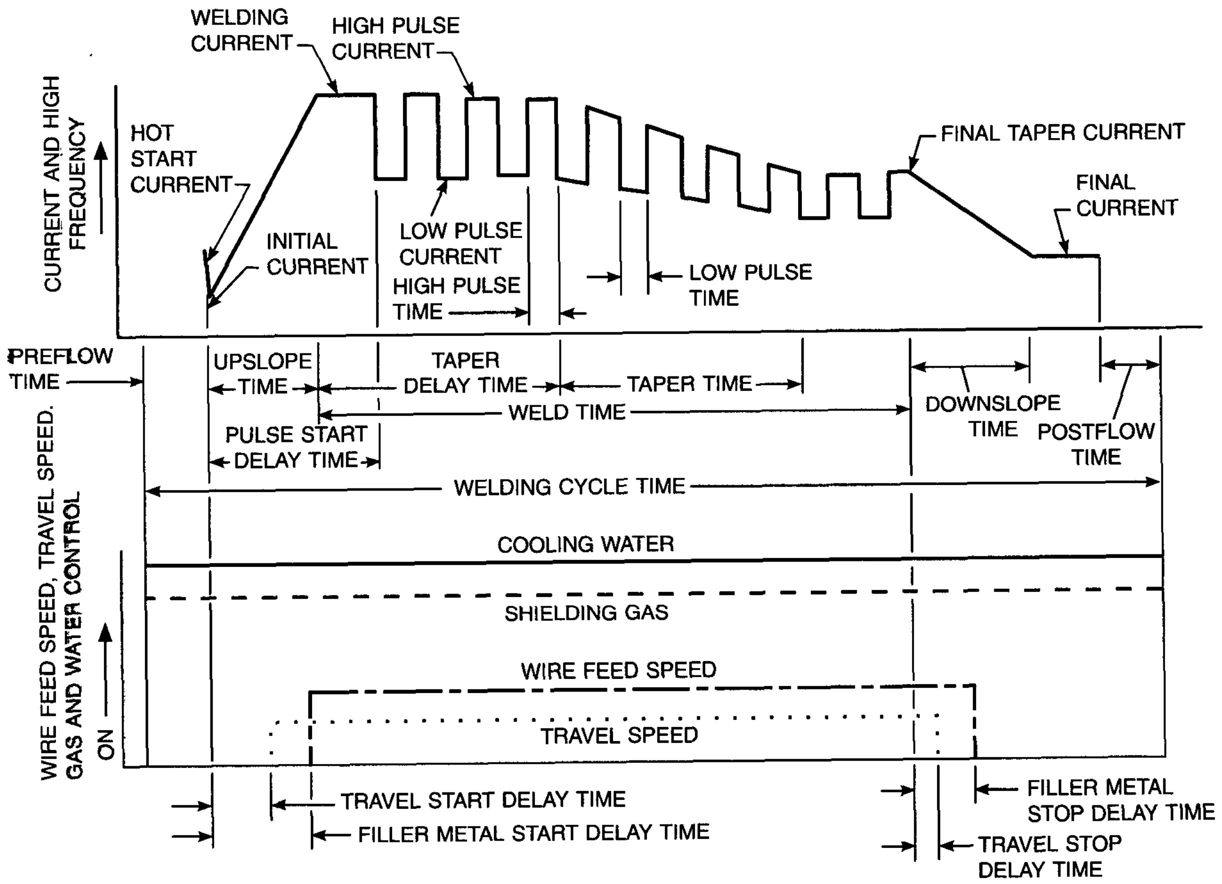


Figure 19-1—Typical GTAW or PAW Program for Automatic Welding

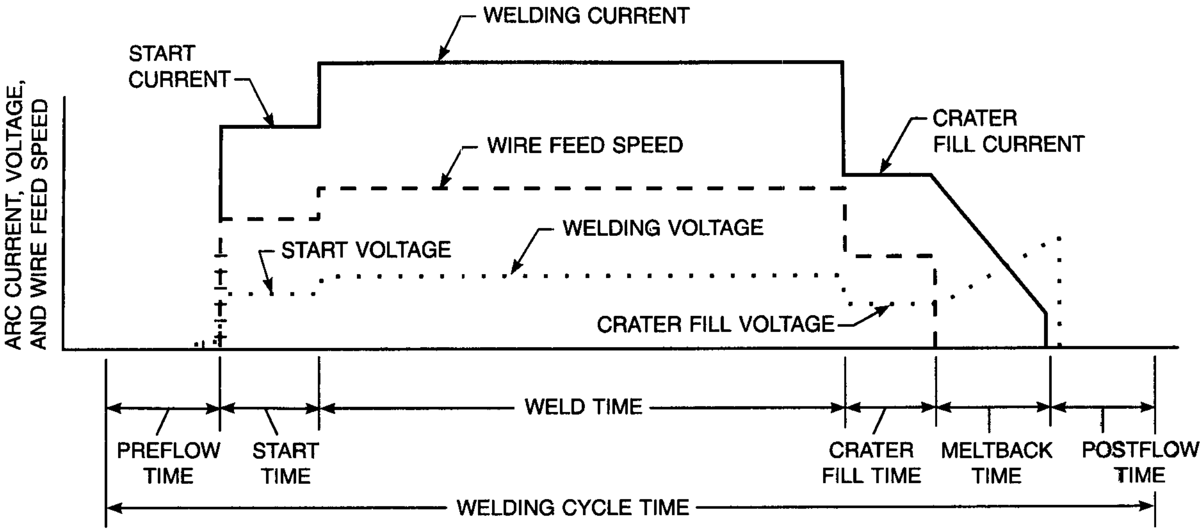


Figure 19-2—Typical GMAW, FCAW, and SAW Program for Automatic Welding

Buyer's Guide

The Buyer's Guide is a list of products, manufacturers, and suppliers representative of major categories of welding-related products. Companies listed were exhibitors at the 1996 AWS International Welding and Fabricating Exposition in Chicago, Illinois. The list is categorized by product type, followed by an alphabetical list of the names and addresses of manufacturers and suppliers, with telephone and fax numbers.

WELDING EQUIPMENT

AUTOMATIC VOLTAGE CONTROLS

AMET, Inc.
Dimetrics, Incorporated
Gas Tech, Inc.
Hobart Brothers Company
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
Liburdi Pulsweld Corporation
Miller Electric Manufacturing Company
Motoman, Inc.
Oxo Welding Equipment
Powcon Incorporated
Tri Tool Inc.
Weldline Automation

BRAZING

AGA Gas, Inc.
Aluminum Association, Inc., The
American Torch Tip Company
BTU Contracts, Inc.
Controls Corporation of America
Engelhard Corporation
Flame Technologies, Incorporated
Fusion Incorporated
Gas Tech, Inc.
Goss Incorporated
Harris Calorific Division, The Lincoln Electric Company
The Lincoln Electric Company
Harris Welco — Division of J.W. Harris
Lepel Corporation
Lucas-Milhaupt, Inc., A Handy & Harman Company
Metalworks, S.D. Hawkins
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Nattco Products-An NTT Company
OTC-Daihen, Inc.
Pillar/Cycle-Dyne
Robinson Technical Products Midwest
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Unitek Miyachi Corporation
Unitrol Electronics Incorporated
Uniweld Products, Inc.
Wall Colmonoy Corporation
Weldit, Inc.

CONTROLS

Computer Weld Technology, Incorporated
CYBO Robots
Dimetrics, Incorporated
Entron Controls, Incorporated
Esab Welding & Cutting Products
Gilbert Industrial
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
Liburdi Pulsweld Corporation
Livingston, Incorporated
Medar, Inc.
Modular Vision Systems
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Oxo Welding Equipment
Process Welding Systems, Inc.
Robotron
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Unitrol Electronics Incorporated
Weldcomputer Corporation
Weldline Automation

ELECTROGAS/ELECTROSLAG

Lincoln Electric Company, The
National Excellence In Materials Joining (NEMJ)
Navy Joining Center

ELECTRON BEAM

American Torch Tip Company
AMET, Inc.
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Sciaky, Incorporated
Special Welding Services, Inc.
Technical Materials Inc.

FRICTION WELDING

National Excellence In Materials Joining (NEMJ)
Ramstud [USA] Inc.
Special Welding Services, Inc.

GMAW AUTOMATIC

ABB Flexible Automation Incorporated
AGA Gas, Inc.
American & European Machinery, Incorporated
American Torch Tip Company
American Weldquip Inc.
AMET, Inc.
Binzel Corporation, Alexander
C.E.A. Welding Equipment
Cemont
CYBO Robots
D/F Machine Specialties Incorporated
Dimetrics, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
Genesis Systems Group
Hobart Brothers Company
IRC
Jetline Engineering Inc.
K & K Welding Products, Inc.
Kawasaki Robotics (USA) Incorporated
Lincoln Electric Company, The
Livingston, Incorporated
Magnatech Limited Partnership
Miller Automation Incorporated
Miller Electric Manufacturing Company
MK Products, Inc.
Modular Vision Systems
Motoman, Inc.
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Nu-Tecsys Corporation
Ocim Welding Products S.R.L.
Ogden Engineering Corporation
OTC-Daihen, Inc.
Oxo Welding Equipment
PAC*MIG, Inc.
Panasonic Factory Automation Co.
Pandjiris Incorporated
Profax
S.I.A.T. Spa Section Pittarc
Servo-Robot Inc.
Tecnar Automation Ltd.
Thermacut
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Trafimet USA, Inc.
Tregaskiss Ltd.
Tweco/Arcair
Weld-Motion Inc.
Weldline Automation
Winona Manufacturing

GMAW MANUAL

AGA Gas, Inc.
American & European Machinery, Incorporated
American Torch Tip Company
American Weldquip Inc.
Bernard Welding
Binzel Corporation, Alexander
C.E.A. Welding Equipment
Cebora S.P.A.
Cemont
Cho Heung Electric Ind. Co., Ltd.
D/F Machine Specialties Incorporated
Doyle's Supply Inc.
ESAB Welding & Cutting Products
Frimar Sas
Gas Tech, Inc.
Henning Hansen Incorporated
Hobart Brothers Company
K & K Welding Products, Inc.
Korea Welding Industry Cooperative
Lincoln Electric Company, The
Miller Electric Manufacturing Company
MK Products, Inc.
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Nu-Tecsys Corporation
Ocim Welding Products S.R.L.
OTC-Daihen, Inc.
Oxo Welding Equipment
PAC*MIG, Inc.
Panasonic Factory Automation Co.
Pandjiris Incorporated
Profax
S.I.A.T. Spa Section Pittarc
Systematics, Inc.
Thermacut
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Trafimet USA, Inc.

Tregaskiss Ltd.
Tweco/Arcair
Winona Manufacturing
Protective Metal Alloys, Incorporated

HARDFACING/SURFACING

AGA Gas, Inc.
BTU Contracts, Inc.
ESAB Welding & Cutting Products
Gas Tech, Inc.
Gullco International Incorporated
Harris Calorific Division, The Lincoln Electric Company
Hobart Brothers Company
Hobart Lasers & Advanced Systems
Lincoln Electric Company, The
Miller Thermal Incorporated
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Pandjiris Incorporated
Rexarc International, Inc.
Stoody Company
Thermadyne Industries
UTP Welding Materials
Victor Equipment Company
Wall Colmonoy Corporation
Weartech International, Inc.
Weldline Automation

INVERTER POWER SUPPLY/ARC WELD

American & European Machinery, Incorporated
Arc Machines, Incorporated
Arcmaster
Burco Welding & Cutting Products Incorporated
C.E.A. Welding Equipment
Cebora S.P.A.
Cemont
Cho Heung Electric Ind. Co., Ltd.
Dimetrics, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
Hill Technical Division — Serv-Tech, Inc.
Hobart Brothers Company
Hobart Lasers & Advanced Systems
Inweld Corporation
Korea Welding Industry Cooperative
Liburdi Pulsweld Corporation
Lincoln Electric Company, The
MK Products, Inc.
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Panasonic Factory Automation Co.
Powcon Incorporated
RED-D-ARC Incorporated
Russian American Technology Inventions L.C.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Trexim

LASER BEAM WELDING

American Torch Tip Company
AMET, Inc.
Convergent Energy
Directed Light, Inc.
Gas Tech, Inc.
Gullco International Incorporated
Hobart Lasers & Advanced Systems
IRC
Jetline Engineering Inc.
Laser Applications, Inc. (LAI)
Laser Machining, Incorporated
M.Braun, Inc.
Modular Vision Systems
Motoman, Inc.
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Sciaky, Incorporated
Servo-Robot Inc.
Special Welding Services, Inc.
Trumpf Incorporated
Unitek Miyachi Corporation

OXYACETYLENE WELDING

AGA Gas, Inc.
American Torch Tip Company
Controls Corporation of America
Flame Technologies, Incorporated
Gas Tech, Inc.
Genesis Systems Group
Goss Incorporated
Great Wei Lung Industry Co., Ltd.
Harris Calorific Division, The Lincoln Electric Company
High Purity Gas Co.
Lincoln Electric Company, The
National Excellence In Materials Joining (NEMJ)

National Torch Tip Co., Inc.
Nattco Products-An NTT Company
Oxygen Generating Systems, Inc. (OGSI)
RED-D-ARC Incorporated
Rexarc International, Inc.
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Uniweld Products, Inc.
Victor Equipment Company
Wall Colmonoy Corporation
Weldit, Inc.

PIPE WELDING

AGA Gas, Inc.
American Torch Tip Company
Arc Machines, Incorporated
Astro Arc Polysoude
Bug-O Systems, Inc.
Cypress Welding Equipment Inc.
Dimetrics, Incorporated
Gas Tech, Inc.
GE Welding & Machining
Harris Calorific Division, The Lincoln Electric Company
Hobart Lasers & Advanced Systems
IRC
Lincoln Electric Company, The
Magnatech Limited Partnership
Mathey/Leland International, Ltd.
Miller Electric Manufacturing Company
MK Products, Inc.
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Nu-Tecsys Corporation
Ogden Engineering Corporation
Pandjiris Incorporated
RED-D-ARC Incorporated
Servo-Robot Inc.
Tecnar Automation Ltd.
Tri Tool Inc.
Wachs Company, E.H.
Weld-Motion Inc.
Weldline Automation
Weldsale Company

PLASMA ARC WELDING

AGA Gas, Inc.
American Torch Tip Company
AMET, Inc.
Astro Arc Polysoude
Cho Heung Electric Ind. Co., Ltd.
CYBO Robots
Dimetrics, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
Genesis Systems Group
Great Wei Lung Industry Co., Ltd.
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
K & K Welding Products, Inc.
Korea Welding Industry Cooperative
Liburdi Pulsweld Corporation
Modular Vision Systems
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
North American Sales Distribution Center, Inc. (NASDC)
Pandjiris Incorporated
Powcon Incorporated
Process Welding Systems, Inc.
RED-D-ARC Incorporated
Sciaky, Incorporated
Thermacut
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Trafimet USA, Inc.

PLASTIC WELDING EQUIPMENT

AGA Gas, Inc.
Bug-O Systems, Inc.
National Excellence In Materials Joining (NEMJ)
Thermal Dynamics
UTP Welding Materials
Wegener North America, Inc.

POSITIONERS, MANIPULATORS

ABB Flexible Automation Incorporated
AGA Gas, Inc.
AMET, Inc.
Atlas Welding Accessories, Inc.
Bear Paw Magnetic Tools Incorporated
Bug-O Systems, Inc.
C & G Systems, Inc.
Cloos International Inc.
CYBO Robots
Dimetrics, Incorporated
Gas Tech, Inc.

Gilbert Industrial
Gullco International Incorporated
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
Kawasaki Robotics (USA) Incorporated
Miller Automation Incorporated
Miller Electric Manufacturing Company
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Panasonic Factory Automation Co.
Pandjiris Incorporated
Process Welding Systems, Inc.
Ransome Company
RED-D-ARC Incorporated
Servo-Robot Inc.
Tweco/Arcair
Weld-Motion Inc.
Weldcoa
Weldline Automation
Weldsale Company

POWER SUPPLIES GMAW

AGA Gas, Inc.
American & European Machinery, Incorporated
Burco Welding & Cutting Products Incorporated
C.E.A. Welding Equipment
Cebora S.P.A.
Cemont
Century Manufacturing
Cho Heung Electric Ind. Co., Ltd.
Cloos International Inc.
CNI-Ceramic Nozzles, Inc.
Computer Weld Technology, Incorporated
Cooptim Industrial Ltd.
Dimetrics, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
Henning Hansen Incorporated
Hobart Brothers Company
IRC
Korea Welding Industry Cooperative
Lincoln Electric Company, The
Miller Electric Manufacturing Company
MK Products, Inc.
Nattco Products-An NTT Company
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Panasonic Factory Automation Co.
Powcon Incorporated
RED-D-ARC Incorporated
Systematics, Inc.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
United Proarc Corporation
Vista Equipment Company, Inc.

POWER SUPPLIES GTAW

AGA Gas, Inc.
American & European Machinery, Incorporated
Arc Machines, Incorporated
Burco Welding & Cutting Products Incorporated
C.E.A. Welding Equipment
Cebora S.P.A.
Cemont
Cho Heung Electric Ind. Co., Ltd.
CNI-Ceramic Nozzles, Inc.
Dimetrics, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
GE Welding & Machining
Hobart Brothers Company
Hobart Lasers & Advanced Systems
Liburdi Pulsweld Corporation
Lincoln Electric Company, The
Magnatech Limited Partnership
Miller Electric Manufacturing Company
MK Products, Inc.
Nattco Products-An NTT Company
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Panasonic Factory Automation Co.
Powcon Incorporated
RED-D-ARC Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Tri Tool Inc.
Vista Equipment Company, Inc.
Welding Nozzle International

POWER SUPPLIES SMAW

AGA Gas, Inc.
American & European Machinery, Incorporated
Belco Products, Incorporated
Burco Welding & Cutting Products Incorporated
C.E.A. Welding Equipment
Cebora S.P.A.
Cemont

Century Manufacturing
ESAB Welding & Cutting Products
Gas Tech, Inc.
Hobart Brothers Company
Lincoln Electric Company, The
Miller Electric Manufacturing Company
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Powcon Incorporated
RED-D-ARC Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Vista Equipment Company, Inc.

POWER SUPPLIES SAW

AGA Gas, Inc.
American & European Machinery, Incorporated
C.E.A. Welding Equipment
ESAB Welding & Cutting Products
Gas Tech, Inc.
Hobart Brothers Company
Lincoln Electric Company, The
Miller Electric Manufacturing Company
Nu-Tecsys Corporation
Powcon Incorporated
RED-D-ARC Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Vista Equipment Company, Inc.

RESISTANCE WELDING & CONTROLS

AGA Gas, Inc.
American & European Machinery, Incorporated
Applied Robotics Inc.
Banner Welder Incorporated
Bosch — Industrial Electronics Division
C.E.A. Welding Equipment
Centerline (Windsor) Limited
Cho Heung Electric Ind. Co., Ltd.
Darrah Electric Company
Engineering Products & Services (E.P.S.)
Entron Controls, Incorporated
Flex-Cable
Gas Tech, Inc.
Gilbert Industrial
Henning Hansen Incorporated
Kirkhof/Goodrich Corporation
Korea Welding Industry Cooperative
Lenco
Livingston, Incorporated
Medar, Inc.
Miller Electric Manufacturing Company
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Nippert Company, The
Panasonic Factory Automation Co.
Resistance Welder Manufacturers' Association (RWMA)
Robotron
Sciaky, Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair
Unitek Miyachi Corporation
Unitrol Electronics Incorporated
Weld Technology Industries, L.L.C.
Weldcomputer Corporation
Weltronic/Technitron Corporation

ROBOTS ARC

ABB Flexible Automation Incorporated
AGA Gas, Inc.
American Torch Tip Company
Applied Robotics Inc.
Banner Welder Incorporated
Binzel Corporation, Alexander
CYBO Robots
ESAB Welding & Cutting Products
Fanuc Robotics North America, Inc.
Gas Tech, Inc.
Genesis Systems Group
Hobart Lasers & Advanced Systems
IRC
Kawasaki Robotics (USA) Incorporated
Liburdi Pulsweld Corporation
Lincoln Electric Company, The
Miller Automation Incorporated
Miller Electric Manufacturing Company
Motoman, Inc.
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Ogden Engineering Corporation
PAC*MIG, Inc.
Panasonic Factory Automation Co.
Servo-Robot Inc.
Tecnar Automation Ltd.

United Proarc Corporation

ROBOTS RESISTANCE

Applied Robotics Inc.
Banner Welder Incorporated
Bosch — Industrial Electronics Division
Centerline (Windsor) Limited
CYBO Robots
Electrode Dressers, Inc.
Engineering Products & Services (E.P.S.)
Genesis Systems Group
Kawasaki Robotics (USA) Incorporated
Livingston, Incorporated
Medar, Inc.
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Weltronic/Technitron Corporation

SOLDERING

AGA Gas, Inc.
Coral Spa
Flame Technologies, Incorporated
Fusion Incorporated
Gas Tech, Inc.
Goss Incorporated
Lepel Corporation
Lucas-Milhaupt, Inc., A Handy & Harman Company
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Nattco Products-An NTT Company
Pillar/Cycle-Dyne
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Uniweld Products, Inc.
UTP Welding Materials
Weldit, Inc.

SPOT WELDING & CONTROLS

AGA Gas, Inc.
American & European Machinery, Incorporated
Applied Robotics Inc.
Banner Welder Incorporated
Bosch — Industrial Electronics Division
C.E.A. Welding Equipment
Cemont
Centerline (Windsor) Limited
Cherokee Industries, Incorporated
Cho Heung Electric Ind. Co., Ltd.
Engineering Products & Services (E.P.S.)
Entron Controls, Incorporated
Genesis Systems Group
Gilbert Industrial
Henning Hansen Incorporated
Korea Welding Industry Cooperative
Livingston, Incorporated
Medar, Inc.
Miller Electric Manufacturing Company
National Excellence In Materials Joining (NEMJ)
Nippert Company, The
Robotron
Sciaky, Incorporated
Tec Torch — Weldtec
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Unitek Miyachi Corporation
Unitrol Electronics Incorporated
Weldcomputer Corporation
Weltronic/Technitron Corporation

STUD WELDING & CONTROLS

Applied Robotics Inc.
Bettermann of America, Incorporated
Burco Welding & Cutting Products Incorporated
Cemont
Centerline (Windsor) Limited
Cho Heung Electric Ind. Co., Ltd.
Gas Tech, Inc.
Gilbert Industrial
Korea Welding Industry Cooperative
Livingston, Incorporated
Miller Electric Manufacturing Company
National Excellence In Materials Joining (NEMJ)
Oxo Welding Equipment
Ramstud [USA] Inc.
RED-D-ARC Incorporated
Soyer Gmbh, Heinz
Stud Welding Associates
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Trw Nelson Stud Welding Div
Weldcomputer Corporation
Weldline Automation
Weltronic/Technitron Corporation

SUBMERGED ARC (AUTOMATIC)

AGA Gas, Inc.
American Torch Tip Company
American Weldquip Inc.
Bug-O Systems, Inc.

