CHAPTER 2

STEEL

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2.1 METALLOGRAPHY AND HEAT TREATMENT

The great advantage of steel as an engineering material is its versatility, which arises from the fact that its properties can be controlled and changed by heat treatment.[1-3] Thus, if steel is to be formed into some intricate shape, it can be made very soft and ductile by heat treatment; on the other hand, heat treatment can also impart high strength.

The physical and mechanical properties of steel depend on its constitution, that is, the nature, distribution, and amounts of its metallographic constituents as distinct from its chemical composition. The amount and distribution of iron and iron carbide determine the properties, although most plain carbon steels also contain manganese, silicon, phosphorus, sulfur, oxygen, and traces of nitrogen, hydrogen, and other chemical elements such as aluminum and copper. These elements may modify, to a certain extent, the main effects of iron and iron carbide, but the influence of iron carbide always predominates. This is true even of medium-alloy steels, which may contain considerable amounts of nickel, chromium, and molybdenum.

The iron in steel is called ferrite. In pure iron-carbon alloys, the ferrite consists of iron with a trace of carbon in solution, but in steels it may also contain alloying elements such as manganese, silicon, or nickel. The atomic arrangement in crystals of the allotrophic forms of iron is shown in Fig. 2.1.

Cementite, the term for iron carbide in steel, is the form in which carbon appears in steels. It has the formula Fe_3C, and consists of 6.67% carbon and 93.33% iron. Little is known about its properties, except that it is very hard and brittle. As the hardest constituent of plain carbon steel, it scratches glass and feldspar but not quartz. It exhibits about two-thirds the induction of pure iron in a strong magnetic field.

Austenite is the high-temperature phase of steel. Upon cooling, it gives ferrite and cementite. Austenite is a homogeneous phase, consisting of a solid solution of carbon in the γ form of iron. It forms when steel is heated above 790°C. The limiting temperatures for its formation vary with composition and are discussed below. The atomic structure of austenite is that of γ iron, fcc; the atomic spacing varies with the carbon content.

When a plain carbon steel of ~ 0.80% carbon content is cooled slowly from the temperature range at which austenite is stable, ferrite and cementite precipitate together in a characteristically lamellar structure known as pearlite. It is similar in its characteristics to a eutectic structure but, since it is formed from a solid solution rather than from a liquid phase, it is known as a eutectoid structure. At carbon contents above and below 0.80%, pearlite of ~ 0.80% carbon is likewise formed on slow cooling, but excess ferrite or cementite precipitates first, usually as a grain-boundary network, but occasionally also along the cleavage planes of austenite. The excess ferrite or cementite rejected by the cooling austenite is known as a proeutectoid constituent. The carbon content of a slowly cooled steel can be estimated from the relative amounts of pearlite and proeutectoid constituents in the microstructure.

Bainite is a decomposition product of austenite consisting of an aggregate of ferrite and cementite. It forms at temperatures lower than those where very fine pearlite forms and higher than those at which martensite begins to form on cooling. Metallographically, its appearance is feathery if formed

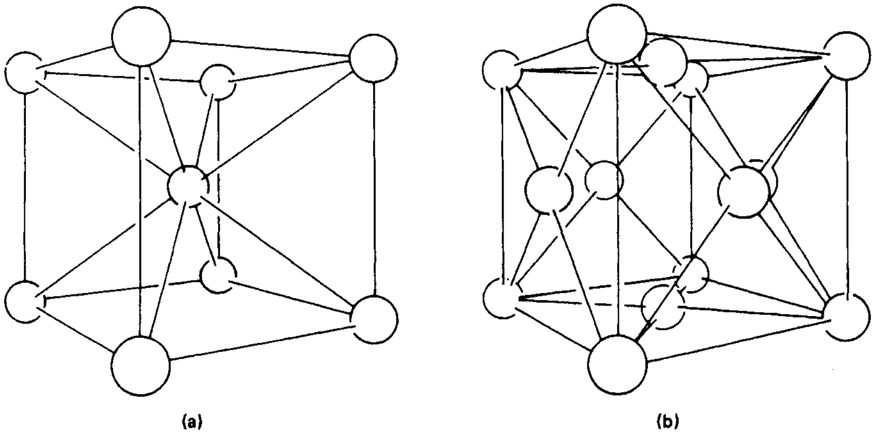
(a) (b)

Fig. 2.1 Crystalline structure of allotropic forms of iron. Each white sphere represents an atom of (*a*) α and δ iron in bcc form, and (*b*) γ iron, in fcc (from Ref. 1).

in the upper part of the temperature range, or acicular (needlelike) and resembling tempered martensite if formed in the lower part.

Martensite in steel is a metastable phase formed by the transformation of austenite below the temperature called the M_s temperature, where martensite begins to form as austenite is cooled continuously. Martensite is an interstitial supersaturated solid solution of carbon in iron with a body-centred tetragonal lattice. Its microstructure is acicular.

2.2 IRON–IRON CARBIDE PHASE DIAGRAM

The iron–iron carbide phase diagram (Fig. 2.2) furnishes a map showing the ranges of compositions and temperatures in which the various phases such as austenite, ferrite, and cementite are present in slowly cooled steels. The diagram covers the temperature range from 600°C to the melting point of iron, and carbon contents from 0 to 5%. In steels and cast irons, carbon can be present either as iron carbide (cementite) or as graphite. Under equilibrium conditions, only graphite is present because iron carbide is unstable with respect to iron and graphite. However, in commercial steels, iron carbide is present instead of graphite. When a steel containing carbon solidifies, the carbon in the steel usually solidifies as iron carbide. Although the iron carbide in a steel can change to graphite and iron when the steel is held at ~ 900°C for several days or weeks, iron carbide in steel under normal conditions is quite stable.