Cho Heung Electric Ind. Co., Ltd.
CYBO Robots
ESAB Welding & Cutting Products
Gas Tech, Inc.
Genesis Systems Group
Invincible Airflow Systems
IRC
Jetline Engineering Inc.
Lincoln Electric Company, The
Miller Electric Manufacturing Company
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
OTC-Daihen, Inc.
Pandjiris Incorporated
Ransome Company
RED-D-ARC Incorporated
S.I.A.T. Spa Section Pittarc
Servo-Robot Inc.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair
Weld Engineering Co., Inc.
Weld-Motion Inc.
Weldline Automation

SUBMERGED ARC (MANUAL)

AGA Gas, Inc.
American Torch Tip Company
American Weldquip Inc.
ESAB Welding & Cutting Products
Invincible Airflow Systems
Korea Welding Industry Cooperative
Lincoln Electric Company, The
Miller Electric Manufacturing Company
National Excellence In Materials Joining (NEMJ)
Oxo Welding Equipment
Profax
RED-D-ARC Incorporated
S.I.A.T. Spa Section Pittarc
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair

THERMAL SPRAYING

AGA Gas, Inc.
American Torch Tip Company
BTU Contracts, Inc.
Bug-O Systems, Inc.
ESAB Welding & Cutting Products
High Purity Gas Co.
Miller Thermal Incorporated
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Stellite Coatings
Sulzer Metco
Tafa Incorporated
Thermadyne Industries
Thermadyne International
Thyssen Welding
UTP Welding Materials
Wall Colmonoy Corporation

VERTICAL AUTOMATIC WELDING

AGA Gas, Inc.
Bug-O Systems, Inc.
GE Welding & Machining
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
Lincoln Electric Company, The
Magnatech Limited Partnership
National Excellence In Materials Joining (NEMJ)
PAC*MIG, Inc.
Pandjiris Incorporated
Powcon Incorporated
Ransome Company
Tweco/Arcair
United Proarc Corporation
Weld-Motion Inc.
Weldline Automation

WELD JOINT TRACKING SYSTEMS

ABB Flexible Automation Incorporated
AGA Gas, Inc.
Bug-O Systems, Inc.
Computer Weld Technology, Incorporated
Gullco International Incorporated
Hobart Lasers & Advanced Systems
IRC
Jetline Engineering Inc.
Kawasaki Robotics (USA) Incorporated
Lincoln Electric Company, The
Modular Vision Systems
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Ogden Engineering Corporation
Panasonic Factory Automation Co.
Powcon Incorporated
Servo-Robot Inc.

Tecnar Automation Ltd.
Weld-Motion Inc.
Weldline Automation

WELD SEAMERS

Hobart Lasers & Advanced Systems
IRC
Jetline Engineering Inc.
Modular Vision Systems
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Pandjiris Incorporated
Servo-Robot Inc.
United Proarc Corporation
Weld-Motion Inc.
Weldline Automation
Weltronic/Technitron Corporation

WELD SENSORS

ABB Flexible Automation Incorporated
CYBO Robots
Gilbert Industrial
Hobart Lasers & Advanced Systems
IRC
Jetline Engineering Inc.
Livingston, Incorporated
Modular Vision Systems
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Ogden Engineering Corporation
Servo-Robot Inc.
Tecnar Automation Ltd.
Unitrol Electronics Incorporated
Weldcomputer Corporation

WELDING OSCILLATION

Computer Weld Technology, Incorporated
Gullco International Incorporated
Hobart Lasers & Advanced Systems
Jetline Engineering Inc.
Lincoln Electric Company, The
Magnatech Limited Partnership
Miller Electric Manufacturing Company
Powcon Incorporated
Tri Tool Inc.
Weldline Automation

OTHER WELDING EQUIPMENT

Accra-Weld Controls, Incorporated
Alsimag Technical Ceramics, Inc.
American & European Machinery, Incorporated
American Saw & Manufacturing Company
AMET, Inc.
Bernard Welding
Bluco Corporation
Broco Incorporated
Burco/Mosa
C & G Systems, Inc.
C-K Worldwide Inc.
C.E.A. Welding Equipment
Cajon Company
CNI-Ceramic Nozzles, Inc.
Computer Weld Technology, Incorporated
D/F Machine Specialties Incorporated
Darrah Electric Company
Doyle's Supply Inc.
FHP Elmotor Ab
Gilbert Industrial
Hobart Lasers & Advanced Systems
Ibeda Incorporated
Inert Systems Inc.
Jackson Industries
K & K Welding Products, Inc.
Koolant Koolers, Inc.
Larco
Larco/Safety Controls Corporation
M.Braun, Inc.
Mechafin Ag
Medar, Inc.
Modular Vision Systems
Motoman, Inc.
National Torch Tip Co., Inc.
Nattco Products-An NTT Company
Nupro Company
Ocim Welding Products S.R.L.
Oxo Welding Equipment
Process Equipment Company
Seal Seat Company
Stellite Coatings
Swagelok Company
Tec Torch — Weldtec
Thyssen Welding
Tri Tool Inc.
United Proarc Corporation
UTP Welding Materials
Weldcoa
Weldcomputer Corporation
Weldcraft Products, Inc.
Welding Institute (TWI), The
Welding Nozzle International

ULTRASONIC WELDING
National Excellence In Materials Joining (NEMJ)

INDUSTRIAL GASES & RELATED EQUIPMENT

FUEL GASES
AGA Gas, Inc.
Air Liquide America Corporation
Air Products & Chemicals, Incorporated
Boc Gases (Formerly Airco Gases)
BTU Contracts, Inc.
Gas Tech, Inc.
High Purity Gas Co.
MG Industries Gas Products Division
Mittler Supply Inc.
Praxair, Inc.
Rockford Industrial Welding Supply, Inc.

SHIELDING PUMPS
AGA Gas, Inc.
Air Liquide America Corporation
Air Products & Chemicals, Incorporated
Boc Gases (Formerly Airco Gases)
BTU Contracts, Inc.
Gas Tech, Inc.
M.Braun, Inc.
MG Industries Gas Products Division
Mittler Supply Inc.
Praxair, Inc.
Rockford Industrial Welding Supply, Inc.

CRYOGENIC GASES
Cryogenic Industries
CTR of Charlotte Inc.
Fiba Technologies, Inc.
Mid America Cryogenics
Taylor-Wharton
Woodland Cryogenics, Inc.

CYLINDER COATINGS
Dynaflux, Inc.

GAS CYLINDERS
AGA Gas, Inc.
BTU Contracts, Inc.
Catalina Cylinders, Cliff Impact Division
Compressed Gas Association (CGA)
Contemporary Products, Inc. (CPI)
CTR of Charlotte Inc.
Fiba Technologies, Inc.
High Purity Gas Co.
Mittler Supply Inc.
Norris Cylinder Company
Queen Cylinder Company
SCM Technologies
Taylor-Wharton
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Weldship Corporation
Worthington Cylinders

GAS GENERATING EQUIPMENT
AGA Gas, Inc.
Air Liquide America Corporation
Air Products & Chemicals, Incorporated
Compressed Gas Association (CGA)
Gas Tech, Inc.
MG Industries Gas Products Division
Mittler Supply Inc.
Oxygen Generating Systems, Inc. (OGSI)
Praxair, Inc.
Rexarc International, Inc.
Rockford Industrial Welding Supply, Inc.

GAS REGULATORS/CONTROLS
AGA Gas, Inc.
Air Liquide America Corporation
BTU Contracts, Inc.
Ceodeux Incorporated
Contemporary Products, Inc. (CPI)
Controls Corporation of America
CTR of Charlotte Inc.
ESAB Welding & Cutting Products
Flame Technologies, Incorporated
Gas Tech, Inc.
Goss Incorporated
Ibeda Incorporated
Lincoln Electric Company, The
Mid America Cryogenics
National Standard
National Torch Tip Co., Inc.
Nattco Products-An NTT Company
Rego Products/Ecii
Rexarc International, Inc.
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Uniweld Products, Inc.
Victor Equipment Company

Weldit, Inc.
Western Enterprises

HANDLING EQUIPMENT

AGA Gas, Inc.
Bear Paw Magnetic Tools Incorporated
Ceodeux Incorporated
Contemporary Products, Inc. (CPI)
Fiba Technologies, Inc.
Galt Industries, Inc.
Gas Tech, Inc.
Gow-Mac Instrument Company
M.Braun, Inc.
Mathey/Leland International, Ltd.
MG Industries Gas Products Division
Mid America Cryogenics
Miller Thermal Incorporated
Saftcart
Taylor-Wharton
Thermadyne Industries
Thermadyne International
Unisource Manufacturing Inc.
Victor Equipment Company
Weldcoa

STORAGE & DISTRIBUTION EQUIPMENT

AGA Gas, Inc.
Contemporary Products, Inc. (CPI)
Controls Corporation of America
Cryogenic Industries
CTR of Charlotte Inc.
Fab-Tech Incorporated
Fiba Technologies, Inc.
H & H Sales Company, Incorporated
High Purity Gas Co.
MG Industries Gas Products Division
Mid America Cryogenics
Minnesota Valley Engineering
Quality Cryogenics Incorporated
Rexarc International, Inc.
Saftcart
Superior Products, Inc.
Taylor-Wharton
Tomco Equipment Company
Weldcoa
Weldship Corporation
Wire Crafters Incorporated
Wireway/Husky
Woodland Cryogenics, Inc.

OTHER GAS RELATED EQUIPMENT

Ametek — U.S. Gauge
Cajon Company
Centerflex
Ceodeux Incorporated
CTR of Charlotte Inc.
Fiba Technologies, Inc.
Gow-Mac Instrument Company
H & H Sales Company, Incorporated
Hannay Reels
Ibeda Incorporated
Jackson Industries
K-Tron, Inc.
Mid America Cryogenics
National Torch Tip Co., Inc.
Nattco Products-An NTT Company
Nupro Company
Rexarc International, Inc.
Swagelok Company
Taylor-Wharton
Thermco Instrument Corporation
Unisource Manufacturing Inc.
Weldcoa
Weldit, Inc.
Weldship Corporation
Whitey Company
Wika Instrument Corporation

WELDING ACCESSORIES & ALLIED PRODUCTS

ABRASIVE PRODUCTS

Abmast Abrasives Corporation
AGA Gas, Inc.
Anderson Products
Bates Abrasive Products, Inc.
Bosch Power Tools
Camel Grinding Wheel
Carborundum Abrasives
Chicago Pneumatic Tool Company
Crown/North American Professional Products
Dynabrade, Inc.
Express Wholesale/Worldwide Welding, Inc.
Flexovit USA, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hitachi Power Tools
Inweld Corporation
Jepson Power Tools
Kasco Abrasives
Klingspor Abrasives, Inc.

L S Industries
Los Angeles Diamond Tools, Inc.
M.K. Morse
Metabo Corporation
MG Industries Welding Products Division
Milwaukee Electric Tool Corp
Norton Company
Pangborn Corporation
Pearl Abrasive Company
Pferd, Inc.
Rex-Cut Products, Inc.
Robinson Technical Products Midwest
Skil Power Tools
Sparky Abrasives
Standard Abrasives
Suhner Industrial Products
T. C. Service Co.
United Abrasives, Incorporated
Walter, Incorporated, J.
Weiler Brush Company, Inc.

AIR CLEANERS/FUME COLLECTORS

Aercology, Inc.
AGA Gas, Inc.
Airflow Systems, Incorporated
Arcmaster
CFA
Coppus Portable Ventilation Division, Tuthill Corp.
Coral Spa
Dcm Clean-Air Products, Inc.
Diversi-Tech Inc.
Dualdraw By IMM
Fab-Tech Incorporated
Farr Company
Gardner Environmental Products
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Inweld Corporation
L S Industries
Lincoln Electric Company, The
Micro Air Air Clnrs By Metal-Fab Inc.
Nederman, Inc.
Nu-Tecsys Corporation
Optrel Ag
Pangborn Corporation
Plymovent Corporation
Roberts-Gordon, Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Torit-Donaldson Company
Tweco/Arcair
United Air Specialists, Inc.
Weldsale Company

ANTI SPATTER COMPOUNDS

AGA Gas, Inc.
Crown/North American Professional Products
Dynaflux, Inc.
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Genesis Systems Group
Harris Welco — Division of J.W. Harris
Inweld Corporation
James Morton, Incorporated
K & K Welding Products, Inc.
Lenco
National Torch Tip Co., Inc.
Nattco Products — An NTT Company
Nu-Tecsys Corporation
Robinson Technical Products Midwest
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair
Walter, Incorporated, J.
Weld-Aid Products
Weldsale Company
York Sales Company

BACKING MATERIALS

Alsimag Technical Ceramics, Inc.
Cerbaco Ltd.
Imperial Weld Ring Corporation

BOOTHS & BENCHES

Bluco Corporation
Coral Spa
Dualdraw By IMM
M.Braun, Inc.
Wilson Industries, Inc.

CHEMICAL PRODUCTS

Arcal Chemicals, Incorporated
Crown/North American Professional Products
Dynaflux, Inc.
ESAB Welding & Cutting Products
Harris Welco — Division of J.W. Harris
High Purity Gas Co.
Inweld Corporation
La-Co Industries, Inc./Markal Co.
Lenco

MG Industries Welding Products Division
Nissen Co., J. P.
Screenpro
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
Tweco/Arcair
Walter, Incorporated, J.
Winter Inc. & Co., F.W.

CLAMPS, CONNECTORS, LUGS, FITTINGS

Bluco Corporation
Crouse-Hinds Cam-Lok
De-Sta-Co A Dover Resources Company
Enerpac
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Gross Stabil Corporation
Harris Welco — Division of J.W. Harris
Inweld Corporation
Jackson Industries
James Morton, Incorporated
K & K Welding Products, Inc.
Lenco
Oetiker, Incorporated
Pandjiris Incorporated
RED-D-ARC Incorporated
Robinson Technical Products Midwest
Superior Products, Inc.
Symington & Co., Inc., C.H.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair
Walhonde Tools Inc.
Welding Nozzle International
Weldsale Company
Western Enterprises
Wilton Corporation

ELECTRODE HOLDERS

AGA Gas, Inc.
Alsimag Technical Ceramics, Inc.
Binzel Corporation, Alexander
Cemont
Centerline (Windsor) Limited
Cmw Incorporated
Doyle's Supply Inc.
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Harris Welco — Division of J.W. Harris
Inweld Corporation
K & K Welding Products, Inc.
Lenco
Lincoln Electric Company, The
MG Industries Welding Products Division
Nu-Tecsys Corporation
Profax
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair
Washington Alloy Company

FACE PROTECTORS/HELMETS

AGA Gas, Inc.
Arcmaster
Cherokee Industries, Incorporated
Doyle's Supply Inc.
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Fibre-Metal Products Co.
Harris Welco — Division of J.W. Harris
Inweld Corporation
Kopo International (Fiprom; Globtrade USA)
Korea Welding Industry Cooperative
Kromer Cap Co., Inc.
Lincoln Electric Company, The
Mack Products Company/Ohio Goggles Division
MG Industries Welding Products Division
MSA
Nederman, Inc.
OptreL AG
Robinson Technical Products Midwest
Sellstrom Manufacturing Company
Symington & Co., Inc., C.H.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Weiler Brush Company, Inc.
Weldrite Welding Products, Inc.

FLUX RECOVERY EQUIPMENT

American Vacuum Company
ESAB Welding & Cutting Products
Invincible Airflow Systems
Miller Electric Manufacturing Company
Pandjiris Incorporated
Weld Engineering Co., Inc.

HANDLING EQUIPMENT

Accra-Weld Controls, Incorporated
Bear Paw Magnetic Tools Incorporated
Miller Electric Manufacturing Company
Pandjiris Incorporated
Sumner Manufacturing Company Incorporated
Tri-State Industries, Incorporated

HEATING TORCHES

AGA Gas, Inc.
American Torch Tip Company
Belchfire Corporation
BTU Contracts, Inc.
Ceodeux Incorporated
Controls Corporation of America
ESAB Welding & Cutting Products
Flame Technologies, Incorporated
Gas Tech, Inc.
Goss Incorporated
High Purity Gas Co.
Inweld Corporation
National Torch Tip Co., Inc.
Rexarc International, Inc.
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Uniweld Products, Inc.
Victor Equipment Company
Weldit, Inc.

MARKERS

Carmel Industries
Express Wholesale/Worldwide Welding, Inc.
Harris Welco — Division of J.W. Harris
La-Co Industries, Inc./Markal Co.
Mark-Tex Corporation
Nissen Co., J. P.
Ransome Company
Robinson Technical Products Midwest
Tempil, Air Liquide America Corp.

OVENS

Express Wholesale/Worldwide Welding, Inc.
Gullco International Incorporated
Inweld Corporation
M.Braun, Inc.
Mannings USA
Phoenix Products Company, Inc.
RED-D-ARC Incorporated
Robinson Technical Products Midwest
Weld Engineering Co., Inc.

PLATENS

Bluco Corporation
Weldsale Company

PROTECTIVE CLOTHING

AGA Gas, Inc.
American Kanox Corporation
Auburn Manufacturing Incorporated
Cherokee Industries, Incorporated
Doyle's Supply Inc.
Elliott Corporation
ESAB Welding & Cutting Products
Gerson Co., Inc., Louis M.
Guard-Line, Inc.
Inweld Corporation
Kinco International, Incorporated
Kromer Cap Co., Inc.
MSA
N.L.F. Protective Products
Nattco Products — An NTT Company
Revco Industries (Black Stallion)
Robinson Technical Products Midwest
Stanco Manufacturing, Inc.
Steiner Industries
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tillman & Company, John
Triple Crown Products
Weldas Company
Whitestone Corporation
Wilson Industries, Inc.

PROTECTIVE GLOVES

AGA Gas, Inc.
American Kanox Corporation
Atlas Welding Accessories, Inc.
Doyle's Supply Inc.
Elliott Corporation
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Guard-Line, Inc.
Harris Welco — Division of J.W. Harris
Inweld Corporation
Johnson Wilshire, Inc.
Kinco International, Incorporated
MG Industries Welding Products Division
MSA
N.L.F. Protective Products
Revco Industries (Black Stallion)
Robinson Technical Products Midwest

Stanco Manufacturing, Inc.
Steiner Industries
Tillman & Company, John
Washington Alloy Company
Weldas Company
Wilson Industries, Inc.

PURGING EQUIPMENT

Cms Gilbreth Packaging Systems
Expansion Seal Technologies (Formerly Expando Seal Tools)
Magnatech Limited Partnership
North American Sales Distribution Center, Inc. (NASDC)

SCREENS, SHIELDS & CURTAINS

AGA Gas, Inc.
American Kanox Corporation
Auburn Manufacturing Incorporated
Frommelt Safety Products
Hitco Technologies Incorporated
Inweld Corporation
King Bag & Manufacturing Co.
Korea Welding Industry Cooperative
N.L.F. Protective Products
Revco Industries (Black Stallion)
Robinson Technical Products Midwest
Rockwell Laser Industries
Scientific Technologies, Inc./STI
Sellstrom Manufacturing Company
Stanco Manufacturing, Inc.
Steiner Industries
Tillman & Company, John
Weldsale Company
Wilson Industries, Inc.
Wire Crafters Incorporated
Wireway/Husky

TEMPERATURE MEASURING INSTRUMENTS

James Morton, Incorporated
La-Co Industries, Inc./Markal Co.
Mannings USA
Ransome Company
Robinson Technical Products Midwest
Tempil, Air Liquide America Corp.
UTP Welding Materials

TOOLS (MANUAL)

AGA Gas, Inc.
Atlas Welding Accessories, Inc.
Atrax
Bear Paw Magnetic Tools Incorporated
Contour Sales Div of Jackson Products
Electrode Dressers, Inc.
Enerpac
Expansion Seal Technologies (Formerly Expando Seal Tools)
Harris Welco — Division of J.W. Harris
James Morton, Incorporated
Jancy Engineering Co. "Home of The Slugger"
M.K. Morse
Robinson Technical Products Midwest
Suhner Industrial Products
Sumner Manufacturing Company Incorporated
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Walhonde Tools Inc.
TOOLS (POWER)
AGA Gas, Inc.
Atrax
Black And Decker
Bosch Power Tools
Chicago Pneumatic Tool Company
Dynabrade, Inc.
Electrode Dressers, Inc.
Express Wholesale/Worldwide Welding, Inc.
Fein Power Tools Inc.
Hitachi Power Tools
Indresco Inc., Industrial Tool Division
Jancy Engineering Co. "Home of The Slugger"
Jepson Power Tools
M.K. Morse
Makita USA Inc.
Metabo Corporation
Milwaukee Electric Tool Corp
Nitto Kohki U.S.A., Inc.
Skil Power Tools
Suhner Industrial Products
T. C. Service Co.
Tri Tool Inc.
Trumpf Incorporated
Walhonde Tools Inc.

WATER COOLING EQUIPMENT

Alpha Environmental Refrigeration Company
Bernard Welding
Binzel Corporation, Alexander
Cemont
Dynaflux, Inc.
Frimar Sas
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris

K & K Welding Products, Inc.
Koolant Koolers, Inc.
Lepel Corporation
Lincoln Electric Company, The
Nu-Tecsys Corporation
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Unitrol Electronics Incorporated
Weldcraft Products, Inc.

WELDING CABLE

Direct Wire & Cable, Inc.
Electron Beam Technologies, Inc.
Engineering Products & Services (E.P.S.)
Essex Group, Incorporated
Express Wholesale/Worldwide Welding, Inc.
Frimar Sas
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Inweld Corporation
K & K Welding Products, Inc.
Lincoln Electric Company, The
Mannings USA
Nu-Tecsys Corporation
Otto Tool Co. Div. of Alsana
RED-D-ARC Incorporated
Robinson Technical Products Midwest
Unitek Miyachi Corporation
Washington Alloy Company
Welding Nozzle International

WELDING HELMETS

AGA Gas, Inc.
Arcmaster
Cemont
Cherokee Industries, Incorporated
Doyle's Supply Inc.
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Fibre-Metal Products Co.
Harris Welco — Division of J.W. Harris
Hornell Speedglas, Inc.
Inweld Corporation
Jackson Products, Inc.
Jackson Products, Inc.
Kedman Company
Kopo International (Fiprom; Globtrade USA)
Korea Welding Industry Cooperative
Kromer Cap Co., Inc.
Lincoln Electric Company, The
MG Industries Welding Products Division
MSA
Nattco Products — An NTT Company
Nederman, Inc.
Nu-Tecsys Corporation
Optrel AG
Racal Health & Safety, Inc.
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Sellstrom Manufacturing Company
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Washington Alloy Company

WIRE BRUSHES

Advance Milwaukee Brush
AGA Gas, Inc.
Anderson Products
Doyle's Supply Inc.
Express Wholesale/Worldwide Welding, Inc.
Harris Welco — Division of J.W. Harris
High Purity Gas Co.
Inweld Corporation
Jaz-Zubiaurre S.A.
MG Industries Welding Products Division
Pferd, Inc.
Robinson Technical Products Midwest
Walter, Incorporated, J.
Weiler Brush Company, Inc.
Weldcraft Products, Inc.

OTHER ALLIED PRODUCTS

American Torch Tip Company
American Weldquip Inc.
Ametek Inc. — Haveg Division
Arcmaster
Belaire Products Inc.
Bernard Welding
Bluco Corporation
C-K Worldwide Inc.
C.E.M.E./Major
Ceodeux Incorporated
Champion Cutting Tool Corp.
CNI — Ceramic Nozzles, Inc.
Contour Sales Div of Jackson Products
Cooptim Industrial Ltd.
Directed Light, Inc.
Frimar Sas
Gerson Co., Inc., Louis M.
Hannay Reels

Hornell Speedglas, Inc.
Jackson Industries
James Morton, Incorporated
Larco
Larco/Safety Controls Corporation
M.K. Morse
Naltex
Nippert Company, The
Optrel AG
Pferd, Inc.
Racal Health & Safety, Inc.
Roberts-Gordon, Incorporated
Rockwell Laser Industries
Scientific Technologies, Inc./Sti
SCM Metal Products, Inc.
Screenpro
Servo-Robot Inc.
Solar Flux (Golden Empire Corp)
Superior Flux & Manufacturing Company
Systematics, Inc.
Tec Torch — Weldtec
Thermadyne Industries
Triple Crown Products
Universal Flow Monitors, Incorporated
Uniweld Products, Inc.
Uvex Safety, Incorporated
Water-Jel Technologies
Weldmatic Inc.
Weldreel Incorporated
Wilton Corporation
Wireway/Husky

CUTTING EQUIPMENT

CARBON ARC GOUGING

AGA Gas, Inc.
Bug-O Systems, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Inweld Corporation
Miller Electric Manufacturing Company
Powcon Incorporated
Profax
RED-D-ARC Incorporated
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair

CUTTING TABLES

Advanced Kiffer Systems, Incorporated
American Torch Tip Company
Anderson Incorporated
ESAB Welding & Cutting Products
Galt Industries, Inc.
Gas Tech, Inc.
Weldsale Company

CUTTING TIPS & FIXTURES

AGA Gas, Inc.
Air Liquide America Corporation
American Torch Tip Company
Ceodeux Incorporated
Controls Corporation of America
Enerpac
Flame Technologies, Incorporated
Gas Tech, Inc.
Goss Incorporated
Great Wei Lung Industry Co., Ltd.
High Purity Gas Co.
Koike Aronson Incorporated
Magic Tip/Total Products International
National Torch Tip Co., Inc.
Robinson Technical Products Midwest
Smith Equipment Manufacturing Company LLC
Symington & Co., Inc., C.H.
Thermacut
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Uniweld Products, Inc.

CUTTING ROBOTS

ABB Flexible Automation Incorporated
AGA Gas, Inc.
American Torch Tip Company
Bug-O Systems, Inc.
CYBO Robots
Gas Tech, Inc.
Genesis Systems Group
IRC
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Servo-Robot Inc.
United Proarc Corporation

EXOTHERMIC CUTTING EQUIPMENT

Broco Incorporated
ESAB Cutting Systems
ESAB Welding & Cutting Products

Symington & Co., Inc., C.H.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Tweco/Arcair

HEATING TORCHES

AGA Gas, Inc.
American Torch Tip Company
Belchfire Corporation
BTU Contracts, Inc.
Controls Corporation of America
Flame Technologies, Incorporated
Gas Tech, Inc.
Goss Incorporated
Harris Calorific Division, The Lincoln Electric Company
High Purity Gas Co.
National Torch Tip Co., Inc.
Rexarc International, Inc.
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Uniweld Products, Inc.
Victor Equipment Company
Weldit, Inc.

LASER BEAM CUTTING

ABB Flexible Automation Incorporated
AGA Gas, Inc.
American Torch Tip Company
Burny Group/Cleveland Machine Controls Inc.
CYBO Robots
Directed Light, Inc.
ESAB Cutting Systems
ESAB Welding & Cutting Products
Gas Tech, Inc.
Hobart Lasers & Advanced Systems
Koike Aronson Incorporated
Laser Applications, Inc. (LAI)
Laser Machining, Incorporated
M.T.C. Ltd.
Modular Vision Systems
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
Sigmatek Corporation
Trumpf Incorporated

OXYFUEL GAS (MANUAL)

AGA Gas, Inc.
American Torch Tip Company
BTU Contracts, Inc.
Burny Group/Cleveland Machine Controls Inc.
Controls Corporation of America
ESAB Cutting Systems
ESAB Welding & Cutting Products
Flame Technologies, Incorporated
Gas Tech, Inc.
Goss Incorporated
Gullco International Incorporated
Harris Calorific Division, The Lincoln Electric Company
High Purity Gas Co.
Koike Aronson Incorporated
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
RED-D-ARC Incorporated
Rexarc International, Inc.
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Victor Equipment Company
Weldit, Inc.

OXYFUEL GAS (AUTOMATIC)

AGA Gas, Inc.
American Torch Tip Company
Anderson Incorporated
BTU Contracts, Inc.
Bug-O Systems, Inc.
Burny Group/Cleveland Machine Controls Inc.
Controls Corporation of America
ESAB Cutting Systems
ESAB Welding & Cutting Products
Flame Technologies, Incorporated
Gas Tech, Inc.
Gullco International Incorporated
Koike Aronson Incorporated
M.T.C. Ltd.
MG Industries Systems Division
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Pandjiris Incorporated
RED-D-ARC Incorporated
Sigmatek Corporation
Smith Equipment Manufacturing Company LLC
Thermadyne Industries
Thermadyne International

Thermadyne Welding Products Canada, Ltd.
United Proarc Corporation
Victor Equipment Company
Weldit, Inc.

PIPE CUTTING & BEVELING

AGA Gas, Inc.
American Torch Tip Company
Bug-O Systems, Inc.
Burny Group/Cleveland Machine Controls Inc.
Cypress Welding Equipment Inc.
D. L. Ricci Corporation
Doringer Manufacturing Company
Esco Tool A Unit of Esco Technologies, Inc.
G.B.C. Industrial Tools
George Fischer Pipe Tools
H & M Pipe Beveling Machine Company, Inc.
Harris Calorific Division, The Lincoln Electric Company
Hobart Lasers & Advanced Systems
Koike Aronson Incorporated
Machine Tech, Incorporated
Mactech — Stresstech
Mathey/Leland International, Ltd.
Milwaukee Electric Tool Corp
National Excellence In Materials Joining (NEMJ)
Nu-Tecsys Corporation
Pandjiris Incorporated
Protem Engineering Corporation
T. C. Service Co.
Tri Tool Inc.
Trumpf Incorporated
Vernon Tool Company
Vogel Tool & Die Corporation
Wachs Company, E.H.
World Machinery & Saws System Company

PLASMA ARC CUTTING

ABB Flexible Automation Incorporated
Advanced Kiffer Systems, Incorporated
AGA Gas, Inc.
American & European Machinery, Incorporated
American Torch Tip Company
Anderson Incorporated
Bernard Welding
Bug-O Systems, Inc.
Burco Welding & Cutting Products Incorporated
Burny Group/Cleveland Machine Controls Inc.
C.E.A. Welding Equipment
Cebora S.P.A.
Century Manufacturing
CYBO Robots
Doyle's Supply Inc.
ESAB Cutting Systems
ESAB Welding & Cutting Products
Express Wholesale/Worldwide Welding, Inc.
Gas Tech, Inc.
Genesis Systems Group
Great Wei Lung Industry Co., Ltd.
Henning Hansen Incorporated
Hypertherm Incorporated
Koike Aronson Incorporated
Lincoln Electric Company, The
M.T.C. Ltd.
MG Industries Systems Division
Miller Electric Manufacturing Company
Motoman, Inc.
National Excellence In Materials Joining (NEMJ)
National Torch Tip Co., Inc.
Nattco Products — An NTT Company
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Peddinghaus Corporation
Powcon Incorporated
Profax
RED-D-ARC Incorporated
Sigmatek Corporation
Smith Equipment Manufacturing Company LLC
Thermacut
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thermal Dynamics
Trafimet USA, Inc.
Weldcraft Products, Inc.

POWER SUPPLIES

AGA Gas, Inc.
American & European Machinery, Incorporated
C.E.A. Welding Equipment
ESAB Welding & Cutting Products
Gas Tech, Inc.
Henning Hansen Incorporated
Lincoln Electric Company, The
Mactech — Stresstech
Medar, Inc.
Miller Electric Manufacturing Company
Nu-Tecsys Corporation
OTC-Daihen, Inc.
Powcon Incorporated
RED-D-ARC Incorporated
Thermadyne Industries

Thermadyne International
Thermadyne Welding Products Canada, Ltd.

SAWS (MECHANICAL)

Doringer Manufacturing Company
George Fischer Pipe Tools
Great Wei Lung Industry Co., Ltd.
Hem Saw
Hyd-Mech Saws Limited
Jepson Power Tools
Milwaukee Electric Tool Corp
Otto Tool Co. Div. of Alsana
Production Machinery, Inc.
Scotchman Industries, Incorporated
T. C. Service Co.
Wachs Company, E.H.
Wilton Corporation
World Machinery & Saws System Company

SAWS (ABRASIVE)

Bosch Power Tools
Chicago Pneumatic Tool Company
Doringer Manufacturing Company
Esco Tool A Unit of Esco Technologies, Inc.
Everett Industries Incorporated
Femi S.R.L.
Hitachi Power Tools
Jepson Power Tools
Los Angeles Diamond Tools, Inc.
Milwaukee Electric Tool Corp
Skil Power Tools
T. C. Service Co.
Tri Tool Inc.

WATER TABLES

Anderson Incorporated
ESAB Cutting Systems
Galt Industries, Inc.
M.T.C. Ltd.
MG Industries Systems Division
Weldsale Company

OTHER CUTTING EQUIPMENT

Cardinal Eg Saws Corporation
Champion Cutting Tool Corp.
Doringer Manufacturing Company
Mactech — Stresstech
Mathey/Leland International, Ltd.
National Torch Tip Co., Inc.
Nattco Products — An NTT Company
Seal Seat Company
Sigmatek Corporation
Tri Tool Inc.
United Proarc Corporation
Vogel Tool & Die Corporation
Wachs Company, E.H.
Welding Institute (TWI), The
Weldsale Company
Wikus Inc.
WATER JET CUTTING
Burny Group/Cleveland Machine Controls Inc.
ESAB Cutting Systems
Laser Applications, Inc. (LAI)
M.T.C. Ltd.
Sigmatek Corporation

JOINING MATERIALS

BRAZING ALLOYS (BASE METAL)

AGA Gas, Inc.
Alcotec Wire Company
American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Engelhard Corporation
ESAB Welding & Cutting Products
Fusion Incorporated
Gas Tech, Inc.
Gasflux Company, The
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Inweld Corporation
Lucas-Milhaupt, Inc., A Handy & Harman Company
National Torch Tip Co., Inc.
Prince & Izant Company
Protective Metal Alloys, Incorporated
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Weldrite Welding Products, Inc.

BRAZING ALLOYS (FOIL)

AGA Gas, Inc.
Champion Welding Products, Incorporated
Engelhard Corporation
ESAB Welding & Cutting Products
Handy & Harman of Canada Limited
Hi-Alloy Weld Specialists
Lucas-Milhaupt, Inc., A Handy & Harman Company
MG Industries Welding Products Division

National Torch Tip Co., Inc.
Prince & Izant Company
Robinson Technical Products Midwest

BRAZING ALLOYS (POWDER)

AGA Gas, Inc.
American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Engelhard Corporation
ESAB Welding & Cutting Products
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Kytex Solutions, Inc.
Lucas-Milhaupt, Inc., A Handy & Harman Company
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Praxair Specialty Powders
Prince & Izant Company
Protective Metal Alloys, Incorporated
SCM Metal Products, Inc.
Sherritt Incorporated
Sulzer Metco
Thyssen Welding
UTP Welding Materials
Wall Colmonoy Corporation
Winter Inc. & Co., F.W.

BRAZING ALLOYS (PRECIOUS METAL)

AGA Gas, Inc.
Astrolite Alloys
Champion Welding Products, Incorporated
Engelhard Corporation
ESAB Welding & Cutting Products
Fusion Incorporated
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Lucas-Milhaupt, Inc., A Handy & Harman Company
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Prince & Izant Company
Robinson Technical Products Midwest
Selectrode Industries, Inc.
UTP Welding Materials
Washington Alloy Company
Welding Rod Factory, The

CONSUMABLE WELDING INSERTS

AGA Gas, Inc.
Arcos Alloys
Champion Welding Products, Incorporated
ESAB Welding & Cutting Products
Harris Welco — Division of J.W. Harris
Imperial Weld Ring Corporation
National Torch Tip Co., Inc.
Russian American Technology Inventions L.C.
Trafimet USA, Inc.
UTP Welding Materials
Welding Rod Factory, The

HARDFACING/SURFACING (POWER ALLOYS)

AGA Gas, Inc.
American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
ESAB Welding & Cutting Products
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Indura S.A.
Inweld Corporation
James Morton, Incorporated
MG Industries Welding Products Division
Mitsubishi Materials U S A Corporation
National Torch Tip Co., Inc.
National Welding Alloys
Osram Sylvania Inc.
Postle Industries
Praxair Specialty Powders
Protective Metal Alloys, Incorporated
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Stellite Coatings
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weartech International, Inc.
Welding Rod Factory, The
Winter Inc. & Co., F.W.

HARDFACING/SURFACING (STRIP CLADDING)

AGA Gas, Inc.
Champion Welding Products, Incorporated
Midwest Alloys & Technology, Inc.

National Torch Tip Co., Inc.
Oerlikon Offshore
Ransome Company
Sandvik Steel Company
Stoody Company
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
UTP Welding Materials

HARDFACING/SURFACING (WIRE)

AGA Gas, Inc.
American Welding Alloys
Ampco Metal
Arcos Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
COR-MET, Inc.
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
GE Welding & Machining
Harris Welco — Division of J.W. Harris
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Polymet Corporation
Postle Industries
Protective Metal Alloys, Incorporated
Rexarc International, Inc.
Robinson Technical Products Midwest
Rolled Alloys
Selectrode Industries, Inc.
Stoody Company
Techalloy Company, Inc. — Baltimore Welding Division
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
United States Welding Corporation
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weartech International, Inc.
Weld Mold Company
Welding Rod Factory, The

SOLDERING ALLOYS

American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Engelhard Corporation
ESAB Welding & Cutting Products
Fusion Incorporated
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Inweld Corporation
Lucas-Milhaupt, Inc., A Handy & Harman Company
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Prince & Izant Company
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Welding Rod Factory, The

WELDING WIRE (ALUMINUM)

Alcotec Wire Company
Aluminum Association, Inc., The
American Filler Metals Inc.
American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Gulf Wire Corporation
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The

MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
OTC-Daihen, Inc.
Polymet Corporation
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Thermadyne Industries
Thermadyne International
United States Welding Corporation
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

WELDING WIRE (COPPER ALLOYS)

American Filler Metals Inc.
American Welding Alloys
Ampco Metal
Arcos Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
ESAB Welding & Cutting Products
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
MG Industries Welding Products Division
National Standard
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Thermadyne International
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.
Wisconsin Wire Works Inc.

WELDING WIRE (NICKEL/HIGH NICKEL ALLOYS)

American Filler Metals Inc.
American Welding Alloys
Arcos Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
COR-MET, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hyundai Welding & Metal Company, Ltd.
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Midwest Alloys & Technology, Inc.
National Standard
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Protective Metal Alloys, Incorporated
Robinson Technical Products Midwest
Rolled Alloys
Sandvik Steel Company
Techalloy Company, Inc. — Baltimore Welding Division
Thermadyne Industries
Thermadyne International
Thyssen Welding
United States Welding Corporation
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

WELDING WIRE (MILD STEEL)

American Filler Metals Inc.
American Welding Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
Conarco Alambres Y Soldaduras S.A.
Eagle Wire Company, Inc.
ESAB Welding & Cutting Products
Faiter Elettrodi S.P.A.

Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hyundai Welding & Metal Company, Ltd.
Indura S.A.
Inweld Corporation
Kobelco Welding of America Inc.
Kopo International (Fiprom; Globtrade USA)
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
MidSTATES Wire
National Standard
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
OTC-Daihen, Inc.
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

WELDING WIRE (STAINLESS STEEL)

American Filler Metals Inc.
American Welding Alloys
Arcos Alloys
Astrolite Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
COR-MET, Inc.
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Gulf Wire Corporation
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
High Purity Gas Co.
Hyundai Welding & Metal Company, Ltd.
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Kopo International (Fiprom; Globtrade USA)
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Midwest Alloys & Technology, Inc.
National Standard
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
OTC-Daihen, Inc.
Robinson Technical Products Midwest
Rolled Alloys
Sandvik Steel Company
Symington & Co., Inc., C.H.
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Trader S.P.A.
United States Welding Corporation
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

OTHER JOINING MATERIALS

Alcotec Wire Company
Astrolite Alloys
Bettermann of America, Incorporated
Inweld Corporation
Navy Joining Center
Sulzer Metco
Trader S.P.A.
United States Welding Corporation
UTP Welding Materials
Welding Institute (TWI), The

THERMAL SPRAY WIRES

Arcos Alloys
Champion Welding Products, Incorporated
MidSTATES Wire
Miller Thermal Incorporated
National Torch Tip Co., Inc.
Sulzer Metco
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Wall Colmonoy Corporation

ELECTRODES/FILLER METALS

ALUMINUM

Alcotec Wire Company
Aluminum Association, Inc., The
American Welding Alloys
Burny Group/Cleveland Machine Controls Inc.
Cemont
Champion Welding Products, Incorporated
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weldrite Welding Products, Inc.

CAST IRON

American Welding Alloys
Ampco Metal
Champion Welding Products, Incorporated
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hobart Brothers Company
Indura S.A.
Inweld Corporation
Kopo International (Fiprom; Globtrade USA)
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Midwest Alloys & Technology, Inc.
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weld Mold Company
Weldrite Welding Products, Inc.

COPPER/COPPER ALLOYS

American Welding Alloys
Ampco Metal
Arcos Alloys
Centerline (Windsor) Limited
Champion Welding Products, Incorporated
Cmw Incorporated
Femi S.R.L.
Filler Metals, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Nippert Company, The
Oerlikon Offshore
Robinson Technical Products Midwest
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weld Mold Company
Weldrite Welding Products, Inc.

FLUX CORED WIRE (STEEL)

American Welding Alloys
Cemont
Champion Welding Products, Incorporated
Chosun Steel Wire Company
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
Eagle Wire Company, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.

Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hobart Brothers Company
Hyundai Welding & Metal Company, Ltd.
Inweld Corporation
Kobelco Welding of America Inc.
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Thyssen Welding
Washington Alloy Company
Weld Mold Company
Weldrite Welding Products, Inc.

FLUX CORED WIRE (LOW ALLOY STEEL)

American Welding Alloys
Cemont
Champion Welding Products, Incorporated
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hobart Brothers Company
Hyundai Welding & Metal Company, Ltd.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Symington & Co., Inc., C.H.
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weldrite Welding Products, Inc.

FLUX CORED WIRE-STAINLESS STEEL

American Filler Metals Inc.
American Welding Alloys
Cemont
Champion Welding Products, Incorporated
Chosun Steel Wire Company
COR-MET, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hobart Brothers Company
Hyundai Welding & Metal Company, Ltd.
Inweld Corporation
Kobelco Welding of America Inc.
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Midwest Alloys & Technology, Inc.
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Sandvik Steel Company
Symington & Co., Inc., C.H.
Thyssen Welding
UTP Welding Materials
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

FLUX CORED WIRE (NICKEL AND HIGH NICKEL ALLOYS)

American Filler Metals Inc.
American Welding Alloys
Champion Welding Products, Incorporated
COR-MET, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.
Hi-Alloy Weld Specialists
Ibeda Incorporated
Inco Alloys International, Inc.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Welding Alloys
Protective Metal Alloys, Incorporated
Symington & Co., Inc., C.H.
Thyssen Welding
UTP Welding Materials
Washington Alloy Company
Weartech International, Inc.

Weld Mold Company
Weldrite Welding Products, Inc.