The portion of the iron–iron carbide diagram of interest here is that part extending from 0 to 2.01% carbon. Its application to heat treatment can be illustrated by considering the changes occurring on heating and cooling steels of selected carbon contents.

Iron occurs in two allotropic forms, α or δ (the latter at a very high temperature) and γ (see Fig. 2.1.) The temperatures at which these phase changes occur are known as the critical temperatures, and the boundaries in Fig. 2.2 show how these temperatures are affected by composition. For pure iron, these temperatures are 910°C for the α–γ phase change and 1390° for the γ–δ phase change.

2.2.1 Changes on Heating and Cooling Pure Iron

The only changes occurring on heating or cooling pure iron are the reversible changes at ~910°C from bcc α iron to fcc γ iron and from the fcc δ iron to bcc γ iron at ~1390°C.

2.2.2 Changes on Heating and Cooling Eutectoid Steel

Eutectoid steels are those that contain 0.8% carbon. The diagram shows that at and below 727°C the constituents are α–ferrite and cementite. At 600°C, the α-ferrite may dissolve as much as 0.007% carbon. Up to 727°C, the solubility of carbon in the ferrite increases until, at this temperature, the

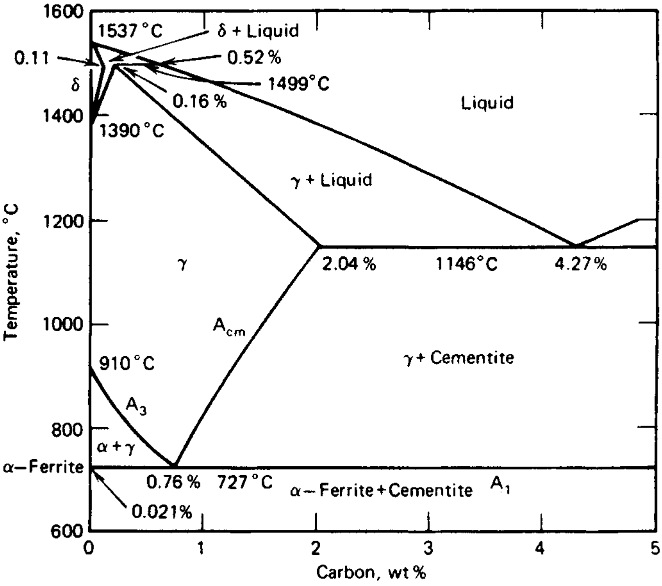

Fig. 2.2 Iron–iron carbide phase diagram (from Ref. 1).

ferrite contains about 0.02% carbon. The phase change on heating an 0.8% carbon steel occurs at 727°C which is designated as A_1, as the eutectoid or lower critical temperature. On heating just above this temperature, all ferrite and cementite transform to austenite, and on slow cooling the reverse change occurs.

When a eutectoid steel is slowly cooled from ~738°C, the ferrite and cementite form in alternate layers of microscopic thickness. Under the microscope at low magnification, this mixture of ferrite and cementite has an appearance similar to that of a pearl and is therefore called pearlite.

2.2.3 Changes on Heating and Cooling Hypoeutectoid Steels

Hypoeutectoid steels are those that contain less carbon than the eutectoid steels. If the steel contains more than 0.02% carbon, the constituents present at and below 727°C are usually ferrite and pearlite; the relative amounts depend on the carbon content. As the carbon content increases, the amount of ferrite decreases and the amount of pearlite increases.

The first phase change on heating, if the steel contains more than 0.02% carbon, occurs at 727°C. On heating just above this temperature, the pearlite changes to austenite. The excess ferrite, called proeutectoid ferrite, remains unchanged. As the temperature rises further above A_1, the austenite dissolves more and more of the surrounding proeutectoid ferrite, becoming lower and lower in carbon content until all the proeutectoid ferrite is dissolved in the austenite, which now has the same average carbon content as the steel.

On slow cooling the reverse changes occur. Ferrite precipitates, generally at the grain boundaries of the austenite, which becomes progressively richer in carbon. Just above A_1, the austenite is substantially of eutectoid composition, 0.8% carbon.

2.2.4 Changes on Heating and Cooling Hypereutectoid Steels

The behavior on heating and cooling hypereutectoid steels (steels containing >0.80% carbon) is similar to that of hypoeutectoid steels, except that the excess constituent is cementite rather than ferrite. Thus, on heating above A_1, the austentie gradually dissolves the excess cementite until at the A_{cm} temperature the proeutectoid cementite has been completely dissolved and austenite of the same carbon content as the steel is formed. Similarly, on cooling below A_{cm}, cementite precipitates and the carbon content of the austenite approaches the eutectoid composition. On cooling below A_1, this eutectoid austenite changes to pearlite and the room-temperature composition is, therefore, pearlite and proeutectoid cementite.

Early iron-carbon equilibrium diagrams indicated a critical temperature at ~768°C. It has since been found that there is no true phase change at this point. However, between ~768 and 790°C there is a gradual magnetic change, since ferrite is magnetic below this range and paramagnetic above it. This change, occurring at what formerly was called the A_2 change, is of little or no significance with regard to the heat treatment of steel.

2.2.5 Effect of Alloys on the Equilibrium Diagram

The iron–carbon diagram may, of course, be profoundly altered by alloying elements, and its application should be limited to plain carbon and low-alloy steels. The most important effects of the alloying elements are that the number of phases that may be in equilibrium is no longer limited to two as in the iron–carbon diagram; the temperature and composition range, with respect to carbon, over which austenite is stable may be increased or reduced; and the eutectoid temperature and composition may change.