HARDFACING/SURFACING

American Filler Metals Inc.
American Welding Alloys
Ampco Metal
Arcos Alloys
Champion Welding Products, Incorporated
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Hi-Alloy Weld Specialists
Hobart Brothers Company
Indura S.A.
Inweld Corporation
Kopo International (Fiprom; Globtrade USA)
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Mitsubishi Materials U S A Corporation
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Protective Metal Alloys, Incorporated
Rexarc International, Inc.
Robinson Technical Products Midwest
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Stoody Company
Thermadyne Industries
Thyssen Welding
Trader S.P.A.
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weartech International, Inc.
Weld Mold Company
Welding Rod Factory, The

NICKEL

American Filler Metals Inc.
American Welding Alloys
Arcos Alloys
Champion Welding Products, Incorporated
COR-MET, Inc.
Femi S.R.L.
Filler Metals, Inc.
Hi-Alloy Weld Specialists
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
Midwest Alloys & Technology, Inc.
National Torch Tip Co., Inc.
National Welding Alloys
Protective Metal Alloys, Incorporated
Robinson Technical Products Midwest
Rolled Alloys
Sandvik Steel Company
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Sherritt Incorporated
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Washington Alloy Company
Weartech International, Inc.
Weld Mold Company
Welding Rod Factory, The

STAINLESS STEEL

American Filler Metals Inc.
American Welding Alloys
Arcos Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Hobart Brothers Company
Hyundai Welding & Metal Company, Ltd.
Inco Alloys International, Inc.
Indura S.A.
Inweld Corporation
Kopo International (Fiprom; Globtrade USA)
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division

Midwest Alloys & Technology, Inc.
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Rolled Alloys
Sandvik Steel Company
SCM Metal Products, Inc.
Selectrode Industries, Inc.
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Weld Mold Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

STEEL

American Filler Metals Inc.
American Welding Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
ESAB Welding & Cutting Products
Femi S.R.L.
Filler Metals, Inc.
Gas Tech, Inc.
Hi-Alloy Weld Specialists
Hobart Brothers Company
Indura S.A.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Robinson Technical Products Midwest
Techalloy Company, Inc. — Baltimore Welding Division
Thyssen Welding
Trader S.P.A.
Uniweld Products, Inc.
UTP Welding Materials
Washington Alloy Company
Welding Rod Factory, The
Weldrite Welding Products, Inc.

GTAW

American Welding Alloys
American Weldquip Inc.
Arcos Alloys
C-K Worldwide Inc.
Cemont
Champion Welding Products, Incorporated
CNI — Ceramic Nozzles, Inc.
Conarco Alambres Y Soldaduras S.A.
COR-MET, Inc.
ESAB Welding & Cutting Products
Filler Metals, Inc.
Gas Tech, Inc.
Hi-Alloy Weld Specialists
Inco Alloys International, Inc.
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products
MG Industries Welding Products Division
National Torch Tip Co., Inc.
National Welding Alloys
Navy Joining Center
Nu-Tecsys Corporation
Oerlikon Offshore
Osram Sylvania Inc.
OTC-Daihen, Inc.
Robinson Technical Products Midwest
Sandvik Steel Company
Techalloy Company, Inc. — Baltimore Welding Division
Teledyne Advanced Materials
Thyssen Welding
UTP Welding Materials
Washington Alloy Company
Weld-Motion Inc.
Welding Nozzle International
Welding Rod Factory, The
Weldrite Welding Products, Inc.

METAL CORED WIRES

American Welding Alloys
Champion Welding Products, Incorporated
Chosun Steel Wire Company
COR-MET, Inc.
ESAB Welding & Cutting Products
Gas Tech, Inc.
Hi-Alloy Weld Specialists
Hobart Brothers Company
Inweld Corporation
Lincoln Electric Company, The
McKay Welding Products

Oerlikon Offshore
Robinson Technical Products Midwest
Thyssen Welding
Weld Mold Company

UNDERWATER

American Welding Alloys
Anderson Incorporated
Broco Incorporated
Champion Welding Products, Incorporated
Hi-Alloy Weld Specialists
National Torch Tip Co., Inc.
National Welding Alloys
Oerlikon Offshore
Sandvik Steel Company
Thermadyne Industries
Thermadyne International
Thermadyne Welding Products Canada, Ltd.
Thyssen Welding
Tweco/Arcair

OTHER ELECTRODES FILLER METALS

Bettermann of America, Incorporated
Navy Joining Center
North American Sales Distribution Center, Inc. (NASDC)
Weartech International, Inc.
Welding Institute (TWI), The

TESTING EQUIPMENT

DESTRUCTIVE TEST EQUIPMENT

Enerpac
Unitek Miyachi Corporation

NONDESTRUCTIVE TEST EQUIPMENT

Centurion Ndt, Inc.
Crown/North American Professional Products
Dynaflux, Inc.
Enerpac
IRC
Krautkramer Branson
Leco Corporation
Livingston, Incorporated
Magnaflux
Metorex Incorporated
Modular Vision Systems
Navy Joining Center
Ogden Engineering Corporation
Olympus America Incorporated
Panametrics, Inc.
Pandjiris Incorporated
Servo-Robot Inc.
Sherwin, Incorporated
Spectro Analytical Instruments, Inc.
Spectronics Corporation
Staveley Instruments, Inc.
Unitek Miyachi Corporation
Welch Allyn, Inc — Imaging Products Division
Welding Consultants, Inc.

NDT SERVICES

Fiba Technologies, Inc.
GE Welding & Machining
Krautkramer Branson
Magnaflux
Metorex Incorporated
Mqs Inspection Inc.
National Excellence In Materials Joining (NEMJ)
Panametrics, Inc.
Weldship Corporation

OTHER TESTING EQUIPMENT

AMET, Inc.
Equotip Associates
Expansion Seal Technologies (Formerly Expando Seal Tools)
Fiba Technologies, Inc.
Herron Testing Laboratories, Inc.
Leco Corporation
Liburdi Pulsweld Corporation
Modular Vision Systems
Olympus America Incorporated
Welch Allyn, Inc — Imaging Products Division
Welding Consultants, Inc.
Welding Institute (TWI), The
Weldship Corporation

RELATED PRODUCTS AND SERVICES

CAD/CAM

Advanced Kiffer Systems, Incorporated
Anderson Incorporated
Burny Group/Cleveland Machine Controls Inc.
Generative N/C Technology, Inc.
Koike Aronson Incorporated
M.T.C. Ltd.
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Shop Data Systems, Inc.
Sigmatek Corporation

COMPUTER SOFTWARE

ABB Flexible Automation Incorporated
American Welding Institute (Awi)
Anderson Incorporated
Aw Johnson & Associates
Burny Group/Cleveland Machine Controls Inc.
C-Spec
Canadian Welding Bureau
Computer Engineering, Incorporated
Computers Unlimited
Dataweld Inc.
Directed Light, Inc.
EWI
Generative N/C Technology, Inc.
Hobart Lasers & Advanced Systems
IRC
Koike Aronson Incorporated
M.T.C. Ltd.
MG Industries Systems Division
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Rockwell Laser Industries
Servo-Robot Inc.
Shop Data Systems, Inc.
Sigmatek Corporation

CONSULTING

Akron Area Partners For Progress
American Weldquip Inc.
AMET, Inc.
Anderson Incorporated
Aw Johnson & Associates
C-Spec
CYBO Robots
Directed Light, Inc.
Entergy Corporation
Ewi
Factory Mutual
Generative N/C Technology, Inc.
Gilbert Industrial
Herron Testing Laboratories, Inc.
Hobart Lasers & Advanced Systems
IRC
Lincoln Electric Company, The
M.T.C. Ltd.
Mid America Cryogenics
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Ogden Engineering Corporation
Pandjiris Incorporated
Rockwell Laser Industries
Servo-Robot Inc.
Spanish Association of Welding And Joining Technologies
Walhonde Tools Inc.
Weldcomputer Corporation
Welding Consultants, Inc.

ENGINES, GAS & DIESEL

American Honda Motor Co., Inc.
Detroit Diesel Corporation
Deutz Corporation
Kohler Co., Engine Division
Onan Corporation
Wis-Con Total Power Corporation

FURNACES

Mannings USA
National Excellence In Materials Joining (NEMJ)
Technical Materials Inc.

HEAT TREATING/STRESS RELIEVING

Ametek Inc. — Haveg Division
Bonal Technologies, Inc.
Global Heat Incorporated
Herron Testing Laboratories, Inc.
Hill Technical Division — Serv-Tech, Inc.
Laser Applications, Inc. (LAI)
Laser Machining, Incorporated
Lepel Corporation
Mannings USA
Pillar/Cycle-Dyne
Sqwincher, The Activity Drink
Technical Materials Inc.
Wall Colmonoy Corporation

LADDERS & SCAFFOLDING

Pandjiris Incorporated
Wing Enterprises Incorporated

METAL WORKING EQUIPMENT

Accra-Weld Controls, Incorporated
Bluco Corporation
Bonal Technologies, Inc.
Centerline (Windsor) Limited
Cml USA Inc (Ercolina)
Dynabrade, Inc.
Eagle Bending Machines, Inc.
Enerpac
Hellers Son Inc., E.G.

Jepson Power Tools
Metal Muncher/Fab Center Sales
Milwaukee Electric Tool Corp
Mubea Machinery And Systems, Inc.
National Excellence In Materials Joining (NEMJ)
Pangborn Corporation
Peddinghaus Corporation
Pillar/Cycle-Dyne
Project Tool & Die, Inc.
Technical Materials Inc.
Walhonde Tools Inc.
Wilton Corporation

NUMERICALLY CONTROLLED EQUIPMENT

Anderson Incorporated
Burny Group/Cleveland Machine Controls Inc.
C & G Systems, Inc.
Eagle Bending Machines, Inc.
ESAB Welding & Cutting Products
Hellers Son Inc., E.G.
IRC
MG Industries Systems Division
Mubea Machinery And Systems, Inc.
National Excellence In Materials Joining (NEMJ)
Ogden Engineering Corporation
Peddinghaus Corporation
Servo-Robot Inc.

PIPE END PREPARATION

Advance Milwaukee Brush
Eagle Bending Machines, Inc.
Esco Tool A Unit of Esco Technologies, Inc.
G.B.C. Industrial Tools
George Fischer Pipe Tools
H & S Tool
Jancy Engineering Co. "Home of The Slugger"
Mactech — Stresstech
Mathey/Leland International, Ltd.
Mid America Cryogenics
Otto Tool Co. Div. of Alsana
Project Tool & Die, Inc.
Tri Tool Inc.
Trumpf Incorporated
Vogel Tool & Die Corporation
Wachs Company, E.H.
Wilton Corporation
World Machinery & Saws System Company

RESEARCH & DEVELOPEMENT

American Welding Institute (Awi)
American Welding Society, The
AMET, Inc.
CYBO Robots
Directed Light, Inc.
Ewi
Herron Testing Laboratories, Inc.
IRC
N. A. Technologies Co.
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Ogden Engineering Corporation
Paton Welding Institute
Rockwell Laser Industries
Russian American Technology Inventions L.C.
Servo-Robot Inc.
Technical Materials Inc.
Tri Tool Inc.
Welding Consultants, Inc.
Welding Institute (TWI), The

TECHNICAL TRAINING

American Welding Society, The
CYBO Robots
Divers Academy of The Eastern Seaboard Inc.
EWI
Gow-Mac Instrument Company
Herron Testing Laboratories, Inc.
Hobart Institute of Welding Technology
Ilisagvik College
Letourneau University
Lincoln Electric Company, The
Mannings USA
Mid America Cryogenics
Miller Electric Manufacturing Company
Miller Thermal Incorporated
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Pennsylvania College of Technology
Rockwell Laser Industries
Texas State Technical College Welding Department
Welding Consultants, Inc.
Welding Institute (TWI), The

TUBE BENDING EQUIPMENT

Cml USA Inc (Ercolina)
Eagle Bending Machines, Inc.
George Fischer Pipe Tools
Hellers Son Inc., E.G.
Vogel Tool & Die Corporation
World Machinery & Saws System Company

WELDING PUBLICATIONS

American Welding Society, The
ASM International
EWI
Fabricators & Manufacturer's Association
Forming & Fabricating/SME
Hobart Institute of Welding Technology
Industrial Market Place
Industrial Product Bulletin
Lincoln Electric Company, The
Metal Forming Magazine
National Excellence In Materials Joining (NEMJ)
Navy Joining Center
Resistance Welder Manufacturers' Association (RWMA)
Welding Design & Fabrication

OTHER PRODUCTS AND SERVICES

69 Design Inc.
Abs Quality Evaluations
Advanta Business Services
Air Quality Engineering Inc.
Akron Area Partners For Progress
Aluminum Association, Inc., The
American Welder, The
American Welding Society, The
AMET, Inc.
Arthur Ross Cady — Arc Enterprises
Artists Kafka Metal-Sculpture
Assembly Magazine
Austrian Trade Commission
AWS Foundation
AWS Travel Club
Belleville Area College — Welding Technology Division
Burnfree/Nortrade International, Inc.
Cajon Company
Carvalho, Adriana
Cary — Cary Founds
Casilio, Martin A.
Celestial Ironworks
Chemclean Corp
Clemco Industries Corporation
CNA Insurance Companies
CNI — Ceramic Nozzles, Inc.
Contemporary Products, Inc. (Cpi)
Dataweld Inc.
Divers Academy of The Eastern Seaboard Inc.
Doblinger, Don
Dunn, Michael T.
Eagle Bending Machines, Inc.
Eastern Etching & Manufacturing
Entergy Corporation
Fisher Container Corporation
Galvanizing Company, Rogers
Gases And Welding Distributor
Generative N/C Technology, Inc.
Gte Scientific Society of Mechanical Engineers (Hungary)
H & S Tool
Havens Sculptures, James
Heath Jewelry, Michelle & Andy
Herron Testing Laboratories, Inc.
Hobart Institute of Welding Technology
Industrial Maintenance & Plant Operation
Inweld Corporation
Italian Trade Commission
Kiel, Adele
King Bag & Manufacturing Co.
Larco
Larco/Safety Controls Corporation
Letourneau University
Lyall's Labors Ltd.
Mannings USA
Maros Welding (Metal Working Artist), Keith
Mmm Metalworking Machinery Mailer
Modern Application News
Moore Industrial Hardware
Mqs Inspection Inc.
Naltex
Navy Joining Center
Nupro Company
Ohio State University/Welding Engineering, The
Otto Tool Co. Div. of Alsana
P.B.J. Enterprises
Permadur Industries, Inc.
Products Unlimited
Project Tool & Die, Inc.
Richard Prazen
Schweissen & Schneiden 97/Essen Welding Fair 97
Scientific Technologies, Inc./Sti
Sculpture By Niemi
Sigmatek Corporation
Stel Di A.M. Mazzucco
Store Fixtures Unlimited
Swagelok Company
Systematics, Inc.
Vocational Industrial Clubs of America, Inc.
Wachs Company, E.H.
Watteredge-Uniflex, Inc.
Weld Systems International Incorporated
Welding Consultants, Inc.

Whitey Company
Willing Arts, Todd
Zero Products, A Division of Clemco Industries Corp.

PROTECTIVE COATINGS

Dynaflux, Inc.
Engelhard Surface Technologies
Miller Thermal Incorporated
Naltex
Spatz/Pratt & Lambert United Inc.
Thyssen Welding
UTP Welding Materials
Wall Colmonoy Corporation
Walter, Incorporated, J.
Watson Coatings Incorporated

METAL WORKING EQUIPMENT

ROLL FORMING EQUIPMENT

Accra-Weld Controls, Incorporated
Cml USA Inc (Ercolina)
Comeq, Incorporated
Eagle Bending Machines, Inc.
Hellers Son Inc., E.G.

SHEET METALWORKING EQUIPMENT

Eagle Bending Machines, Inc.
Hellers Son Inc., E.G.
Unipunch Products, Inc.

STAMPING & PUNCHING EQUIPMENT

Accra-Weld Controls, Incorporated
Centerline (Windsor) Limited
Cleveland Steel Tool Company, The
Edwards Manufacturing Co.
Enerpac
Metal Muncher/Fab Center Sales
Mubea Machinery And Systems, Inc.
Peddinghaus Corporation
Piranha-Mega Manufacturing Incorporated
Trumpf Incorporated
Unipunch Products, Inc.
Vogel Tool & Die Corporation

BENDING & SHEARING EQUIPMENT

Centerline (Windsor) Limited
Cml USA Inc (Ercolina)
Comeq, Incorporated
Eagle Bending Machines, Inc.
Edwards Manufacturing Co.
Hellers Son Inc., E.G.
Metal Muncher/Fab Center Sales
Piranha-Mega Manufacturing Incorporated
Production Machinery, Inc.
Trumpf Incorporated
Uni-Hydro, Incorporated

OTHER METALWORKING EQUIPMENT

Abrasive Engineering & Manufacturing (Aem)
Chicago Pneumatic Tool Company
Convergent Energy
Dynabrade, Inc.
Eagle Bending Machines, Inc.
Eagle Industries
Edwards Manufacturing Co.
Enerpac
Fein Power Tools Inc.
Gullco International Incorporated
Henning Hansen Incorporated
James Morton, Incorporated
Jancy Engineering Co. "Home of The Slugger"
Ken Kosiorek Metal Sculpture
L S Industries
Milwaukee Area Technical College
Mubea Machinery And Systems, Inc.
Pangborn Corporation
Piranha-Mega Manufacturing Incorporated
Project Tool & Die, Inc.
Scotchman Industries, Incorporated
Technical Materials Inc.
Uni-Hydro, Incorporated
United Proarc Corporation
Vogel Tool & Die Corporation
Walhonde Tools Inc.
Weld Systems International Incorporated

FLUXES/POWDERS

FLUX (GAS WELDING/BRAZING)

Astrolite Alloys
Controls Corporation of America
Engelhard Corporation
ESAB Welding & Cutting Products
Fusion Incorporated
Gas Tech, Inc.
Gasflux Company, The
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Ibeda Incorporated
Inweld Corporation
La-Co Industries, Inc./Markal Co.

Lucas-Milhaupt, Inc., A Handy & Harman Company
Metalworks, S.D. Hawkins
MG Industries Welding Products Division
National Welding Alloys
Navy Joining Center
Prince & Izant Company
Robinson Technical Products Midwest
Selectrode Industries, Inc.
Superior Flux & Manufacturing Company
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Wall Colmonoy Corporation
Welding Rod Factory, The

FLUX (SOLDERING)

Astrolite Alloys
Engelhard Corporation
ESAB Welding & Cutting Products
Fusion Incorporated
Gas Tech, Inc.
Handy & Harman of Canada Limited
Harris Welco — Division of J.W. Harris
Hi-Alloy Weld Specialists
Inweld Corporation
La-Co Industries, Inc./Markal Co.
Lucas-Milhaupt, Inc., A Handy & Harman Company
National Welding Alloys
Prince & Izant Company
Selectrode Industries, Inc.
Superior Flux & Manufacturing Company
Thyssen Welding
Uniweld Products, Inc.
UTP Welding Materials
Welding Rod Factory, The

FLUX (SUBMERGED ARC)

ESAB Welding & Cutting Products
Filler Metals, Inc.
Gas Tech, Inc.
Hyundai Welding & Metal Company, Ltd.
Inco Alloys International, Inc.
Lincoln Electric Company, The
McKay Welding Products
Midwest Alloys & Technology, Inc.
Oerlikon Offshore
Sandvik Steel Company
Thyssen Welding

Suppliers

3M OCCUPATIONAL HEALTH & ENVIRONMENTAL SAFETY DIVISION
3M Center Building, 275-6W-01
Saint Paul, MN 55144-1000
(612) 733-5608
FAX: (612) 735-2555

69 DESIGN INC.
2030 NW 7th Avenue
Miami, FL 33127

ABB FLEXIBLE AUTOMATION INCORPORATED
4600 Innovation Drive
Fort Collins, CO 80525
(970) 225-7600
FAX: (970) 225-7700

ABMAST ABRASIVES CORPORATION
13 Industrial Boulevard
Plattsburgh, NY 12901
(800) 361-2297
FAX: (800) 300-2420

ABRASIVE ENGINEERING & MANUFACTURING (AEM)
540 East Old Highway 56
Olathe, KS 66061
(800) 875-6040
FAX: (913) 764-0429

ABS QUALITY EVALUATIONS
16855 Northchase Drive
Houston, TX 77060
(713) 874-6360
FAX: (713) 874-5974

ACCRA-WELD CONTROLS, INCORPORATED
10891 Northland Drive
Rockford, MI 49341
(616) 866-3434
FAX: (616) 866-9468

ADVANCE MILWAUKEE BRUSH
W142 N9251 Fountain Blvd.
P.O. Box 830
Menomonee Falls, WI 53052
(414) 255-3200
FAX: (414) 255-1412

ADVANCED KIFFER SYSTEMS, INCORPORATED
15666 Snow Road
Cleveland, OH 44142-2351
(216) 267-8181
FAX: (216) 267-8182

ADVANTA BUSINESS SERVICES
1020 Laurel Oak Road
Voorhees, NJ 08043
(800) 469-0825
FAX: (800) 446-7129

AERCOLOGY, INC.
8 Custom Drive
Old Saybrook, CT 06475
(203) 399-7941
FAX: (203) 399-7049

AGA GAS, INC.
6225 Oak Tree Blvd.
Cleveland, OH 44131
(216) 573-7800
FAX: (216) 573-7870

AIR LIQUIDE AMERICA CORPORATION
2121 North California Blvd., #350
Walnut Creek, CA 94596
(510) 977-6218
FAX: (510) 746-6306

AIR PRODUCTS & CHEMICALS, INCORPORATED
12200 East Iliff Avenue, Ste. 200
Aurora, CO 80014
(303) 755-5230
FAX: (303) 755-3723

AIR QUALITY ENGINEERING INC.
3340 Winpark Drive
Minneapolis, MN 55427
(612) 544-4426
FAX: (612) 544-4013

AIRFLOW SYSTEMS, INCORPORATED
11370 Pagemill Road
Dallas, TX 75243-8306
(214) 272-3003
FAX: (214) 503-9596

AKRON AREA PARTNERS FOR PROGRESS
One Cascade Plaza, Ste. 800
Akron, OH 44308
(216) 376-5550
FAX: (216) 379-3164

ALCOTEC WIRE COMPANY
2750 Aero Park Drive
Traverse City, MI 49686
(616) 941-4111
FAX: (616) 941-9154

ALPHA ENVIRONMENTAL REFRIGERATION COMPANY
2619 Bond Street
Rochester Hills, MI 48309
(810) 852-4711
FAX: (810) 852-0155

ALSIMAG TECHNICAL CERAMICS, INC.
One Technology Place, Hwy. 14
Laurens, SC 29360
(803) 682-1150
FAX: (803) 682-1140

ALUMINUM ASSOCIATION, INC., THE
900 19th Street North West
Washington, DC 20006
(202) 862-5124
FAX: (202) 862-5164

AMERICAN & EUROPEAN MACHINERY, INCORPORATED
Post Office Box 2518
Whitehouse, OH 43571
(419) 877-1000
FAX: (419) 877-1001

AMERICAN FILLER METALS INC.
6060 Donoho
Houston, TX 77033
(713) 649-8785
FAX: (713) 644-9628

AMERICAN HONDA MOTOR CO., INC.
4475 River Green Parkway
Duluth, GA 30136
(770) 497-6063
FAX: (770) 497-6011

AMERICAN KANOX CORPORATION
3728 Rockwell Avenue
El Monte, CA 91731
(818) 443-8489
FAX: (818) 443-8597

AMERICAN SAW & MANUFACTURING COMPANY
301 Chestnut Street
East Longmeadow, MA 01028
(413) 525-3961
FAX: (413) 525-8867

AMERICAN TORCH TIP COMPANY
6212 29th Street East
Bradenton, FL 34203
(800) 342-8477
FAX: (941) 753-6917

AMERICAN VACUUM COMPANY
7301 North Monticello Avenue
Skokie, IL 60076
(800) 321-2849
FAX: (847) 674-0214

AMERICAN WELDER, THE
550 N. W. LeJeune Road
Miami, FL 33126
(305) 443-9353
FAX: (305) 443-7559

AMERICAN WELDING ALLOYS
380 West Martin Luther King Jr. Blvd.
Unit 3
Los Angeles, CA 90037
(213) 233-9733
FAX: (213) 233-9749

AMERICAN WELDING INSTITUTE (AWI)
10628 Dutchtown Road
Knoxville, TN 37932
(423) 675-2150
FAX: (423) 675-6081

AMERICAN WELDING SOCIETY, THE
550 N. W. LeJeune Road
Miami, FL 33126
(305) 443-9353
FAX: (305) 443-7559

AMERICAN WELDQUIP INC.
620 East Smith Road
Medina, OH 44256
(216) 723-5333
FAX: (800) 949-9353

AMET, INC.
4191 West Highway 33
Rexburg, ID 83440
(208) 356-7274
FAX: (208) 356-8612

AMETEK — U.S. GAUGE
900 Clymer Avenue
Sellersville, PA 18960
(215) 257-6531
FAX: (215) 257-3058

AMETEK INC. — HAVEG DIVISION
900 Greenbank Road
Wilmington, DE 19808
(800) 441-7777
FAX: (302) 995-0491

AMPCO METAL
Post Office Box 2004
Milwaukee, WI 53201
(414) 645-3750
FAX: (414) 645-3225

AMPROCORP U.S.A INCORPORATED
4111 South West 47th Avenue
Suite 321
Fort Lauderdale, FL 33314
(954) 581-7935
FAX: (954) 581-7515

ANDERSON INCORPORATED
307 Foxcroft, Suite 10
Pittsburgh, PA 15220
(412) 429-8760
FAX: (412) 429-8754

ANDERSON PRODUCTS
1040 Southbridge Street
Worcester, MA 01610
(508) 755-6100
FAX: (508) 755-4694

APPLIED ROBOTICS INC.
648 Saratoga Road
Glenville, NY 12302
(518) 384-1000
FAX: (518) 384-1200

ARC MACHINES, INCORPORATED
10280 Glenoaks Blvd
Pacoima, CA 91331
(818) 896-9556
FAX: (818) 890-3724

ARCAL CHEMICALS, INCORPORATED
223 Westhampton Avenue
Capital Heights, MD 20743
(301) 336-9300
FAX: (301) 336-6597

ARCMASTER
25 Walpole Park South
Walpole, MA 02081
(508) 668-5149
FAX: (508) 668-4640

ARCOS ALLOYS
One Arcos Drive
Mount Carmel, PA 17851
(717) 339-5200
FAX: (717) 339-5206

ARTHUR ROSS CADY — ARC ENTERPRISES
36248 Camp Creek Road
Springfield, OR 97478
(541) 741-6215
FAX: (541) 741-6215

ARTISTS KAFKA METAL-SCULPTURE
2802 Lexington Drive
Hazelcrest, IL 60429
(708) 335-0445

ASM INTERNATIONAL
Materials Park, OH 44073
(216) 338-5151
FAX: (216) 338-4634

ASSEMBLY MAGAZINE
191 South Gary Avenue
Carol Stream, IL 60188
(708) 665-1000
FAX: (708) 462-2225

ASTRO ARC POLYSOUDE
10941 La Tuna Cannon Road
Sun Valley, CA 91352
(818) 768-5660
FAX: (818) 767-3180

ASTROLITE ALLOYS
1201 Vanguard Drive
Oxnard, CA 93033
(805) 487-7131
FAX: (805) 487-9694

ATLANTIC MACHINE TOOLS INCORPORATED
11629 North Houston Rosslyn Road
Houston, TX 77086
(713) 445-3985
FAX: (713) 445-3989

ATLAS WELDING ACCESSORIES, INC.
501 Stephenson Highway, P.O. Box 969
Troy, MI 48099
(810) 588-4666
FAX: (810) 588-2706

ATRAX
2150 West Lawrence Avenue
Chicago, IL 60625
(800) 633-5994
FAX: (800) 329-7301

AUBURN MANUFACTURING INCORPORATED
Post Office Box 220
Mechanic Falls, ME 04256
(207) 345-8271
FAX: (207) 345-3380

AUSTRIAN TRADE COMMISSION
500 North Michigan Avenue
Chicago, IL 60611
(312) 644-5556
FAX: (312) 644-6526

AW JOHNSON & ASSOCIATES
149 Avenida Cota
San Clemente, CA 92672
(714) 498-7000
FAX: (714) 498-3889

AWS FOUNDATION
550 N. W. LeJeune Road
Miami, FL 33126
(305) 443-9353
FAX: (305) 443-7559

AWS TRAVEL CLUB
550 N. W. LeJeune Road
Miami, FL 33126
(305) 443-9353
FAX: (305) 443-7559

BANNER WELDER INCORPORATED
N117 W18200 Fulton Drive
West Bend, WI 53022
(414) 253-2900
FAX: (414) 253-2919

BATES ABRASIVE PRODUCTS, INC.
6230 South Oak Park Avenue
Chicago, IL 60638
(312) 586-8700
FAX: (312) 586-0187

BEAR PAW MAGNETIC TOOLS INCORPORATED
4613 Aircenter Circle
Reno, NV 89502
(702) 829-1810
FAX: (702) 829-1819

BELAIRE PRODUCTS INC.
763 South Broadway Avenue
Akron, OH 44311
(216) 253-3116
FAX: (216) 376-7790

BELCHFIRE CORPORATION
2900-C Vera Avenue
Glendale, WI 53209
(414) 258-5700
FAX: (414) 228-5702

BELCO PRODUCTS, INCORPORATED
205 Alexander Drive
Woodbury, TN 37190
(615) 563-4060
FAX: (615) 563-4070

BELLEVILLE AREA COLLEGE — WELDING TECHNOLOGY DIVISION
2500 Carlyle Road
Belleville, IL 62221
(618) 235-2700
FAX: (618) 235-1578

BERNARD WELDING
667 West Corning Road
Beecher, IL 60401
(708) 946-2281
FAX: (708) 946-6738

BETTERMANN OF AMERICA, INCORPORATED
503 Parkway View Drive
Pittsburgh, PA 15205
(412) 787-5970
FAX: (412) 788-6627

BINZEL CORPORATION, ALEXANDER
650 Research Drive, Suite 110
Frederick, MD 21703
(301) 846-4196
FAX: (301) 831-8072

BLACK AND DECKER
701 East Joppa Road
Towson, MD 21286
(410) 716-3900
FAX: (410) 716-2238

BLUCO CORPORATION
509 Weston Ridge Drive
Naperville, IL 60563
(800) 535-0135
FAX: (708) 637-1847

BOC GASES (FORMERLY AIRCO GASES)
575 Mountain Avenue
Murray Hill, NJ 07974
(908) 771-1218
FAX: (908) 771-1764

BONAL TECHNOLOGIES, INC.
21178 Bridge Street
Southfield, MI 48034
(810) 353-2041
FAX: (810) 353-2028

BOSCH — INDUSTRIAL ELECTRONICS DIVISION
97 River Road
Collinsville, CT 06022
(203) 693-1738
FAX: (203) 693-1739

BOSCH POWER TOOLS
4300 West Peterson Avenue
Chicago, IL 60646
(312) 481-3830
FAX: (312) 481-3654

BRIGGS AND STRATTON CORPORATION
Post Office Box 702
Milwaukee, WI 53201
(414) 259-5333
FAX: (414) 259-5313

BROCO INCORPORATED
8690 Red Oak Street
Rancho Cucamonga, CA 91730
(909) 483-3222
FAX: (909) 483-3233

BTU CONTRACTS, INC.
6432 North Ridgeway Avenue
Lincolnwood, IL 60645
(708) 673-7790
FAX: (708) 673-7794

BUG-O SYSTEMS, INC.
3001 West Carson Street
Pittsburgh, PA 15204
(412) 331-1776
FAX: (412) 331-0383

BURCO WELDING & CUTTING PRODUCTS INCORPORATED
614 Old Thomasville Road
High Point, NC 27260
(910) 887-6100
FAX: (910) 887-6194

BURCO/MOSA
Post Office Box 2804
High Point, NC 27261
(800) 982-8726
FAX: (910) 887-6194

BURNFREE/NORTRADE INTERNATIONAL, INC.
9382 South 670 West
Sandy, UT 84070
(801) 569-9090
FAX: (801) 569-3733

BURNY GROUP/CLEVELAND MACHINE CONTROLS INC.
7550 Hub Parkway
Cleveland, OH 44147
(216) 524-8800
FAX: (216) 642-2199

C & G SYSTEMS, INC.
1290 Louis Avenue
Elk Grove Village, IL 60007
(708) 437-6450
FAX: (708) 437-6478

C-K WORLDWIDE INC.
3501 "C" Street North East
Auburn, WA 98002
(206) 854-5820
FAX: (206) 939-1746

C-SPEC
2291 Heritage Hills Drive
Pleasant Hill, CA 94523
(510) 943-1120
FAX: (510) 930-8223
E-mail: info@cspec.com
http://www.cspec.com

C.E.A. WELDING EQUIPMENT
Post Office Box 2518
Whitehouse, OH 43571
(419) 877-1000
FAX: (419) 877-1001

C.E.M.E./MAJOR
33900 Curtis Boulevard
Eastlake, OH 44095
(216) 942-0054
FAX: (216) 942-2102

CAJON COMPANY
9760 Shepard Road
Macedonia, OH 44056
(216) 467-0200
FAX: (216) 467-5000

CAMEL GRINDING WHEEL
7530 N. Caldwell Avenue
Niles, IL 60714
(847) 647-5994
FAX: (847) 647-1861

CANADIAN WELDING BUREAU
7250 West Credit Avenue
Mississauga, Ontario, L5N 5N1
Canada
(905) 542-1312
FAX: (905) 542-1318

CARBORUNDUM ABRASIVES
6600 Walmore Road
Niagara Falls, NY 14304
(716) 731-7777
FAX: (716) 731-2467

CARDINAL EG SAWS CORPORATION
1255 Tonne Road
Elk Grove Village, IL 60007
(708) 364-5640
FAX: (708) 228-7067

CARMEL INDUSTRIES
6845 De Lepee
Montreal, Quebec H3N 2C7
Canada
(514) 270-5377
FAX: (514) 270-2025

CARVALHO, ADRIANA
1441 West Wyler
Chicago, IL 60613
(312) 226-7521
FAX: (312) 226-7688

CARY — CARY FOUNDS
7337 Highway 60 East
East Lake Wales, FL 33853
(813) 696-2412

CASILIO, MARTIN A.
437 Shawmut Avenue
Johnsonburg, PA 15845
(814) 965-5834

CATALINA CYLINDERS, CLIFF IMPACT DIVISION
33800 Lakeland Blvd.
Eastlake, OH 44095
(216) 946-9090
FAX: (216) 946-2573

CEBORA S.P.A.
Via Andrea Costa N 24 Cadriano
Bologna, 40057
Italy
(39) 51765000
FAX: (39) 51765222

CELESTIAL IRONWORKS
R.R.3, Box 64AA
Great Bend, KS 67530
(316) 564-3625
FAX: (316) 564-3142

CEMONT
7903 Jefferson Circle
Colleyville, TX 76034
(817) 581-9982
FAX: (817) 581-9984

CENTERFLEX
2145 South Platte River Drive
Denver, CO 80223
(800) 385-3539
FAX: (303) 742-9514

CENTERLINE (WINDSOR) LIMITED
Post Office Box 32966
Detroit, MI 48232-0966
(313) 961-0746
FAX: (519) 734-1838

CENTURION NDT, INC.
707 Remington Road
Schaumburg, IL 60173
(708) 884-4949
FAX: (708) 884-8772

CENTURY MANUFACTURING
9231 Penn Avenue South
Minneapolis, MN 55431
(612) 885-4481
FAX: (612) 885-4569

CEODEUX INCORPORATED
1002 Corporate Drive
Export, PA 15632
(412) 325-5720
FAX: (412) 325-5723

CERBACO LTD.
2899 Nostrand Avenue
Brooklyn, NY 11229
(718) 252-9200
FAX: (718) 252-9201

CFA
8031 Jarry E.
Montreal, Quebec, H1J 1H6
Canada
(800) 565-5326
FAX: (800) 665-6889

CHAMPION CUTTING TOOL CORP.
100 North Park Avenue
Rockville Centre, NY 11570
(516) 536-8200
FAX: (516) 678-4064

CHAMPION WELDING PRODUCTS INCORPORATED
7619 Detour Avenue
Cleveland, OH 44103
(216) 431-9353
FAX: (216) 431-1155

CHEMCLEAN CORP
130-45 180th Street
Springfield Gardens, NY 11434
(718) 525-4500

CHEROKEE INDUSTRIES, INCORPORATED
Post Office Box 352
Rte. 3, North Hwy. 11
Ord, NE 68862
(308) 728-3113
FAX: (308) 728-3481

CHICAGO PNEUMATIC TOOL COMPANY
2220 Bleecker Street
Utica, NY 13501-1795
(315) 792-2600
FAX: (315) 792-2672

CHO HEUNG ELECTRIC IND. CO., LTD.
Room 1008 Cheil Building
256-13 GongDuk-Dong
Mapo-Ku
Seoul, 121-020,Korea
(82) 7193679
FAX: (82) 7193672

CHOSUN STEEL WIRE COMPANY
253 North Santa Fe
Salina, KS 67401
(913) 827-4529
FAX: (913) 827-5804

CLEMCO INDUSTRIES CORPORATION
One Cable Car Drive
Washington, MO 63090
(314) 239-0300
FAX: (314) 239-0788

CLEVELAND STEEL TOOL COMPANY, THE
474 East 105th Street
Cleveland, OH 44108
(800) 446-4402
FAX: (216) 681-7009

CLOOS INTERNATIONAL INC.
911 Albion Avenue
Schaumburg, IL 60193
(708) 924-9988
FAX: (708) 924-9989

CML USA INC (ERCOLINA)
Post Office Box 111095
Cleveland, OH 44111
(216) 631-3444
FAX: (216) 631-3313

CMS GILBRETH PACKAGING SYSTEMS
8 Neshaminy Interplex, No. 219
Trevose, PA 19053
(215) 244-2400
FAX: (215) 244-2390

CMW INCORPORATED
70 South Gray Street
Indianapolis, IN 46206
(317) 634-8884
FAX: (317) 638-2706

CNA INSURANCE COMPANIES
CNA Plaza 9West
Chicago, IL 60685
(800) 262-6241
FAX: (312) 822-1645

CNI-CERAMIC NOZZLES, INC.
100 Marine Street
Farmingdale, NY 11735
(516) 293-5720
FAX: (516) 293-5882

COLORADO SCHOOL OF MINES
15th and Illinois
Golden, CO 80401
(303) 273-3797
FAX: (303) 273-3795

COMEQ, INCORPORATED
Post Office Box 2193
Baltimore, MD 21203
(410) 325-7900
FAX: (410) 325-1025

COMPRESSED GAS ASSOCIATION (CGA)
1725 Jefferson Davis Hwy
Arlington, VA 22202-4102
(703) 412-0900
FAX: (703) 412-0128

COMPUTER ENGINEERING, INCORPORATED
Post Office Box 1657
Blue Springs, MO 64013
(816) 228-2976
FAX: (816) 228-0680

COMPUTER WELD TECHNOLOGY INCORPORATED
4544 South Pinemont, Suite 200
Houston, TX 77041
(713) 462-2118
FAX: (713) 462-2503

COMPUTERS UNLIMITED
2407 Montana Avenue
Billings, MT 59101
(406) 255-9500
FAX: (406) 255-9595

CONARCO ALAMBRES Y SOLDADURAS S.A.
Calle 18 Nro. 4079
Buenos Aires, 1672,
Argentina
(54) 7527521
FAX: (54) 7537571

CONTEMPORARY PRODUCTS, INC. (CPI)
530 Riverside Industrial Parkway
Portland, ME 04103
(800) 424-2444
FAX: (207) 797-9411

CONTINENTAL ABRASIVES
16871 Noyes Avenue
Irvine, CA 92714
(714) 474-1101
FAX: (714) 863-3076

CONTOUR SALES DIV OF JACKSON PRODUCTS
5801 Safety Drive N.E.
Belmont, MI 49306
(800) 253-7281
FAX: (616) 784-7870

CONTROLS CORPORATION OF AMERICA
1501 Harpers Road
Virginia Beach, VA 23454
(804) 422-8330
FAX: (804) 422-3125

CONVERGENT ENERGY
1 Picker Road
Sturbridge, MA 01566
(508) 347-2681
FAX: (508) 347-5134

COOPTIM INDUSTRIAL LTD.
Petofi S. 21
Diosd 2049
Hungary
(36) 23382431
FAX: (36) 23382321

COPPUS PORTABLE VENTILATION DIVISION, TUTHILL CORP.
Millbury Industrial Park
Millbury, MA 01527-8000
(508) 756-8391
FAX: (508) 756-8375

COR-MET, INC.
988 Rickett Road
Brighton, MI 48116
(810) 227-3257
FAX: (810) 227-9266

CORAL SPA
Strada Volpiano 52/54
Leini Torino, 10040
Italy
(39) 119989211
FAX: (39) 119988460

CROUSE-HINDS CAM-LOK
Route 4, Box 156
La Grange, NC 28551
(919) 566-3014
FAX: (919) 566-9337

CROWN/NORTH AMERICAN PROFESSIONAL PRODUCTS
1500 McConnell Road
Woodstock, IL 60098-7310
(815) 334-0020
FAX: (815) 334-0021

CRYOGENIC INDUSTRIES
25720 Jefferson Avenue
Murrieta, CA 92562
(909) 696-7840
FAX: (909) 698-7484

CTR OF CHARLOTTE INC.
298 Porter Road
Rock Hill, SC 29730-6341
(803) 324-8101
FAX: (803) 324-8187

CYBO ROBOTS
2701 Fortune Circle East
Indianapolis, IN 46241
(317) 484-2926
FAX: (317) 241-2727

CYPRESS WELDING EQUIPMENT INC.
11902 Rockville Drive
Houston, TX 77064
(713) 469-0746
FAX: (713) 469-9354

D. L. RICCI CORPORATION
2722 North Service Drive
Red Wing, MN 55066
(612) 388-8661
FAX: (612) 388-0002

D/F MACHINE SPECIALTIES INCORPORATED
1750 Howard Drive
North Mankato, MN 56003
(507) 625-6200
FAX: (507) 625-6203

DARRAH ELECTRIC COMPANY
5914 Merrill Avenue
Cleveland, OH 44102
(216) 631-0912
FAX: (216) 631-0440

DATAWELD INC.
1909 Citizens Bank Drive
Bossier City, LA 71111
(318) 746-6111
FAX: (318) 746-0323

DCM CLEAN-AIR PRODUCTS, INC.
6850 Manhattan Boulevard, Suite 500
Fort Worth, TX 76120
(817) 654-2829
FAX: (817) 451-0615

DE-STA-CO A DOVER RESOURCES COMPANY
Post Office Box 2800
Troy, MI 48007-2800
(810) 589-2008
FAX: (810) 644-3929

DEL-LIFTGATES, INC.
190 Lewis Street
Buffalo, NY 14240
(716) 853-7994
FAX: (716) 854-5424

DETROIT DIESEL CORPORATION
13400 Outer Drive West
Detroit, MI 48239-4001
(313) 592-5000
FAX: (313) 592-7590

DEUTZ CORPORATION
3883 Steve Reynolds Boulevard
Norcross, GA 30093
(404) 564-7100
FAX: (404) 564-7222

DEXTER AXLE
Post Office Box 250
Elkhart, IN 46515
(219) 295-1900
FAX: (219) 522-5208

DIMETRICS, INCORPORATED
404 Armour Street
Post Office Box 339
Davidson, NC 28036
(704) 892-8872
FAX: (704) 892-4713

DIRECT WIRE & CABLE, INC.
68 Denver Road
Post Office Box 57
Denver, PA 17517
(717) 336-2842
FAX: (717) 336-0505

DIRECTED LIGHT, INC.
633 River Oaks Parkway
San Jose, CA 95134
(408) 321-8500
FAX: (408) 321-8466

DIVERS ACADEMY OF THE EASTERN SEABOARD INC.
2500 South Broadway
Camden, NJ 08104
(800) 238-3483
FAX: (609) 541-4355

DIVERSI-TECH INC.
131 Montee De Liesse
Montreal, Quebec, H4T 1V2
Canada
(514) 340-1774
FAX: (514) 340-9408

DOBLINGER, DON
10414 Reed
Monclova, OH 43542
(419) 873-5458

DORINGER MANUFACTURING COMPANY
13400 Estrella Avenue
Gardena, CA 90248
(800) 962-6800
FAX: (213) 746-9245

DOYLE'S SUPPLY INC.
Post Office Box 1943
Decatur, AL 35602
(205) 353-7515
FAX: (205) 353-8792

DUALDRAW BY IMM
5495 East 69th Avenue
Commerce City, CO 80022
(800) 977-2125
FAX: (303) 287-0109

DUNN, MICHAEL T.
Post Office Box 249
Petersburg, NY 12138
(518) 658-3119

DYNABRADE, INC.
8989 Sheridan Drive
Clarence, NY 14031
(716) 631-0100
FAX: (716) 631-2073

DYNAFLUX, INC.
241 Brown Farm Road
Cartersville, GA 30120
(800) 334-4420
FAX: (404) 382-9034

EAGLE BENDING MACHINES, INC.
Post Office Box 189
Bay Minette, AL 36507
(334) 937-0947
FAX: (334) 937-4742

EAGLE INDUSTRIES
16011 South East Belair Drive
Portland, OR 97216
(503) 254-1749
FAX: (800) 959-6601