Alloying elements either enlarge the austenite field or reduce it. The former include manganese, nickel, cobalt, copper, carbon, and nitrogen and are referred to as austenite formers.

The elements that decrease the extent of the austenite field include chromium, silicon, molybdenum, tungsten, vanadium, tin, niobium, phosphorus, aluminum, and titanium; they are known as ferrite formers.

Manganese and nickel lower the eutectoid temperature, whereas chromium, tungsten, silicon, molybdenum, and titanium generally raise it. All these elements seem to lower the eutectoid carbon content.

2.2.6 Grain Size—Austenite

A significant aspect of the behavior of steels on heating is the grain growth that occurs when the austenite, formed on heating above A_3 or A_{cm}, is heated even higher; A_3 is the upper critical temperature and A_{cm} is the temperature at which cementite begins to form. The austenite, like any metal composed of a solid solution, consists of polygonal grains. As formed at a temperature just above A_3 or A_{cm}, the size of the individual grains is very small but, as the temperature is increased above the critical temperature, the grain sizes increase. The final austenite grain size depends, therefore, on the temperature above the critical temperature to which the steel is heated. The grain size of the austenite has a marked influence on transformation behavior during cooling and on the grain size of the constituents of the final microstructure. Grain growth may be inhibited by carbides that dissolve slowly or by dispersion of nonmetallic inclusions. Hot working refines the coarse grain formed by reheating steel to the relatively high temperatures used in forging or rolling, and the grain size of hot-worked steel is determined largely by the temperature at which the final stage of the hot-working process is carried out. The general effects of austenite grain size on the properties of heat-treated steel are summarized in Table 2.1.

2.2.7 Microscopic-Grain-Size Determination

The microscopic grain size of steel is customarily determined from a polished plane section prepared in such a way as to delineate the grain boundaries. The grain size can be estimated by several methods. The results can be expressed as diameter of average grain in millimeters (reciprocal of the square root of the number of grains per mm^2), number of grains per unit area, number of grains per unit volume, or a micrograin-size number obtained by comparing the microstructure of the sample with a series of standard charts.

2.2.8 Fine- and Coarse-Grain Steels

As mentioned previously, austenite-grain growth may be inhibited by undissolved carbides or nonmetallic inclusions. Steels of this type are commonly referred to as fine-grained steels, whereas steels that are free from grain-growth inhibitors are known as coarse-grained steels.

The general pattern of grain coarsening when steel is heated above the critical temperature is as follows: Coarse-grained steel coarsens gradually and consistently as the temperature is increased, whereas fine-grained steel coarsens only slightly, if at all, until a certain temperature known as the coarsening temperature is reached, after which abrupt coarsening occurs. Heat treatment can make any type of steel either fine or coarse grained; as a matter of fact, at temperatures above its coarsening temperature, the fine-grained steel usually exhibits a coarser grain size than the coarse-grained steel at the same temperature.

Making steels that remain fine grained above 925°C involves the judicious use of deoxidation with aluminum. The inhibiting agent in such steels is generally conjectured to be a submicroscopic dispersion of aluminum nitride or, perhaps at times, aluminum oxide.

2.2.9 Phase Transformations—Austenite

At equilibrium, that is, with very slow cooling, austenite transforms to pearlite when cooled below the A_1 temperature. When austenite is cooled more rapidly, this transformation is depressed and occurs at a lower temperature. The faster the cooling rate, the lower the temperature at which transformation occurs. Furthermore, the nature of the ferrite-carbide aggregate formed when the austenite transforms varies markedly with the transformation temperature, and the properites are found to vary correspondingly. Thus, heat treatment involves a controlled supercooling of austenite, and in order to take full advantage of the wide range of structures and properties that this treatment permits, a knowledge of the transformation behavior of austenite and the properties of the resulting aggregates is essential.

2.2.10 Isothermal Transformation Diagram

The transformation behavior of austenite is best studied by observing the isothermal transformation at a series of temperatures below A_1. The transformation progress is ordinarily followed metallographically in such a way that both the time-temperature relationships and the manner in which the microstructure changes are established. The times at which transformation begins and ends at a given temperature are plotted, and curves depicting the transformation behavior as a function of temperature are obtained by joining these points (Fig. 2.3) Such a diagram is referred to as an isothermal transformation (IT) diagram, a time-temperature-transformation (TTT) diagram, or, an S curve.[4]

Table 2.1 Trends in Heat-Treated Products

Property	Coarse-grain Austenite	Fine-grain Austenite
Quenched and Tempered Products		
Hardenability	Increasing	Decreasing
Toughness	Decreasing	Increasing
Distortion	More	Less
Quench cracking	More	Less
Internal stress	Higher	Lower
Annealed or Normalized Products		
Machinability		
Rough finish	Better	Inferior
Fine finish	Inferior	Better

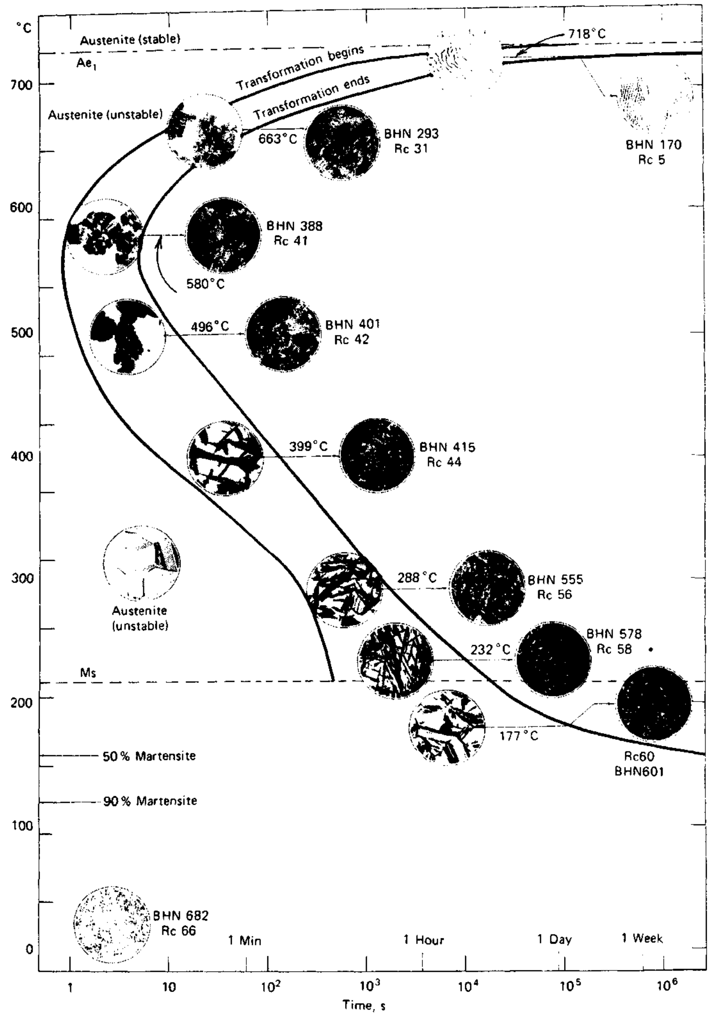

Fig. 2.3 Isothermal transformation diagram for a plain carbon eutectoid steel; Ae_1 = A_1 temperature at equilibrium; BHN = Brinell hardness number; Rc = Rockwell hardness scale C. C,0.89%; Mn, 0.29% austenitized at 885°C; grain size, 4–5; photomicrographs originally ×2500.

The IT diagram for a eutectoid carbon steel is shown in Fig. 2.3 In addition to the lines depicting the transformation, the diagram shows microstructures at various stages of transformation and hardness values. Thus, the diagram illustrates the characteristic subcritical austenite transformation behavior, the manner in which microstructure changes with transformation temperature, and the general relationship between these microstructural changes and hardness.

As the diagram indicates, the characteristic isothermal transformation behavior at any temperature above the temperature at which transformation to martensite begins (the M_s temperature) takes place over a period of time, known as the incubation period, in which no transformation occurs, followed by a period of time during which the transformation proceeds until the austenite has been transformed completely. The transformation is relatively slow at the beginning and toward the end, but much more rapid during the intermediate period in which ~25–75% of the austenite is transformed. Both the incubation period and the time required for completion of the transformation depend on the temperature.

The behavior depicted in this program is typical of plain carbon steels, with the shortest incubation period occurring at ~540°C. Much longer times are required for transformation as the temperature approaches either the Ae_1 or the M_s temperature. This A_1 temperature is lowered slightly during cooling and increased slightly during heating. The 540°C temperature, at which the transformation begins in the shortest time period is commonly referred to as the nose of the IT diagram. If complete transformation is to occur at temperatures below this nose, the steel must be cooled rapidly enough to prevent transformation at the nose temperature. Microstructures resulting from transformation at these lower temperatures exhibit superior strength and toughness.

2.2.11 Pearlite

In carbon and low-alloy steels, transformation over the temperature range of ~700–540°C gives pearlite microstructures of the characteristic lamellar type. As the transformation temperature falls, the lamellae move closer and the hardness increases.

2.2.12 Bainite

Transformation to bainite occurs over the temperature range of ~540–230°C. The acicular bainite microstructures differ markedly from the pearlite microstructures. Here again, the hardness increases as the transformation temperature decreases, although the bainite formed at the highest possible temperature is often softer than pearlite formed at a still higher temperature.

2.2.13 Martensite

Transformation to martensite, which in the steel illustrated in Fig. 2.3 begins at ~230°C, differs from transformation to pearlite or bainite because it is not time dependent, but occurs almost instantly during cooling. The degree of transformation depends only on the temperature to which it is cooled. Thus, in this steel of Fig. 2.3, transformation to martensite starts on cooling to 230°C (designated as the M_s temperature). The martensite is 50% transformed on cooling to ~150°C, and the transformation is essentially completed at ~90°C (designated as the M_f temperature). The microstructure of martensite is acicular. It is the hardest austenite transformation product but brittle; this brittleness can be reduced by tempering as discussed below.

2.2.14 Phase Properties—Pearlite

Pearlites are softer than bainites or martensites. However, they are less ductile than the lower-temperature bainites and, for a given hardness, far less ductile than tempered martensite. As the transformation temperature decreases within the pearlite range, the interlamellar spacing decreases, and these fine pearlites, formed near the nose of the isothermal diagram, are both harder and more ductile than the coarse pearlites formed at higher temperatures. Thus, although as a class pearlite tends to be soft and not very ductile, its hardness and toughness both increase markedly with decreasing transformation temperatures.

2.2.15 Phase Properties—Bainite

In a given steel, bainite microstructures are generally found to be both harder and tougher than pearlite, although less hard than martensite. Bainite properites generally improve as the transformation temperature decreases and lower bainite compares favorably with tempered martensite at the same hardness or exceeds it in toughness. Upper bainite, on the other hand, may be somewhat deficient in toughness as compared with fine pearlite of the same hardness.^{4}

2.2.16 Phase Properties—Martensite

Martensite is the hardest and most brittle microstructure obtainable in a given steel. The hardness of martensite increases with increasing carbon content up to the eutectoid composition, and, at a given carbon content, varies with the cooling rate.