EAGLE WIRE COMPANY, INC.
325 Emmett Avenue
Box 70067
Bowling Green, KY 42101
(502) 843-1035
FAX: (502) 782-6177

EASTERN ETCHING & MANUFACTURING
Foot of Grape Street
Chicopee, MA 01013
(413) 594-6601
FAX: (413) 594-6600

EDWARDS MANUFACTURING CO.
Post Office Box 166
Northaire Industrial Park
Albert Lea, MN 56007
(507) 373-8206
FAX: (507) 373-9433

ELECTRODE DRESSERS, INC.
4506 Roger Chaffee S.E.
Post Office Box 8187
Grand Rapids, MI 49518
(616) 538-6224
FAX: (616) 538-6777

ELECTRON BEAM TECHNOLOGIES, INC.
1275 Harvard Drive
Kankakee, IL 60901
(815) 935-2211
FAX: (815) 935-8605

ELLIOTT CORPORATION
504 Pecor Street
Oconto, WI 54153
(414) 834-5622
FAX: (414) 834-2884

ENERPAC
13000 West Silver Spring Drive
Butler, WI 53007
(414) 781-6600
FAX: (414) 781-7403

ENGELHARD CORPORATION
235 Kilvert Street
Warwick, RI 02886
(401) 739-9550
FAX: (401) 739-9555

ENGELHARD SURFACE TECHNOLOGIES
12 Thompson Road
East Windsor, CT 06088
(860) 623-9901
FAX: (860) 623-4657

ENGINEERING PRODUCTS & SERVICES (E.P.S.)
330 East Maple, Building J
Troy, MI 48083
(810) 616-0200
FAX: (810) 616-9795

ENTERGY CORPORATION
308 East Pearl Street
Jackson, MS 39215
(601) 824-0479
FAX: (601) 824-0483

ENTRON CONTROLS, INCORPORATED
465 East Randy Road
Carol Stream, IL 60188
(708) 682-9600
FAX: (708) 682-3374

EQUOTIP ASSOCIATES
Post Office Box 15580
Pittsburgh, PA 15244
(800) 397-7821
FAX: (412) 788-8984

ESAB CUTTING SYSTEMS
411 South Ebenezer Road
Florence, SC 29501
(803) 664-4394
FAX: (803) 664-4403

ESAB WELDING & CUTTING PRODUCTS
Post Office Box 100545
Florence, SC 29501
(803) 664-4393
FAX: (803) 664-5575

ESCO TOOL, A UNIT OF ESCO TECHNOLOGIES, INC.
50 Park Street
Box 530
Medfield, MA 02052
(508) 359-4311
FAX: (508) 359-4145

ESSEX GROUP, INCORPORATED
1601 Wall Street
Fort Wayne, IN 46802
(219) 461-4159
FAX: (219) 461-4150

EVERETT INDUSTRIES INCORPORATED
3601 Larchmont North East
Post Office Box 2068
Warren, OH 44484
(216) 372-3700
FAX: (216) 372-3118

EWI
1100 Kinnear Road
Columbus, OH 43212-1161
(614) 486-9400
FAX: (614) 486-9528

EXPANSION SEAL TECHNOLOGIES (FORMERLY EXPANDO SEAL TOOLS)
334 Godshall Drive
Harleysville, PA 19438
(800) 355-7044
FAX: (215) 513-4333

EXPRESS WHOLESALE/WORLDWIDE WELDING, INC.
Post Office Box 1050
Pineville, NC 28134
(803) 547-0123
FAX: (803) 547-0800

FAB-TECH INCORPORATED
21 Hercules Drive
Colchester, VT 05446
(802) 655-8800
FAX: (802) 655-8804

FABRICATORS & MANUFACTURER'S ASSOCIATION
833 Featherstone Road
Rockford, IL 61107
(815) 399-8700
FAX: (815) 399-7679

FACTORY MUTUAL
1151 Boston-Providence Turnpike
Norwood, MA 02062
(617) 762-4300
FAX: (617) 762-9375

FAITER ELETTRODI S.P.A.
Via Per Azzano S. Paolo Nr. 32/E
Grassobbio (BG) I-24050,
Italy
(39) 525029
FAX: (39) 526756

FANUC ROBOTICS NORTH AMERICA, INC.
2000 South Adams Road
Auburn Hills, MI 48326
(810) 377-7000
FAX: (810) 377-7366

FARR COMPANY
2221 Park Place
El Segundo, CA 90245-4900
(310) 536-6321
FAX: (310) 643-9086

FEIN POWER TOOLS INC.
3019 West Carson Street
Pittsburgh, PA 15204
(412) 331-2325
FAX: (412) 331-3599

FEMI S.R.L.
Via S Caterina 8
Correzzola (PD)
Italy
(049) 585-0244
FAX: (049) 585-0303

FHP ELMOTOR AB
Ankarsrum, S-590 90
Sweden
(46) 49053385
FAX: (46) 49050047

FIBA TECHNOLOGIES, INC.
97 Turnpike Road
Westboro, MA 01581
(508) 366-8361
FAX: (508) 366-1915

FIBRE-METAL PRODUCTS CO.
Post Office Box 248
Concordville, PA 19331
(610) 459-5300

FILLER METALS, INC.
Post Office Box 276
Pottstown, PA 19464
(610) 323-2120
FAX: (610) 323-8344

FINWELDING S.R.L.
Via Civinelli, 1040
Cesena-Fo 47020
Italy
(39) 547317533
FAX: (39) 547318726

FISHER CONTAINER CORPORATION
2000 Dempster Plaza
Evanston, IL 60202
(708) 866-6050
FAX: (708) 866-7271

FLAME TECHNOLOGIES, INCORPORATED
Post Office Box 1776
Cedar Park, TX 78613
(512) 219-8489
FAX: (512) 219-8477

FLEX-CABLE
16 West Huron Street
Pontiac, MI 48342
(810) 338-6600
FAX: (810) 338-3747

FLEXOVIT USA, INC.
1305 Eden-Evans Center Road
Angola, NY 14006
(716) 549-5100
FAX: (716) 549-5455

FORMING & FABRICATING/SME
Post Office Box 930
Dearborn, MI 48121
(313) 271-1500
FAX: (313) 271-2861

FRIMAR SAS
S.P.Provinciale Verdello-Carvaggio 121
Pognano (BG), 24040
Italy
(39) 0354829333
FAX: (39) 0354829374

FROMMELT SAFETY PRODUCTS
8900 North Arbon Drive
Milwaukee, WI 53223
(800) 553-5560
FAX: (319) 589-2754

FUSION INCORPORATED
4658 East 355th Street
Willoughby, OH 44094
(216) 946-3300
FAX: (216) 942-9083

G.B.C. INDUSTRIAL TOOLS
2519 East Southmore
Pasadena, TX 77502
(713) 472-8122
FAX: (713) 472-6804

GALT INDUSTRIES, INC.
100 First Avenue
Pittsburgh, PA 15222
(412) 232-0952
FAX: (412) 232-0961

GALVANIZING COMPANY, ROGERS
1800 West 21st Street
Tulsa, OK 74107
(918) 584-0303
FAX: (918) 584-1781

GARDNER ENVIRONMENTAL PRODUCTS
1201 West Lake Street
Horicon, WI 53051
(414) 485-4303
FAX: (414) 485-4370

GAS TECH, INC.
12000 Roosevelt Road
Hillside, IL 60162
(708) 449-9300
FAX: (708) 443-0345

GASES AND WELDING DISTRIBUTOR
1100 Superior Avenue
Cleveland, OH 44114
(216) 696-7000
FAX: (216) 696-7658

GASFLUX COMPANY, THE
Post Office Box 1170
Elyria, OH 44035
(216) 365-1941
FAX: (216) 365-3495

GE WELDING & MACHINING
302 Hansen Access Road
King of Prussia, PA 19406
(610) 992-7959
FAX: (610) 992-6158

GENERATIVE N/C TECHNOLOGY, INC.
300 Knickerbacker Road
Cresskill, NJ 07626
(201) 871-2350
FAX: (201) 871-2358

GENESIS SYSTEMS GROUP
4821 Tremont Avenue
Davenport, IA 52807
(319) 386-4034
FAX: (319) 386-3012

GEORGE FISCHER PIPE TOOLS
407 Hadley Street
Holly, MI 48442
(810) 634-8251
FAX: (810) 634-2507

GERSON CO., INC., LOUIS M.
15 Sproat Street
Middleboro, MA 02346
(508) 947-4000
FAX: (508) 947-5442

GILBERT INDUSTRIAL
33-12 Lomar Park Drive
Pepperell, MA 01463
(508) 433-5263
FAX: (508) 433-9508

GLOBAL HEAT INCORPORATED
8501 West 191st Street, Unit 57
Mokena, IL 60448
(800) 443-2893
FAX: (815) 469-8790

GOSS INCORPORATED
1511 Route 8
Glenshaw, PA 15116
(800) 367-4677
FAX: (412) 486-6844

GOW-MAC INSTRUMENT COMPANY
277 Brodhead Road
Bethlehem, PA 18017
(610) 954-9000
FAX: (610) 954-0599

GREAT WEI LUNG INDUSTRY CO., LTD.
1F. No. 23 Chin Ho Street
Tu Cheng City
Taipai, Hsien
Taiwan R.O.C.
(886) 266-8065
FAX: (886) 266-8449

GROSS STABIL CORPORATION
333 Race Street
Post Office Box 368
Coldwater, MI 49036
(517) 278-6121
FAX: (517) 278-5523

GTE SCIENTIFIC SOCIETY OF MECHANICAL ENGINEERS (HUNGARY)
Fo utca 68
Post Office Box 433
Budapest, 1371
Hungary
(36) 12020582
FAX: (36) 12020252

GUARD-LINE, INC.
215-217 South Louise
Atlanta, TX 75551
(903) 796-4111
FAX: (903) 796-7262

GULF WIRE CORPORATION
Post Office Box 29849
New Orleans, LA 70189
(504) 254-0062
FAX: (504) 254-1220

GULLCO INTERNATIONAL INCORPORATED
21568 Alexander Road
Cleveland, OH 44146
(216) 439-8333
FAX: (216) 439-3634

H & H SALES COMPANY, INCORPORATED
Post Office Box 686
Huntertown, IN 46748-0686
(219) 637-3177
FAX: (219) 637-6880

H & M PIPE BEVELING MACHINE COMPANY, INC.
311 East Third Street
Tulsa, OK 74120
(918) 582-9984
FAX: (918) 582-9989

H & S TOOL
212 West Bergey Street
Wadsworth, OH 44281
(216) 335-1536
FAX: (216) 336-9159

HANDY & HARMAN OF CANADA LIMITED
290 Carlingview Drive
Rexdale, ONT, M9W 5G1
Canada
(416) 675-1860
FAX: (416) 675-1956

HANNAY REELS
553 State Route 143
Westerlo, NY 12193
(518) 797-3791
FAX: (518) 797-3259

HARRIS CALORIFIC DIVISION, THE LINCOLN ELECTRIC COMPANY
2345 Murphy Boulevard
Gainsville, GA 30504-6000
(770) 536-8801
FAX: (770) 535-0544

HARRIS WELCO — DIVISION OF J.W. HARRIS
1051 York Road
Post Office Box 69
Kings Mountain, NC 28086
(704) 739-6421
FAX: (704) 739-2801

HAVENS SCULPTURES, JAMES
521 West Main Street
Woodville, OH 43469
(419) 849-3048

HEATH JEWELRY, MICHELLE & ANDY
Post Office Box 2089
Taos, NM 87571

HELLERS SON INC., E.G.
18330 Oxnard Street
Tarzana, CA 91356
(818) 881-0900
FAX: (818) 344-8898

HEM SAW
Post Office Box 1148
Pryor, OK 74362
(918) 825-1000
FAX: (918) 825-4824

HENNING HANSEN INCORPORATED
Post Office Box 220
Pickering, Ontario, L1V 2R4
Canada
(905) 839-7481
FAX: (905) 839-3686

HERRON TESTING LABORATORIES, INC.
5405 East Schaaf Road
Cleveland, OH 44131
(216) 524-1450
FAX: (216) 524-1459

HI-ALLOY WELD SPECIALISTS
1216 Illinois Avenue
South Houston, TX 77587
(713) 943-1818
FAX: (713) 943-7773

HIGH PURITY GAS CO.
4344 South Main
Pearland, TX 77581
(713) 482-7007
FAX: (713) 482-9216

HILL TECHNICAL DIVISION — SERV-TECH, INC.
5200A Cedar Crest Boulevard
Houston, TX 77087
(713) 640-1155
FAX: (713) 640-1166

HITACHI POWER TOOLS
3950 Steve Reynolds Boulevard
Norcross, GA 30093
(770) 925-1774
FAX: (770) 564-7003

HITCO TECHNOLOGIES INCORPORATED
1600 West 135th Street
Gardena, CA 90249-2506
(310) 970-5452
FAX: (310) 515-1779

HOBART BROTHERS COMPANY
600 West Main Street
Troy, OH 45373
(513) 332-4000
FAX: (513) 332-4336

HOBART INSTITUTE OF WELDING TECHNOLOGY
400 Trade Square East
Troy, OH 45373
(513) 332-5000
FAX: (513) 332-5200

HOBART LASERS & ADVANCED SYSTEMS
1191 Trade Road East
Troy, OH 45373
(513) 332-5555
FAX: (513) 339-1718

HORNELL SPEEDGLAS, INC.
2374 Edison Blvd
Twinsburg, OH 44087
(800) 628-9218
FAX: (216) 425-4576

HOUGEN MANUFACTURING INCORPORATED
G-5072 Corunna Road
Flint, MI 48501
(810) 732-5840
FAX: (810) 732-3553

HYD-MECH SAWS LIMITED
1079 Parkinson Road
Woodstock, ONT, N4S 8P6
Canada
(519) 539-6341
FAX: (519) 539-5126

HYPERTHERM INCORPORATED
Etna Road
Post Office Box 5010
Hanover, NH 03755
(603) 643-3441
FAX: (603) 643-5352

HYUNDAI WELDING & METAL COMPANY, LTD.
5455 Corporate Drive
Troy, MI 48098
(810) 641-0105
FAX: (810) 641-0156

IBEDA INCORPORATED
32676 Center Ridge Road
North Ridgeville, OH 44039-2457
(216) 327-7300
FAX: (216) 327-5777

IES UTILITIES
Post Office Box 351
Cedar Rapids, IA 52406
(319) 398-4542
FAX: (319) 398-4567

ILISAGVIK COLLEGE
Post Office Box 749
Barrow, AK 99723
(907) 852-9138
FAX: (907) 852-9122

IMPERIAL WELD RING CORPORATION
80-88 Front Street
Elizabeth, NJ 07206
(908) 354-0011
FAX: (908) 354-9014

INCO ALLOYS INTERNATIONAL, INC.
1401 Burris Road
Newton, NC 28658
(704) 465-0352
FAX: (704) 464-8993

INDRESCO INC., INDUSTRIAL TOOL DIVISION
7007 Pinemont
Houston, TX 77040
(713) 462-4521
FAX: (713) 460-7008

INDURA S.A.
Camino A Nelipilla #7060
Santiago
Chile
(56) 5571777
FAX: (56) 5573471

INDUSTRIAL MAINTENANCE & PLANT OPERATION
One Chilton Way
Radnor, PA 19089
(610) 964-4041
FAX: (610) 964-4947

INDUSTRIAL MARKET PLACE
7842 North Lincoln Avenue
Skokie, IL 60077
(708) 676-1900
FAX: (708) 676-0063

INDUSTRIAL PRODUCT BULLETIN
301 Gibraltar Drive
Morris Plains, NJ 07950
(201) 292-5100
FAX: (201) 539-3476

INERT SYSTEMS INC.
6414 Greeley Hill Road
Coulterville, CA 95311
(209) 878-0420
FAX: (209) 878-0443

INNOVATIVE INDUSTRIES INC.
1525 Deleglise
Antigo, WI 54409
(715) 627-4467
FAX: (715) 627-4528

INVINCIBLE AIRFLOW SYSTEMS
700 North Ray
Post Office Box 380
Baltic, OH 43804
(216) 897-3200
FAX: (216) 897-3400

INWELD CORPORATION
2301 Duss Avenue
Ambridge, PA 15003-0460
(412) 251-9100
FAX: (412) 251-9200

IRC
1380 Graham Bell
Boucherville, Quebec, J4B 6H5
Canada
(514) 655-4410
FAX: (514) 655-4963

ITALIAN TRADE COMMISSION
401 North Michigan Avenue, Suite 3030
Chicago, IL 60611
(312) 670-4360
FAX: (312) 670-5147

JACKSON INDUSTRIES
6000 South Oak Park Avenue
Chicago, IL 60638
(312) 229-0033
FAX: (312) 229-0693

JACKSON PRODUCTS, INC.
101 South Hanley Road
Saint Louis, MO 63303
(314) 746-4850
FAX: (314) 862-5803

JAMES MORTON, INCORPORATED
50 Franklin Street
Post Office Box 399
Batavia, NY 14021
(800) 828-1004
FAX: (716) 344-0025

JANCY ENGINEERING CO.
"HOME OF THE SLUGGER"
2735 Hickory Grove Road
Davenport, IA 52804
(319) 391-1300
FAX: (319) 391-2323

JAZ-ZUBIAURRE S.A.
Asuerreka, 7
Eibar, 20600
Spain
(344) 312-0600
FAX: (344) 312-1704

JEPSON POWER TOOLS
20333 South Western Avenue
Torrance, CA 90501
(310) 320-3890
FAX: (310) 328-1318

JETLINE ENGINEERING INC.
15 Goodyear Street
Irvine, CA 92718
(714) 951-1515
FAX: (714) 951-9237

JOHNSON WILSHIRE, INC.
700 Union Street
Montebello, CA 90640
(213) 888-0022
FAX: (213) 888-0029

K & K WELDING PRODUCTS, INC.
520 Tesler Road
Lake Zurich, IL 60047
(708) 540-9400
FAX: (708) 540-0197

K-TRON, INC.
Post Office Box 488
Jasper, GA 30143
(706) 692-3360
FAX: (706) 692-3451

KASCO ABRASIVES
580 Race Street
Coldwater, MI 49036
(800) 367-7291
FAX: (517) 279-7265

KAWASAKI ROBOTICS (USA) INCORPORATED
28059 Center Oaks Court
Wixom, MI 48393
(810) 305-7610
FAX: (810) 305-7618

KEDMAN COMPANY
Post Office Box 25667
Salt Lake City, UT 84125
(801) 973-9112
FAX: (801) 972-2756

KEN KOSIOREK METAL SCULPTURE
2121 Seagull Lane
San Diego, CA 92123
(619) 279-6344
FAX: (619) 279-6344

KIEL, ADELE
3346 South Seeley
Chicago, IL 60608
(312) 524-0779
FAX: (708) 839-9207

KINCO INTERNATIONAL, INCORPORATED
927 South East Marion
Portland, OR 97202-7031
(503) 238-4588
FAX: (503) 233-9501

KING BAG & MANUFACTURING CO.
1500 Spring Lawn
Cincinnati, OH 45223
(513) 541-5440
FAX: (513) 541-6555

KIRKHOF/GOODRICH CORPORATION
3903 Roger B Chaffee Boulevard
Grand Rapids, MI 49548
(616) 241-1621
FAX: (616) 241-0002

KLINGSPOR ABRASIVES, INC.
2555 Tate Boulevard S.E.
Hickory, NC 28601
(800) 645-5555
FAX: (800) 524-6758

KOBELCO WELDING OF AMERICA INC.
7478 Harwin Drive
Houston, TX 77036
(713) 974-5774
FAX: (713) 974-6543

KOHLER CO., ENGINE DIVISION
444 Highland Drive
Kohler, WI 53044
(414) 457-4441
FAX: (414) 459-1747

KOIKE ARONSON INCORPORATED
635 West Main Street
Arcade, NY 14009
(716) 492-2400
FAX: (716) 457-3517

KOOLANT KOOLERS, INC.
2625 Emerald Drive
Kalamazoo, MI 49001
(616) 349-6800
FAX: (616) 349-8951

KOPO INTERNATIONAL (FIPROM; GLOBTRADE USA)
One Penn Plaza
New York, NY 10119-0002
(212) 465-1350
FAX: (212) 465-1353

KOREA WELDING INDUSTRY COOPERATIVE
16-2 Yoido-dong, Youngsungpo-ko
618 Korea Federation Small Business Bldg.
Seoul, Korea
(82) 02785504
FAX: (82) 02783586

KRAUTKRAMER BRANSON
50 Industrial Park Road
Lewistown, PA 17044
(717) 242-0327
FAX: (717) 242-2606

KROMER CAP CO., INC.
759 North Milwaukee Street
Milwaukee, WI 53202
(414) 276-1800
FAX: (414) 276-8440

KUTON WELDING INCORPORATED
8582 Telfair Avenue
Sun Valley, CA 91352
(818) 771-0964
FAX: (818) 504-9567

KYTEX SOLUTIONS, INC.
14240 Cherry Lane Court
Laurel, MD 20707
(301) 617-0444
FAX: (301) 725-3347

L S INDUSTRIES
710 East 17th Street
Wichita, KS 67214
(316) 265-7997
FAX: (316) 265-0013

LA-CO INDUSTRIES, INC./MARKAL CO.
1201 Pratt Boulevard
Elk Grove, IL 60007
(708) 956-7600
FAX: (708) 956-9885

LARCO
2600 Fernbrook Lane
Plymouth, MN 55447
(612) 557-7055

LARCO/SAFETY CONTROLS CORPORATION
13705 26th Avenue North
Plymouth, MN 55441
(612) 557-7055
FAX: (612) 557-1130

LASER APPLICATIONS, INC. (LAI)
1110 Business Parkway South
Westminster, MD 21157
(410) 857-0770
FAX: (410) 857-0774

LASER MACHINING, INCORPORATED
500 Laser Drive
Somerset, WI 54025
(715) 247-3285
FAX: (715) 247-5650

LECO CORPORATION
3000 Lakeview Avenue
Saint Joseph, MI 49085-2396
(616) 982-5409
FAX: (616) 982-8977

LENCO
319 West Main Street
Jackson, MO 63755
(314) 243-3141
FAX: (314) 243-7122

LEPEL CORPORATION
50 Heartland Boulevard
Edgewood, NY 11717
(516) 586-3300
FAX: (516) 586-3232