Although for some applications, particularly those involving wear resistance, the hardness of martensite is desirable in spite of the accompanying brittleness, this microstructure is mainly important as starting material for tempered martensite structures, which have definitely superior properties.

2.2.17 Tempered Martensite

Martensite is tempered by heating to a temperature ranging from 170 to 700°C for 30 min to several hours. This treatment causes the martensite to transform to ferrite interspersed with small particles of cementite. Higher temperatures and longer tempering periods cause the cementite particles to increase in size and the steel to become more ductile and lose strength. Tempered martensitic structures are, as a class, characterized by toughness at any strength. The diagram of Fig. 2.4 describes, within ±10%, the mechanical properties of tempered martensite, regardless of composition. For example, a steel consisting of tempered martensite, with an ultimate strength of 1035 MPa (150,000 psi), might be expected to exhibit elongation of 16–20%, reduction of area of between 54 and 64%, yield point of 860–980 MPa (125,000–142,000 psi), and Brinell hardness of about 295–320. Because of its high ductility at a given hardness, this is the structure that is preferred.

2.2.18 Transformation Rates

The main factors affecting transformation rates of austenite are composition, grain size, and homogeneity. In general, increasing carbon and alloy content as well as increasing grain size tend to lower

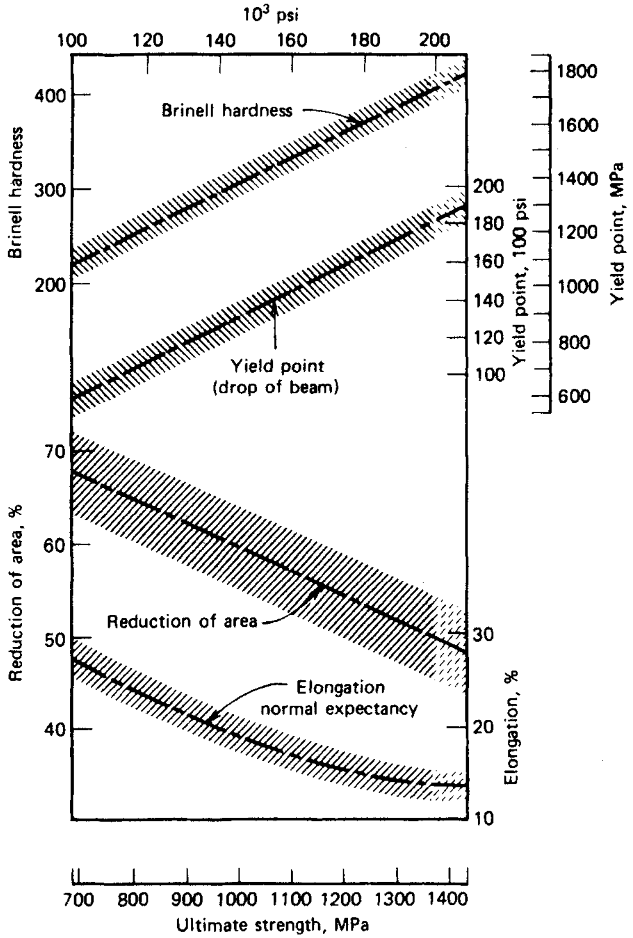

Fig. 2.4 Properties of tempered martensite (from Ref. 1). Fully heat-treated miscellaneous analyses, low-alloy steels; 0.30–0.50% C.

transformation rates. These effects are reflected in the isothermal transformation curve for a given steel.

2.2.19 Continuous Cooling

The basic information depicted by an IT diagram illustrates the structure formed if the cooling is interrupted and the reaction is completed at a given temperature. The information is also useful for interpreting behavior when the cooling proceeds directly without interruption, as in the case of annealing, normalizing, and quenching. In these processes, the residence time at a single temperature is generally insufficient for the reaction to go to completion; instead, the final structure consists of an association of microstructures which were formed individually at successivley lower temperatures as the piece cooled. However, the tendency to form seveal structures is still explained by the isothermal diagram.[5,6]

The final microstructure after continuous cooling depends on the times spent at the various transformation-temperature ranges through which a piece is cooled. The transformation behavior on continuous cooling thus represents an integration of these times by constructing a continuous-cooling diagram at constant rates similar to the isothermal transformation diagram (see Fig. 2.5). This diagram lies below and to the right of the corresponding IT diagram if plotted on the same coordinates; that is, transformation on continuous cooling starts at a lower temperature and after a longer time than the intersection of the cooling curve and the isothermal diagram would predict. This displacement is a function of the cooling rate, and increases with increasing cooling rate.