LETOURNEAU UNIVERSITY
Post Office Box 7001
Longview, TX 75607-7001
(903) 753-0231
FAX: (903) 236-1700

LIBURDI PULSWELD CORPORATION
400 Highway 6 North
Hamilton, ONT, L9J 1E7
Canada
(905) 689-0734
FAX: (905) 689-0739

LINCOLN ELECTRIC COMPANY, THE
22801 Saint Clair Avenue
Cleveland, OH 44117
(216) 481-8100
FAX: (216) 486-1751

LIVINGSTON, INCORPORATED
Unit 1
7 Commerce Avenue
West Lebanon, NH 03784
(603) 298-9600
FAX: (603) 298-7878

LOS ANGELES DIAMOND TOOLS, INC.
9722 Jorden Circle
Santa Fe Springs, CA 90670
(310) 802-1003
FAX: (310) 944-3835

LUCAS-MILHAUPT, INC., A HANDY & HARMAN COMPANY
5656 S. Pennsylvania Avenue
Cudahy, WI 53110
(414) 769-6000
FAX: (414) 769-1093

LYALL'S LABORS LTD.
1305 Summerset
Indianola, IA 50125
(515) 961-0106

M.BRAUN, INC.
2 Centennial Drive, Unit 4F
Peabody, MA 01960
(508) 531-6217
FAX: (508) 531-7245

M.K. MORSE
Post Office Box 8677
Canton, OH 44711
(216) 453-8187
FAX: (216) 453-1111

M.T.C. LTD.
Post Office Box 467
Lockport, NY 14095
(716) 433-7722
FAX: (716) 433-1554

MACHINE TECH, INCORPORATED
2988 East 24th Road
Marseilles, IL 61341
(815) 795-6818
FAX: (815) 795-6535

MACK PRODUCTS COMPANY/OHIO GOGGLES DIVISION
1384 Hird Avenue
Post Office Box 572, Edgewater Branch
Cleveland, OH 44107
(216) 226-5100
FAX: (216) 226-7430

MACTECH — STRESSTECH
Post Office Box 11
Red Wing, MN 55066
(800) 328-1488
FAX: (612) 388-0337

MAGIC TIP/TOTAL PRODUCTS INTERNATIONAL
6953 North West 82nd Avenue
Miami, FL 33166
(305) 373-9009
FAX: (305) 558-8995

MAGNAFLUX
7301 West Ainslie
Harwood Heights, IL 60656
(708) 867-8000
FAX: (708) 867-6833

MAGNATECH LIMITED PARTNERSHIP
Post Office Box 260
East Granby, CT 06026
(203) 653-2573
FAX: (203) 653-0486

MAKITA USA INC.
14930 Northam Street
La Mirada, CA 90638
(714) 522-8088
FAX: (801) 485-6370

MANNINGS USA
53 Abbett Avenue
Morristown, NJ 07960-1365
(800) 447-4473
FAX: (201) 984-5533

MARK-TEX CORPORATION
161 Coolidge Avenue
Engelwood, NJ 07631
(201) 567-4111
FAX: (201) 567-7857

MAROS WELDING (METAL WORKING ARTIST), KEITH
1214 Capitol Drive, Unit 4
Addison, IL 60101
(708) 628-9258
FAX: (708) 628-9471

MATHEY/LELAND INTERNATIONAL, LTD.
Post Office Box 472110
Tulsa, OK 74147
(918) 258-7311
FAX: (918) 251-5200

MCKAY WELDING PRODUCTS
401 Trade Square East
Troy, OH 45373
(513) 332-5705
FAX: (800) 356-4300

MECHAFIN AG
Freilagorstrasse 27
Zurich, CH8047
Switzerland
(41) 4924200
FAX: (41) 4927239

MEDAR, INC.
38700 Grand River Avenue
Farmington Hills, MI 48335
(810) 471-2660
FAX: (810) 615-2971

METABO CORPORATION
1231 Wilson Drive
Westchester, PA 19380
(800) 638-2264
FAX: (800) 638-2261

METAL FORMING MAGAZINE
27027 Chardon Road
Richmond Heights, OH 44143
(216) 585-8800
FAX: (216) 585-3126

METAL MUNCHER/FAB CENTER SALES
Post Office Box 192
Clay Center, KS 67432-0192
(800) 235-6307
FAX: (913) 632-6577

METALWORKS, S.D. HAWKINS
708 Twin View
Rockwall, TX 75087
(214) 701-8113

METOREX INCORPORATED
1900 NE Division Street
Bend, OR 97701
(503) 385-6748
FAX: (503) 385-6750

MG INDUSTRIES GAS PRODUCTS DIVISION
3 Great Valley Parkway
Malvern, PA 19355
(610) 695-7400
FAX: (610) 695-7471

MG INDUSTRIES SYSTEMS DIVISION
W 141 N 9427 Fountain Boulevard
Menomonee Falls, WI 53051
(414) 255-5520
FAX: (414) 255-5170

MG INDUSTRIES WELDING PRODUCTS DIVISION
N94 W14355 Garwin Mace Drive
Menomonee Falls, WI 53051
(414) 255-5520
FAX: (414) 255-5668

MICRO AIR AIR CLNRS BY METAL-FAB INC.
Post Office Box 1138
Wichita, KS 67201
(316) 943-2351
FAX: (316) 943-2717

MID AMERICA CRYOGENICS
7031 Corporate Circle
Indianapolis, IN 46278
(317) 216-7123
FAX: (317) 216-7121

MIDSTATES WIRE
510 South Oak Street
Crawfordsville, IN 47933
317) 362-2200
FAX: (317) 362-4143

MIDWEST ALLOYS & TECHNOLOGY, INC.
2519 Cassens Drive
Fenton, MO 63011
(314) 349-6000
FAX: (314) 349-2240

MILLER AUTOMATION INCORPORATED
1635 West Spencer Street
Appleton, WI 54914
(414) 735-4369
FAX: (414) 735-4003

MILLER ELECTRIC MANUFACTURING COMPANY
1635 West Spencer Street
Appleton, WI 54914
(414) 734-9821
FAX: (414) 735-4033

MILLER THERMAL INCORPORATED
N67 Communications Drive
Appleton, WI 54195
(414) 731-6884
FAX: (414) 734-2160

MILWAUKEE AREA TECHNICAL COLLEGE
700 West State Street
Milwaukee, WI 53233-1443
(414) 297-6315
FAX: (414) 297-6711

MILWAUKEE ELECTRIC TOOL CORP.
13135 West Lisbon Road
Brookfield, WI 53005
(414) 781-3600
FAX: (414) 783-8555

MINNESOTA VALLEY ENGINEERING
407 7th Street North West
New Prague, MN 56071
(612) 758-4400
FAX: (612) 758-8225

MITSUBISHI MATERIALS U S A CORPORATION
7211 Patterson Drive
Garden Grove, CA 92641
(800) 621-4486
FAX: (714) 898-2924

MITTLER SUPPLY INC.
3607 South Main Street
South Bend, IN 46634-1676
(219) 291-5100
FAX: (219) 291-7507

MK PRODUCTS, INC.
16882 Armstrong Avenue
Irvine, CA 92714
(800) 787-9707
FAX: (800) 373-3329

MMM METALWORKING MACHINERY MAILER
29501 Greenfield Road
Southfield, MI 48076
(800) 966-8233
FAX: (810) 552-0466

MODERN APPLICATION NEWS
2504 North Tamiami Trail
Nokomis, FL 34275-3842
(813) 966-9521
FAX: (813) 966-2590

MODULAR VISION SYSTEMS
8133 Leesburg Pike
Vienna, VA 22182
(514) 333-0140
FAX: (514) 333-8636

MOORE INDUSTRIAL HARDWARE
77 Circle Freeway Drive
Cincinnati, OH 45246
(800) 543-1677
FAX: (513) 870-9771

MOTOMAN, INC.
805 Liberty Lane
West Carrollton, OH 45449
(513) 847-3214
FAX: (513) 847-6277

MQS INSPECTION INC.
2301 Arthur Avenue
Elk Grove Village, IL 60007
(800) 638-5227
FAX: (708) 981-9396

MSA
Post Office Box 426
Pittsburgh, PA 15230
(800) 672-2222

MUBEA MACHINERY AND SYSTEMS, INC.
8200 Dixie Highway
Florence, KY 41042
(606) 525-6499
FAX: (606) 525-0078

MVSI
8133 Leesburg Pike
Vienna, VA 22182
(514) 333-0140
FAX: (514) 333-8636

N. A. TECHNOLOGIES CO.
1317 Washington Street, Suite #1
Golden, CO 80401
(303) 279-7942
FAX: (303) 279-5286

N.L.F. PROTECTIVE PRODUCTS
3131 Cedar Cross Court
Dubuque, IA 52003
(319) 582-6488
FAX: (319) 582-5570

NALTEX
220 East Saint Elmo
Austin, TX 78745-1218
(512) 447-7000
FAX: (512) 447-7444

NATIONAL EXCELLENCE IN MATERIALS JOINING (NEMJ)
EWI 1100 Kinnear Road
Columbus, OH 43212
(614) 486-9400
FAX: (614) 486-9528

NATIONAL STANDARD
1618 Terminal Road
Niles, MI 49120
(616) 683-8100
FAX: (616) 683-6249

NATIONAL TORCH TIP CO., INC.
50 Freeport Road
Pittsburgh, PA 15215
(412) 781-4200
FAX: (412) 781-1075

NATIONAL WELDING ALLOYS
1600 South Canal Street
Pittsburgh, PA 15215
(412) 781-4255
FAX: (412) 781-4377

NATTCO PRODUCTS-AN NTT COMPANY
50 Freeport Road
Pittsburgh, PA 15215
(412) 781-4200
FAX: (412) 781-1075

NAVY JOINING CENTER
1100 Kinnear Road
Columbus, OH 43212
(614) 486-9423
FAX: (614) 486-9528

NEDERMAN, INC.
6100 Hix Road
Westland, MI 48185
(313) 729-3344
FAX: (313) 729-3358

NIPPERT COMPANY, THE
801 Pittsburgh Drive
Delaware, OH 43081
(614) 363-1981
FAX: (614) 363-3847

NISSEN CO., J. P.
Post Office Box 339
Glenside, PA 19038
(215) 886-2025
FAX: (215) 886-0707

NITTO KOHKI U.S.A., INC.
4525 Turnberry Drive
Hanover Park, IL 60103
(708) 924-9393
FAX: (706) 924-0303

NORRIS CYLINDER COMPANY
Post Office Box 7486
Longview, TX 75607
(800) 527-8418
FAX: (903) 237-7654

NORTH AMERICAN SALES DISTRIBUTION CENTER,INC. (NASDC)
2313 North Eastman Road
Longview, TX 75605
(800) 524-4188
FAX: (903) 753-7223

NORTON COMPANY
Box 15008
Worcester, MA 01615-0008
(508) 795-5000
FAX: (508) 795-5741

NU-TECSYS CORPORATION
90 Noll Street
Waukegan, IL 60085
(708) 662-8500
FAX: (708) 662-9019

NUPRO COMPANY
4800 East 345th Street
Willoughby, OH 44094
(216) 951-7100
FAX: (216) 951-4872

OCIM WELDING PRODUCTS S.R.L.
Via Benaco 3
S. Giuliano, Milanese (MI), 20098
Italy
(39) 29880320
FAX: (39) 298281773

OERLIKON OFFSHORE
Hayes End Road
Hayes, Middlesex, UB4 8EF
United Kingdom
(44) 01815738371
FAX: (44) 01818488529

OETIKER, INCORPORATED
3305 Wilson Street
Marlete, MI 48453
(517) 635-3621
FAX: (517) 635-2157

OGDEN ENGINEERING CORPORATION
372 West Division Street
Schereville, IN 46375
(219) 322-5252
FAX: (219) 865-1825

OHIO STATE UNIVERSITY/WELDING ENGINEERING, THE
1971 Neil Avenue
Columbus, OH 43210
(614) 292-6841
FAX: (614) 292-6842

OLYMPUS AMERICA INCORPORATED
Two Corporate Center Drive
Melville, NY 11747
(516) 844-5000
FAX: (516) 488-3973

ONAN CORPORATION
1400 73rd Ave North East
Minneapolis, MN 55432
(612) 574-5000
FAX: (612) 574-8289

OPTREL AG
Industriestrasse 2
Wattwil, CH 9630
Switzerland
(41) 71-9871011
FAX: (41) 71-9872104

OSRAM SYLVANIA INC.
Hawes Street
Towanda, PA 18848
(717) 268-5000
FAX: (717) 268-5323

OTC-DAIHEN, INC.
5311 W. T. Harris Boulevard West
Charlotte, NC 28269
(704) 597-8240
FAX: (704) 333-9790

OTTO TOOL CO. DIV. OF ALSANA
3921 Sandstone Drive
El Dorado Hills, CA 95762
(916) 638-0202
FAX: (916) 939-0912

OXO WELDING EQUIPMENT
114 Oak Street
New Lenox, IL 60451
(815) 485-8400
FAX: (815) 485-5280

OXYGEN GENERATING SYSTEMS, INC. (OGSI)
2221 Niagara Falls Boulevard
Niagara Falls, NY 14304
(716) 731-1455
FAX: (716) 731-1358

P.B.J. ENTERPRISES
N93 W29194 Woodchuck Way
Colgate, WI 53017
(414) 538-1495

PAC*MIG, INC.
Post Office Box 2174
Wichita, KS 67201-2174
(316) 269-3040
FAX: (316) 269-2404

PANAMETRICS, INC.
221 Crescent Street
Waltham, MA 02154
(617) 899-2719
FAX: (617) 899-1552

PANASONIC FACTORY AUTOMATION CO.
9377 West Grand Avenue
Franklin Park, IL 60131
(708) 288-4577
FAX: (708) 288-4430

PANDJIRIS INCORPORATED
5151 Northrup Avenue
Saint Louis, MO 63110
(314) 776-6893
FAX: (314) 776-8763

PANGBORN CORPORATION
Pangborn Blvd
Hagerstown, MD 21740
(301) 739-3500
FAX: (301) 739-2279

PATON WELDING INSTITUTE
11 Bozhenko str.
Kiev, 252650
Ukraine
(7) 4466330
FAX: (7) 2680486

PEARL ABRASIVE COMPANY
6210 South Garfield Avenue
Commerce, CA 90040
(310) 927-5561
FAX: (310) 928-3857

PEDDINGHAUS CORPORATION
300 North Washington Avenue
Bradley, IL 60915
(815) 937-3800
FAX: (815) 937-4003

PENNSYLVANIA COLLEGE OF TECHNOLOGY
One College Avenue
Williamsport, PA 17701
(717) 326-3761
FAX: (717) 327-4503

PERMADUR INDUSTRIES, INC.
47 Old Camplain Road
Somerville, NJ 08876
(908) 526-3888
FAX: (908) 707-1796

PFERD, INC.
30 Jytek Drive
Leominster, MA 01453
(508) 840-6420
FAX: (508) 840-6421

PHOENIX PRODUCTS COMPANY, INC.
6161 North 64th Street
Milwaukee, WI 53218
(414) 438-1200
FAX: (414) 438-0213

PILLAR/CYCLE-DYNE
N92 W15800 Megal Drive
Menomonee Falls, WI 53051
(800) 558-7733
FAX: (414) 255-0359

PIRANHA-MEGA MANUFACTURING INCORPORATED
401 South Washington
Hutchinson, KS 67501
(316) 663-1127
FAX: (316) 663-6012

PLYMOVENT CORPORATION
375 Raritan Center Parkway
Edison, NJ 08837
(908) 417-0808
FAX: (908) 417-1818

POLYMET CORPORATION
10073 Commerce Park Drive
Cincinnati, OH 45246
(513) 874-3586
FAX: (513) 874-2880

POSTLE INDUSTRIES
5349 West 161st Street
Cleveland, OH 44142
(216) 265-9000
FAX: (216) 265-9030

POWCON INCORPORATED
8123 Miralani Drive
San Diego, CA 92126
(619) 578-8580
FAX: (619) 621-6301

PRAXAIR SPECIALTY POWDERS
1555 Main Street
Indianapolis, IN 46224
(317) 240-2186
FAX: (317) 240-2225

PRAXAIR, INC.
39 Old Ridgebury Road
Danbury, CT 06810-5113
(716) 879-4077
FAX: (716) 879-2015

PRINCE & IZANT COMPANY
12333 Plaza Drive
Cleveland, OH 44130
(216) 362-7000
FAX: (216) 362-7456

PROCESS EQUIPMENT COMPANY
6555 South State Route 202
Tipp City, OH 45371
(513) 667-4451
FAX: (513) 667-9322

PROCESS WELDING SYSTEMS, INC.
138 Space Park Drive
Nashville, TN 37211
(615) 331-7766
FAX: (615) 331-8822

PRODUCTION MACHINERY, INC.
9000 Yellow Brick Road
Baltimore, MD 21237
(410) 574-2110
FAX: (410) 574-4790

PRODUCTS UNLIMITED
1801 Westwood Drive
Sterling, IL 61081
(815) 626-0300
FAX: (815) 626-8637

PROFAX
Post Office Box 898
Pearland, TX 77588
(713) 485-6258
FAX: (713) 485-8030

PROJECT TOOL & DIE, INC.
6955 Danyeur Road
Redding, CA 96001
(916) 243-8903
FAX: (916) 243-8914

PROTECTIVE METAL ALLOYS, INCORPORATED
8726 Production Avenue
San Diego, CA 92121
(800) 762-9237
FAX: (619) 271-1790

PROTEM ENGINEERING CORPORATION
25570 Rye Canyon Road, Unit L
Valencia, CA 91355
(800) 258-0133
FAX: (805) 294-1041

PROTEUS INDUSTRIES INC.
340 Pioneer Way
Mountain View, CA 94041
(415) 964-4163
FAX: (415) 965-9355

QUALITY CRYOGENICS INCORPORATED
Post Office Box 724
Jasper, GA 30143
(706) 692-6167
FAX: (706) 692-6350

QUEEN CYLINDER COMPANY
239 Lafayette Road
London, OH 43140
(800) 255-2957
FAX: (614) 852-5449

RACAL HEALTH & SAFETY, INC.
7305 Executive Way
Frederick, MD 21701
(301) 695-8200
FAX: (301) 695-4413

RAMSTUD [USA] INC.
400 Technology Court, Suite C
Smyrna, GA 30082
(770) 333-9393
FAX: (770) 333-9479

RANSOME COMPANY
Post Office Box 3047
Houston, TX 77253
(713) 868-0647
FAX: (713) 868-0649

RED-D-ARC INCORPORATED
1668 Jaggie Fox Way
Lexington, KY 40511
(606) 259-2828
FAX: (606) 259-1382

REGO PRODUCTS/ECII
Highway 100
Elon College, NC 27244
(910) 449-7707
FAX: (910) 449-6594

RESISTANCE WELDER MANUFACTURERS' ASSOCIATION (RWMA)
1900 Arch Street
Philadelphia, PA 19103-1498
(215) 564-3484
FAX: (215) 963-9785

REVCO INDUSTRIES (BLACK STALLION)
3110 Harcourt Street
Rancho Dominguez, CA 90224
(800) 321-7515
FAX: (310) 638-5604

REX-CUT PRODUCTS, INC.
960 Airport Road
Fall River, MA 02720
(800) 225-8182
FAX: (800) 638-8501

REXARC INTERNATIONAL, INC.
35 East Third Street
Post Office Box 7
West Alexandria, OH 45381
(513) 839-4604
FAX: (513) 839-5897

RICHARD PRAZEN
11577 South Lamptonview
Salt Lake, UT 84065
(801) 328-0249
FAX: (801) 359-3728

ROBERTS-GORDON, INCORPORATED
Post Office Box 44
Buffalo, NY 14240-0044
(716) 852-4400
FAX: (716) 852-0854

ROBINSON TECHNICAL PRODUCTS MIDWEST
1021 Maryland Avenue
Dolton, IL 60419
(708) 841-2550
FAX: (708) 841-8335

ROBOTRON
21300 Eight Mile Road West
Southfield, MI 48086-5090
(810) 350-1444
FAX: (810) 356-3989

ROCKFORD INDUSTRIAL WELDING SUPPLY, INC.
2935 Eastrock Drive
Rockford, IL 61125
(815) 226-1900
FAX: (815) 226-5617

ROCKWELL LASER INDUSTRIES
Post Office Box 43010
Cincinnati, OH 45243
(800) 945-2737
FAX: (513) 271-1598

ROLLED ALLOYS
125 West Sterns Road
Temperance, MI 48182
(800) 521-0332
FAX: (313) 847-3915

S.I.A.T. SPA SECTION PITTARC
Via Facini N.16
Gemona Del Friuli — Udine, 33010
Italy
(39) 43297022
FAX: (39) 432526010

SAFTCART
Highway 49 South
Clarksdale, MS 38614
(601) 627-3438
FAX: (601) 627-1640

SANDVIK STEEL COMPANY
Post Office Box 1220
Scranton, PA 18501
(717) 587-5191
FAX: (717) 586-8183

SCHWEISSEN & SCHNEIDEN 97/ESSEN WELDING FAIR 97
150 North Michigan Avenue
Chicago, IL 60601
(312) 781-5180
FAX: (312) 781-5188

SCIAKY, INCORPORATED
4915 West 67th Street
Chicago, IL 60638
(708) 594-3800
FAX: (708) 594-9213

SCIENTIFIC TECHNOLOGIES, INC./STI
6550 Dumbarton Circle
Fremont, CA 94555-3611
(510) 608-3400
FAX: (510) 644-1440

SCM METAL PRODUCTS, INC.
2601 Weck Drive
Research Triangle Park, NC 27709
(919) 544-8090
FAX: (919) 544-7996

SCM TECHNOLOGIES
PO Box 1000
Tilbury, ONT., N0P 2L0
Canada
(519) 682-1313
FAX: (519) 682-3630

SCOTCHMAN INDUSTRIES, INCORPORATED
180 East Highway 14
Philip, SD 57567
(605) 859-2542
FAX: (605) 859-2499

SCREENPRO
1219 West Eleventh Street
Los Angeles, CA 90015
(213) 747-7799

SCULPTURE BY NIEMI
83 Ambrogio Drive, Unit C
Gurnee, IL 60031
(708) 249-8480
FAX: (708) 336-5608

SEAL SEAT COMPANY
1200 Monterrey Pass Road
Monterrey Park, CA 91754
(213) 269-1311
FAX: (213) 269-0529

SECKLER STUDIO
1208 Paseo Norte
Box 1100-301
Taos, NM 87571
(505) 751-0320
FAX: (505) 751-0321

SELECTRODE INDUSTRIES, INC.
230 Broadway
Huntington Station, NY 11746
(516) 547-5470
FAX: (516) 547-5475

SELLSTROM MANUFACTURING COMPANY
Post Office Box 355
Palatine, IL 60078
(800) 323-7402
FAX: (708) 358-8564

SERVO-ROBOT INC.
1380 Graham Bell Street
Boucherville, QUE, J4B 6H5
Canada
(514) 655-4223
FAX: (514) 655-4963

SHERRITT INCORPORATED
9405 50th Street
Edmonton, ALB, T6B 2T4
Canada
(403) 440-7905
FAX: (403) 440-7948

SHERWIN, INCORPORATED
5530 Borwick Avenue
South Gate, CA 90280
(310) 861-6324
FAX: (310) 923-8370

SHOP DATA SYSTEMS, INC.
712 East Walnut Street
Garland, TX 75040
(214) 494-2719
FAX: (214) 272-7062

SIGMATEK CORPORATION
13333 Bel-Red Road, No. 100
Bellevue, WA 98005
(206) 649-9021
FAX: (206) 643-8008

SIMPLEX/DIV OF TEMPLETON KENLEY & CO., INC.
2525 Gardner Road
Broadview, IL 60153
(708) 865-1500
FAX: (708) 865-0894

SKIL POWER TOOLS
4300 West Peterson Avenue
Chicago, IL 60646
(312) 481-3830
FAX: (312) 481-3684

SMITH EQUIPMENT MANUFACTURING COMPANY LLC
2601 Lockheed Avenue
Watertown, SD 57201
(605) 882-3200
FAX: (605) 882-2100

SOLAR FLUX (GOLDEN EMPIRE CORP)
Post Office Box 2129
Morehead City, NC 28557
(919) 808-3511
FAX: (919) 808-3711

SOYER GMBH, HEINZ
Inninger Strasse 14
Etterschlag, D-8031
Germany
(49) 008153807
FAX: (49) 0081538030

SPARKY ABRASIVES
4811 Dusharme Drive
Brooklyn Center, MN 55429
(612) 535-2403
FAX: (612) 535-2708

SPATZ/PRATT & LAMBERT UNITED INC.
Post Office Box 2153
Wichita, KS 67201
(800) 325-2661
FAX: (316) 733-4420

SPECIAL WELDING SERVICES, INC.
5225 Davis Road
Saginaw, MI,48604
(517) 791-4595
FAX: (517) 791-1339

SPECTRO ANALYTICAL INSTRUMENTS, INC.
160 Authority Drive
Fitchburg, MA 01420
(508) 342-3400
FAX: (508) 342-8695

SPECTRONICS CORPORATION
956 Brush Hollow Road
Westbury, NY 11590
(800) 274-8888
FAX: (800) 491-6868

SQWINCHER, THE ACTIVITY DRINK
Post Office Box 8250
Columbus, MS 39705
(800) 654-1920
FAX: (601) 327-7821

STAINLESS STEEL SERVICES, INC.
4325 North 3rd Street
Philadelphia, PA 19140
(800) 553-2568
FAX: (215) 457-3019

STANCO MANUFACTURING, INC.
Post Office Box 1148
2004 West Main Street
Atlanta, TX 75551
(903) 796-7936
FAX: (903) 796-9237

STANDARD ABRASIVES
9351 Deering Avenue
Chatsworth, CA 91311
(818) 718-7070
FAX: (818) 718-1171

STAVELEY INSTRUMENTS, INC.
421 North Quay Street
Kennewick, WA 99336
(509) 735-7550
FAX: (509) 735-4672

STEINER INDUSTRIES
5801 North Tripp Avenue
Chicago, IL 60646-6013
(800) 621-4515
FAX: (312) 588-3450

STEL DI A.M. MAZZUCCO
700 East Elm Avenue
La Grange, IL 60525
(708) 579-5893
FAX: (708) 579-5884

STELLITE COATINGS
1201 Eisenhower Drive North
Goshen, IN 46526
(800) 235-9353
FAX: (219) 534-3417

STOODY COMPANY
5557 Nashville Road
Bowling Green, KY 42101
(800) 227-9333
FAX: (800) 243-4322

STORE FIXTURES UNLIMITED
121 Yellowstone Road
Plymouth Meeting, PA 19462
(610) 828-6470
FAX: (610) 828-6455

STUD WELDING ASSOCIATES
41515 Schaden Road
Elyria, OH 44035
(216) 324-3042
FAX: (216) 324-3301

SUHNER INDUSTRIAL PRODUCTS
411 South/Suhner Drive
Post Office Box 1234
Rome, GA 30162
(706) 235-8046
FAX: (706) 235-8045

SULZER METCO
1101 Prospect Avenue
Westbury, NY 11590
(516) 338-2460
FAX: (516) 338-2414

SUMNER MANUFACTURING COMPANY INCORPORATED
7514 Alabonson Road
Houston, TX 77088
(713) 999-6900
FAX: (713) 999-6966

SUPERIOR FLUX & MANUFACTURING COMPANY
95 Alpha Park
Cleveland, OH 44143
(216) 461-3315
FAX: (216) 461-6846

SUPERIOR PRODUCTS, INC.
3786 Ridge Road
Cleveland, OH 44144
(216) 651-9400
FAX: (216) 651-4071

SWAGELOK COMPANY
31400 Aurora Road
Solon, OH 44139
(216) 349-5934
FAX: (216) 349-5843

SYMINGTON & CO., INC., C.H.
77 East Wilson Bridge Road
Worthington, OH 43085
(614) 848-4821
FAX: (614) 848-4861

SYNTAX SOFTWARE CORP.
616 East Southern Avenue, No. 103
Mesa, AZ 85204
(602) 844-3633
FAX: (602) 844-3833

SYSTEMATICS, INC.
Post Office Box 2429
West Chester, PA 19380
(610) 696-9040
FAX: (610) 430-8714

T. C. SERVICE CO.
761 A Beta Drive
Cleveland, OH 44143
(216) 461-1320
FAX: (216) 461-3714

TAFA INCORPORATED
146 Pembroke Road
Concord, NH 03301
(603) 224-9585
FAX: (603) 225-4342

TAIWAN PLASMA CORPORATION
No. 48-12 Kuo Hsi Road
Kaohsiung Hsien
Taiwan R.O.C.
(886) 077876722
FAX: (886) 077876756

TAYLOR-WHARTON
1011 Mumma Road
Camp Hill, PA 17001-8316
(800) 898-2657
FAX: (334) 443-2250

TEC TORCH — ELDTEC
Post Office Box 1870
San Marcos, CA 92079
(619) 744-6401
FAX: (619) 747-2121

TECHALLOY COMPANY, INC. — BALTIMORE WELDING DIVISION
2310 Chesapeake Avenue
Baltimore, MD 21222-4098
(410) 633-9300
FAX: (410) 633-2033

TECHNICAL MATERIALS INC.
5 Wellington Road
Lincoln, RI 02865
(401) 333-1700
FAX: (401) 333-2848

TECNAR AUTOMATION LTD.
3502 First Street
St Hubert, Quebec, J3Y 8Y5
Canada
(514) 443-5335
FAX: (514) 443-4880

TELEDYNE ADVANCED MATERIALS
7300 Highway 20 West
Huntsville, AL 35806
(205) 837-1311
FAX: (205) 722-2284

TEMPIL, AIR LIQUIDE AMERICA CORP.
2901 Hamilton Blvd.
South Plainfield, NJ 07080
(908) 757-8300
FAX: (908) 757-9273

TEXAS STATE TECHNICAL COLLEGE WELDING DEPARTMENT
3801 Campus Drive
Waco, TX 76705
(817) 867-4884
FAX: (817) 867-3550

THERMACUT
Post Office Box 601
Windsor, VT 05089
(603) 542-6715
FAX: (603) 542-6732

THERMADYNE INDUSTRIES
101 South Hanley Road
St Louis, MO 63105
(314) 721-5573
FAX: (314) 721-4822

THERMADYNE INTERNATIONAL
2220 Wyecroft Road
Oakville, ONT, L6L 5V6
Canada
(905) 827-9777
FAX: (905) 827-9797

THERMADYNE WELDING PRODUCTS CANADA, LTD.
2220 Wyecroft Road
Oakville, ONT, L6L 5V6
Canada
(905) 827-1111
FAX: (905) 827-3648

THERMAL DYNAMICS
Industrial Park #2
West Lebanon, NH 03784
(800) 752-7621
FAX: (603) 298-5720

THERMCO INSTRUMENT CORPORATION
Post Office Box 309
Laporte, IN 46352
(219) 362-6258
FAX: (219) 324-3568

THYSSEN WELDING
365 Village Drive
Carol Stream, IL 60188-1828
(708) 682-4112
FAX: (708) 682-5904

TILLMAN & COMPANY, JOHN
2555 South Dominguez Hills Drive
Dominguez Hills, CA 90220
(310) 764-0110
FAX: (310) 764-0104

TOMCO EQUIPMENT COMPANY
3340 Rosebud Road
Loganville, GA 30249
(404) 979-8000
FAX: (404) 985-9179

TORIT-DONALDSON COMPANY
1400 West 94th Street
Minneapolis, MN 55431
(800) 365-1331
FAX: (612) 887-3377

TRADER S.P.A.
Via Ponte Sul Torre Z.I.
Remanzacco (UD), 33047
Italy
(39) 432667265
FAX: (39) 432667208

TRAFIMET USA, INC.
700 East Elm Avenue, Unit B
La Grange, IL 60525
(708) 579-5893
FAX: (708) 579-5884

TREGASKISS LTD.
2570 North Talbot Road
Oldcastle, ONT, N0R 1L0
Canada
(519) 737-6966
FAX: (519) 737-1530

TREXIM
25 Walpole Park South
Walpole, MA 02081
(508) 668-5149
FAX: (508) 668-4640

TRI TOOL INC.
3806 Security Park Drive
Rancho Cordova, CA 95742
(916) 351-0144
FAX: (916) 351-0372

TRI-STATE INDUSTRIES, INCORPORATED
5137 Indianapolis Boulevard
East Chicago, IN 46312
(219) 392-3520
FAX: (219) 392-3530

TRIPLE CROWN PRODUCTS
814 Ela Avenue
Waterford, WI 53185
(414) 534-7878
FAX: (414) 534-7879

TRUMPF INCORPORATED
Farmington Industrial Park
Farmington, CT 06032
(860) 677-9741
FAX: (860) 678-1704

TRW NELSON STUD WELDING DIV.
7900 West Ridge Road
Elyria, OH 44036-2019
(216) 329-0400
FAX: (216) 329-0526

TWECO/ARCAIR
4200 West Harry
Wichita, KS 67277
(800) 231-9353
FAX: (800) 633-9513

UNI-HYDRO, INCORPORATED
Highway Junction 4 & 7
Post Office Box 128
Cosmos, MN 56228
(612) 877-7284
FAX: (612) 877-7204

UNIPUNCH PRODUCTS, INC.
370 Babcock Street
Buffalo, NY 14206
(716) 825-7960
FAX: (716) 825-0581

UNISOURCE MANUFACTURING INC.
2668 North East Riverside Way
Portland, OR 97211
(503) 281-3781
FAX: (503) 287-4818

UNITED ABRASIVES, INCORPORATED
Route 66
Willimantic, CT 06226
(203) 456-7131
FAX: (203) 456-8341

UNITED AIR SPECIALISTS, INC.
4440 Creek Road
Cincinnati, OH 45242
(513) 891-0400
FAX: (513) 891-4882

UNITED PROARC CORPORATION
No.3-1 Kung Yei 10th Road
Peng Chen Ind. Park
Tao Yuan Hsien,
Taiwan R.O.C.
(886) 4698970
FAX: (886) 4694499

UNITED STATES WELDING CORPORATION
3579 Highway 50 East, 104
Carson City, NV 89701
(702) 883-7878
FAX: (702) 883-7776

UNITEK MIYACHI CORPORATION
1820 South Myrtle Avenue
Monrovia, CA 91017
(818) 303-5676
FAX: (818) 358-8048

UNITROL ELECTRONICS INCORPORATED
702 Landwehr Road
Northbrook, IL 60062-2310
(847) 480-0115
FAX: (847) 480-0932

UNIVERSAL FLOW MONITORS, INCORPORATED
1755 East Nine Mile Road
Post Office Box 249
Hazel Park, MI 48030
(810) 542-9635
FAX: (810) 398-4274

UNIWELD PRODUCTS, INC.
2850 Ravenswood Road
Fort Lauderdale, FL 33312
(305) 584-2000
FAX: (305) 587-0109

UTP WELDING MATERIALS
10401 Greenbough Drive
Stafford, TX 77477
(713) 499-1212
FAX: (713) 499-4347

UVEX SAFETY, INCORPORATED
10 Thurber Boulevard
Smithfield, RI 02917
(401) 232-1200
FAX: (401) 232-1830

VERNON TOOL COMPANY
503 Jones Road
Oceanside, CA 92054
(619) 433-5860
FAX: (619) 757-2233

VICTOR EQUIPMENT COMPANY
Post Office Box 1007
Denton, TX 76202-1007
(800) 426-1888
FAX: (800) 535-0557

VISTA EQUIPMENT COMPANY, INC.
Post Office Box 472
Crawfordsville, IN 47933
(317) 362-2060
FAX: (317) 362-3282

VOCATIONAL INDUSTRIAL CLUBS OF AMERICA, INC.
Post Office Box 3000
Leesburg, VA 22075
(703) 777-8810
FAX: (703) 777-8999

VOGEL TOOL & DIE CORPORATION
1825 North 32nd Avenue
Stone Park, IL 60165
(708) 345-0160
FAX: (708) 345-0535

WACHS COMPANY, E.H.
100 Shepard Street
Wheeling, IL 60090
(708) 537-8800
FAX: (708) 520-1147

WALHONDE TOOLS INC.
Route 7, Box 228-A
Charleston, WV 25309
(304) 756-3796
FAX: (304) 756-3834

WALL COLMONOY CORPORATION
30261 Stephenson Highway
Madison Heights, MI 48071-1650
(810) 585-6400
FAX: (810) 585-7960

WALTER, INCORPORATED, J.
141 Locust Street
Hartford, CT 06114-1504
(203) 724-0321
FAX: (203) 560-7300

WASHINGTON ALLOY COMPANY
9809 160th Street East
Puyallup, WA 98373
(800) 558-5825
FAX: (206) 841-0411

WATER-JEL TECHNOLOGIES
243 Veterans Boulevard
Carlstadt, NJ 07072
(800) 275-3433
FAX: (201) 507-8325

WATSON COATINGS INCORPORATED
Post Office Box 35067
Saint Louis, MO 63135
(314) 521-2000
FAX: (314) 521-6582

WATTEREDGE-UNIFLEX, INC.
567 Miller Road
Avon Lake, OH 44012
(216) 871-9215
FAX: (216) 933-8248

WEARTECH INTERNATIONAL, INC.
13032 Park Street
Santa Fe Springs, CA 90670
(310) 698-7847
FAX: (310) 945-5664

WEGENER NORTH AMERICA, INC.
231 Frontage Road, Unit 12
Burr Ridge, IL 60521
(708) 789-0990
FAX: (708) 789-1380

WEILER BRUSH COMPANY, INC.
One Wildwood Drive
Cresco, PA 18326
(717) 595-7495
FAX: (717) 595-2002

WELCH ALLYN, INC — IMAGING PRODUCTS DIVISION
4619 Jordon Road
Skaneateles Falls, NY 13153
(315) 685-4189
FAX: (315) 685-7905

WELD ENGINEERING CO., INC.
34 Fruit Street
Shrewsbury, MA 01545
(508) 842-2224
FAX: (508) 842-3893

WELD MOLD COMPANY
750 Rickett Road
Post Office Box 298
Brighton, MI 48116
(810) 229-9521
FAX: (810) 229-9580

WELD SYSTEMS INTERNATIONAL INCORPORATED
506 Bullis Road
West Seneca, NY 14224
(716) 834-9662
FAX: (416) 674-7139

WELD TECHNOLOGY INDUSTRIES, L.L.C.
2525 Park Street
Muskegon, MI 49444
(616) 737-6444
FAX: (616) 733-2131

WELD-AID PRODUCTS
14650 Dequindre Road
Detroit, MI 48212
(313) 883-6977
FAX: (313) 883-4930

WELD-MOTION INC.
712 Valley Road
Menasha, WI 54952
(414) 739-7861
FAX: (414) 739-7862

WELDAS COMPANY
128 Seaboard Lane
Franklin, TN 37067
(615) 377-4722
FAX: (615) 377-3635

WELDCOA
120 North Railroad Avenue
Northlake, IL 60164
(708) 531-1200
FAX: (708) 531-1222

WELDCOMPUTER CORPORATION
105 Jordan Road
Troy, NY 12180
(518) 283-2897
FAX: (518) 283-2907

WELDCRAFT PRODUCTS, INC.
119 East Graham Place
Burbank, CA 91502
(818) 846-8181
FAX: (818) 846-4257

WELDING CONSULTANTS, INC.
889 North 22nd Street
Columbus, OH 43219-2426
(614) 258-7018
FAX: (614) 258-1996

WELDING DESIGN & FABRICATION
1100 Superior Avenue
Cleveland, OH 44114
(216) 696-7000
FAX: (216) 696-7658

WELDING INSTITUTE (TWI), THE
Abington Hall,
Abington,
Cambridge,CB1 6AL
United Kingdom
(44) 1223891162
FAX: (44) 1223892588

WELDING NOZZLE INTERNATIONAL
1560 12th Street East
Palmetto, FL 34221
(800) 964-9645
FAX: (941) 729-4518

WELDING ROD FACTORY, THE
2301 Duss Avenue, Building 11
Ambridge, PA 15003
(412) 378-7411
FAX: (412) 378-7892

WELDIT, INC.
1700 S. Canal St.
Pitsburgh, PA 15215
(412) 781-4200
FAX: (412) 781-1075

WELDLINE AUTOMATION, INC.
1201 North Las Brisas
Anaheim, CA 92806
(714) 237-7730
FAX: (714) 237-7734

WELDLOGIC INCORPORATED
2550 Azurite Circle
Newbury Park, CA 91320
(805) 498-4006
FAX: (805) 498-1761

WELDMATIC INC.
Post Office Box 1322
Columbus, NE 68602-1322
(402) 564-1808
FAX: (402) 564-1825

WELDREEL INCORPORATED
401 South Jackson Street
El Dorado, AR 71731-0698
(501) 863-5785
FAX: (501) 863-3921

WELDRITE WELDING PRODUCTS, INC.
4239 West 150th Street
Cleveland, OH 44135
(216) 251-4512
FAX: (216) 251-0035

WELDSALE COMPANY
2151 Dreer Street
Philadelphia, PA 19125
(215) 739-7474
FAX: (215) 426-1260

WELDSHIP CORPORATION
225 West 2nd Street
Post Office Box A
Bethlehem, PA 18015
(610) 861-7330
FAX: (610) 861-5175

WELTRONIC/TECHNITRON CORPORATION
150 East St. Charles
Carol Stream, IL 60188
(708) 462-8250
FAX: (708) 462-8259

WESTERN ENTERPRISES
875 Bassett Road
Westlake, OH 44145
(216) 871-2160
FAX: (216) 835-8283

WHITESTONE CORPORATION
RR2, Box 4800
White Stone, VA 22578
(804) 435-6725

WHITEY COMPANY
318 Bishop Road
Highland Heights, OH 44143
(216) 473-1050
FAX: (216) 473-0402

WIKA INSTRUMENT CORPORATION
1000 Wiegand Boulevard
Lawrenceville, GA 30243
(404) 513-8200
FAX: (404) 513-8203

WIKUS INC.
1255 Tonne Road
Elk Grove, IL 60007
(800) 247-2691
FAX: (708) 228-7067

WILLING ARTS, TODD
138 North 11th Street
Saint Charles, IL 60174
(708) 584-6917

WILSON INDUSTRIES, INC.
123 Explorer Street
Pomona, CA 91768
(909) 468-3636
FAX: (909) 468-3640

WILTON CORPORATION
300 South Hicks Road
Palatine, IL 60067
(708) 934-6000
FAX: (708) 934-6730

WING ENTERPRISES INCORPORATED
Post Office Box 3100
Springville, UT 84663-3100
(801) 489-3684
FAX: (801) 489-3685

WINONA MANUFACTURING
50 Freeport Road
Pittsburgh, PA 15215
(412) 781-4200
FAX: (412) 781-1075

WINTER INC. & CO., F.W.
Delaware Ave. & Elm Street
Camden, NJ 08102
(609) 963-7490
FAX: (609) 963-7463

WIRE CRAFTERS INCORPORATED
6208 Strawberry Lane
Louisville, KY 40214
(800) 626-1816
FAX: (502) 361-3857

WIREWAY/HUSKY
Post Office Box 645
Denver, NC 28037
(704) 483-1900
FAX: (704) 483-1911

WIS-CON TOTAL POWER CORPORATION
3409 Democrat Road
Memphis, TN 38118
(901) 365-3600
FAX: (901) 369-4050

WISCONSIN WIRE WORKS INC.
S80 W18878 Apollo Drive
Muskego, WI 53150
(414) 679-8218
FAX: (414) 679-8219

WOODLAND CRYOGENICS, INC.
5322 Woodland Avenue
Philadelphia, PA 19143
(215) 727-0950
FAX: (215) 727-1033

WORLD MACHINERY & SAWS SYSTEM COMPANY
11139 Garvey Avenue
El Monte, CA 91733
(818) 454-1026
FAX: (818) 454-1027

WORTHINGTON CYLINDERS
Post Office Box 128
Citronelle, AL 36522
(205) 866-2400
FAX: (205) 866-7759

YORK SALES COMPANY
1201 Belvidere Street
Waukegan, IL 60085
(708) 662-5206
FAX: (708) 662-2818

ZERO PRODUCTS, A DIVISION OF CLEMCO INDUSTRIES CORP.
One Cable Car Drive
Washington, MO 63090
(314) 239-0300
FAX: (314) 239-0788

This welded sculpture, a flying eagle, was created by Ed Carlson, Glendale, Arizona. Colors are produced by applying heat to the steel with an oxyacetylene torch, developing temper colors and quenching when the desired shade is reached.

Photo courtesy of *Welding Journal*