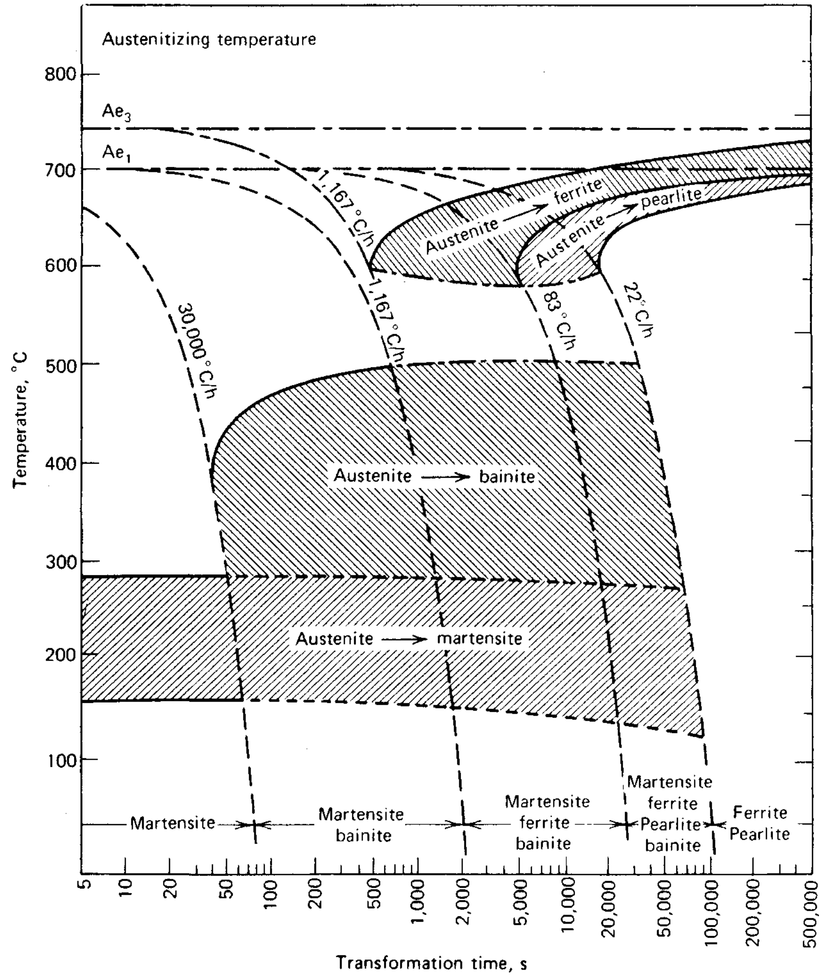

Fig. 2.5 Continuous-cooling transformation diagram for a type 4340 alloy steel, with superimposed cooling curves illustrating the manner in which transformation behavior during continuous cooling governs final microstructure (from Ref. 1). Ae_3 = critical temperature at equilibrium.

Several cooling-rate curves have been superimposed on Fig. 2.5. The changes occurring during these cooling cycles illustrate the manner in which diagrams of this nature can be correlated with heat-treating processes and used to predict the resulting microstructure.

Considering, first, the relatively low cooling rate ($<$ 22°C/hr), the steel is cooled through the regions in which transformations to ferrite and pearlite occur which constitute the final microstructure. This cooling rate corresponds to a slow cooling in the furnace such as might be used in annealing.

At a higher cooling rate (22–83°C/hr), such as might be obtained on normalizing a large forging, the ferrite, pearlite, bainite, and martensite fields are traversed and the final microstructure contains all these constituents.

At cooling rates of 1167–30,000°C/hr, the microstructure is free of proeutectoid ferrite and consists largely of bainite and a small amount of martensite. A cooling rate of at least 30,000°C/hr is necessary to obtain the fully martensitic structure desired as a starting point for tempered martensite.

Thus, the final microstructure, and therefore the properties of the steel, depend upon the transformation behavior of the austenite and the cooling conditions, and can be predicted if these factors are known.

2.3 HARDENABILITY

Hardenability refers to the depth of hardening or to the size of a piece that can be hardened under given cooling conditions, and not to the maximum hardness that can be obtained in a given steel.[7,8]

The maximum hardness depends almost entirely upon the carbon content, whereas the hardenability (depth of hardening) is far more dependent on the alloy content and grain size of the austenite. Steels whose IT diagrams indicate a long time interval before the start of transformation to pearlite are useful when large sections are to be hardened, since if steel is to transform to bainite or martensite, it must escape any transformation to pearlite. Therefore, the steel must be cooled through the high-temperature transformation ranges at a rate rapid enough for transformation not to occur even at the nose of the IT diagram. This rate, which just permits transformation to martensite without earlier transformation at a higher temperature, is known as the critical cooling rate for martensite. It furnishes one method for expressing hardenability; for example, in the steel of Fig. 2.5, the critical cooling rate for martensite is 30,000°C/hr or 8.3°C/sec.

Although the critical cooling rate can be used to express hardenability, cooling rates ordinarily are not constant but vary during the cooling cycle. Especially when quenching in liquids, the cooling rate of steel always decreases as the steel temperature approaches that of the cooling medium. It is therefore customary to express hardenability in terms of depth of hardening in a standardized quench. The quenching condition used in this method of expression is a hypothetical one in which the surface of the piece is assumed to come instantly to the temperature of the quenching medium. This is known as an ideal quench; the diameter of a round steel bar, which is quenched to the desired microstructure, or corresponding hardness value, at the center in an ideal quench, is known as the ideal diameter for which the symbol D_I is used. The relationships between the cooling rates of the ideal quench and those of other cooling conditions are known. Thus, the hardenability values in terms of ideal diameter are used to predict the size of round or other shape that has the same cooling rate when cooled in actual quenches whose cooling severities are known. The cooling severities (usually referred to as severity of quench) which form the basis for these relationships are called H values. The H value for the ideal quench is infinity; those for some commonly used cooling conditions are given in Table 2.2.

Hardenability is most conveniently measured by a test in which a steel sample is subjected to a continuous range of cooling rates. In the end-quench or Jominy test, a round bar, 25 mm in diameter and 102 mm long, is heated to the desired austenitizing temperature and quenched in a fixture by a stream of water impinging on only one end. Hardness measurements are made on flats that are ground along the length of the bar after quenching. The results are expressed as a plot of hardness versus distance from the quenched end of the bar. The relationships between the distance from the quenched end and cooling rates in terms of ideal diameter (D_I) are known, and the hardenability can be evaluated in terms of D_I by noting the distance from the quenched end at which the hardness corresponding to the desired microstructure occurs and using this relationship to establish the corresponding cooling rate or D_I value. Published heat-flow tables or charts relate the ideal-diameter value to cooling rates in quenches or cooling conditions whose H values are known. Thus, the ideal-diameter value can be used to establish the size of a piece in which the desired microstructure can be obtained under the quenching conditions of the heat treatment to be used. The hardenability of steel is such an important property that it has become common practice to purchase steels to specified hardenability limits. Such steels are called H steels.

2.4 HEAT-TREATING PROCESSES

In heat-treating processes, steel is usually heated above the A_3 point and then cooled at a rate that results in the microstructure that gives the desired properties.[9,10]

2.4.1 Austentization

The steel is first heated above the temperature at which austenite is formed. The actual austenitizing temperature should be high enough to dissolve the carbides completely and take advantage of the hardening effects of the alloying elements. In some cases, such as tool steels or high-carbon steels,

Table 2.2 *H* Values Designating Severity of Quench for Commonly Used Cooling Conditions[a]

Degree of Agitation of Medium	Quenching Medium: Oil	Water	Brine
None	0.25-0.30	0.9-1.0	2
Mild	0.30-0.35	1.0-1.1	2.0-2.2
Moderate	0.35-0.40	1.2-1.3	
Good	0.40-0.50	1.4-1.5	
Strong	0.50-0.80	1.6-2.0	
Violent	0.80-1.1	4.0	5.0

[a] H values are proportional to the heat-extracting capacity of the medium.

undissolved carbides may be retained for wear resistance. The temperature should not be high enough to produce pronounced grain growth. The piece should be heated long enough for complete solution; for low-alloy steels in a normally loaded furnace, 1.8 min/mm of diameter or thickness usually suffices.

Excessive heating rates may create high stresses, resulting in distortion or cracking. Certain types of continuous furnaces, salt baths, and radiant-heating furnaces provide very rapid heating, but preheating of the steel may be necessary to avoid distortion or cracking, and sufficient time must be allowed for uniform heating throughout. Unless special precautions are taken, heating causes scaling or oxidation, and may result in decarburization; controlled-atmosphere furnaces or salt baths minimize these effects.

2.4.2 Quenching

The primary purpose of quenching is to cool rapidly enough to suppress all transformation at temperatures above the M_s temperature. The cooling rate required depends on the size of the piece and the hardenability of the steel. The preferred quenching media are water, oils, and brine. The temperature gradients set up by quenching create high thermal and transformational stresses which may lead to cracking and distortion; a quenching rate no faster than necessary should be employed to minimize these stresses. Agitation of the cooling medium accelerates cooling and improves uniformity. Cooling should be long enough to permit complete transformation to martensite. Then, in order to minimize cracking from quenching stresses, the article should be transferred immediately to the tempering furnace (Fig. 2.6).

2.4.3 Tempering

Quenching forms very hard, brittle martensite with high residual stresses. Tempering relieves these stresses and improves ductility, although at some expense of strength and hardness. The operation consists of heating at temperatures below the lower critical temperature (A_1).

Measurements of stress relaxation on tempering indicate that, in a plain carbon steel, residual stresses are significantly lowered by heating to temperatures as low as 150°C, but that temperatures of 480°C and above are required to reduce these stresses to very low values. The times and temperatures required for stress relief depend on the high-temperature yield strength of the steel, since stress relief results from the localized plastic flow that occurs when the steel is heated to a temperature at which yield strength decreases. This phenomenon may be affected markedly by composition, and particularly by alloy additions. The toughness of quenched steel, as measured by the notch impact test, first increases on tempering up to 200°C, then decreases on tempering between 200 and 310°C,

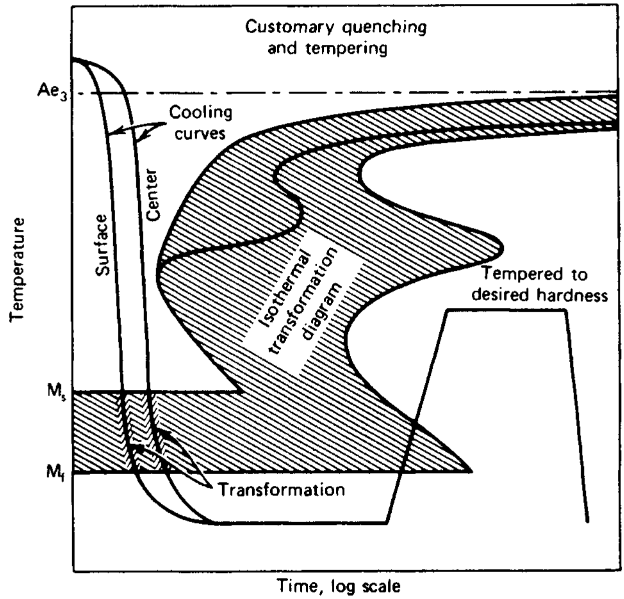

Fig. 2.6 Transformation diagram for quenching and tempering martensite; the product is tempered martensite (from Ref. 1).

and finally increases rapidly on tempering at 425°C and above. This behavior is characteristic and, in general, temperatures of 230-310°C should be avoided.

In order to minimize cracking, tempering should follow quenching immediately. Any appreciable delay may promote cracking.

The tempering of martensite results in a contraction, and if the heating is not uniform, stresses result, Similarly, heating too rapidly may be dangerous because of the sharp temperature gradient set up between the surface and the interior. Recirculating-air furnaces can be used to obtain uniform heating. Oil or salt baths are commonly used for low-temperature tempering; lead or salt baths are used at higher temperatures.

Some steels lose toughness on slow cooling from ~540°C and above, a phenomenon known as temper brittleness; rapid cooling after tempering is desirable in these cases.

2.4.4 Martempering

A modified quenching procedure known as martempering minimizes the high stresses created by the transformation to martensite during the rapid cooling characteristic of ordinary quenching (see Fig. 2.7). In practice, it is ordinarily carried out by quenching in a molten-salt bath just above the M_s temperature. Transformation to martensite does not begin until the piece reaches the temperature of the salt bath and is removed to cool relatively slowly in air. Since the temperature gradient characteristic of conventional quenching is absent, the stresses produced by the transformation are much lower and a greater freedom from distortion and cracking is obtained. After martempering, the piece may be tempered to the desired strength.

2.4.5 Austempering

As discussed earlier, lower bainite is generally as strong as and somewhat more ductile than tempered martensite. Austempering, which is an isothermal heat treatment that results in lower bainite, offers an alternative heat treatment for obtaining optimum strength and ductility.

In austempering the article is quenched to the desired temperature in the lower bainite region, usually in molten salt, and kept at this temperature until transformation is complete (see Fig. 2.8). Usually, it is held twice as long as the period indicated by the IT diagram. The article may be quenched or air cooled to room temperature after transformation is complete, and may be tempered to lower hardness if desired.

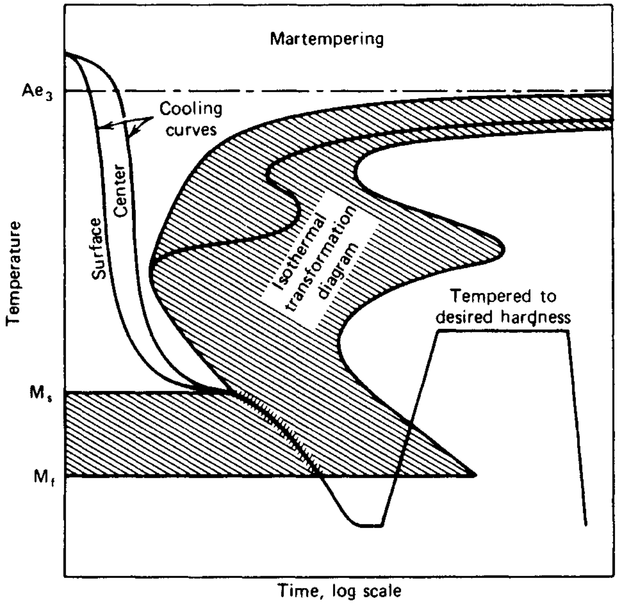

Fig. 2.7 Transformation diagram for martempering; the product is tempered martensite (from Ref. 1).

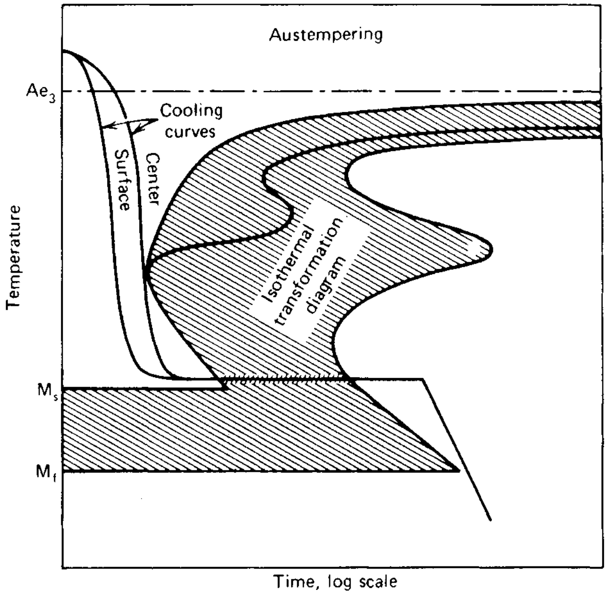

Fig. 2.8 Transformation diagram for austempering; the product is bainite (from Ref. 1).

2.4.6 Normalizing

In this operation, steel is heated above its upper critical temperature (A_3) and cooled in air. The purpose of this treatment is to refine the grain and to obtain a carbide size and distribution that is more favorable for carbide solution on subsequent heat treatment than the earlier as-rolled structure.

The as-rolled grain size, depending principally on the finishing temperature in the rolling operation, is subject to wide variations. The coarse grain size resulting from a high finishing temperature can be refined by normalizing to establish a uniform, relatively fine-grained microstructure.

In alloy steels, particularly if they have been slowly cooled after rolling, the carbides in the as-rolled condition tend to be massive and are difficult to dissolve on subsequent austenitization. The carbide size is subject to wide variations, depending on the rolling and slow cooling. Here again, normalizing tends to establish a more uniform and finer carbide particle size, which facilitates subsequent heat treatment.

The usual practice is to normalize at 50–80°C above the upper critical temperature; however, for some alloy steels considerably higher temperatures may be used. Heating may be carried out in any type of furnace that permits uniform heating and good temperature control.

2.4.7 Annealing

Annealing relieves cooling stresses induced by hot- or cold-working and softens the steel to improve its machinability or formability. It may involve only a subcritical heating to relieve stresses, recrystallize cold-worked material, or spheroidize carbides; it may involve heating above the upper critical temperature (A_3) with subsequent transformation to pearlite or directly to a spheroidized structure on cooling.

The most favorable microstructure for machinability in the low- or medium-carbon steels is coarse pearlite. The customary heat treatment to develop this microstructure is a full annealing, illustrated in Fig. 2.9. It consists of austenitizing at a relatively high temperature to obtain full carbide solution, followed by slow cooling to give transformation exclusively in the high-temperature end of the pearlite range. This simple heat treatment is reliable for most steels. It is, however, rather time-consuming since it involves slow cooling over the entire temperature range from the austenitizing temperature to a temperature well below that at which transformation is complete.

2.4.8 Isothermal Annealing

Annealing to coarse pearlite can be carried out isothermally by cooling to the proper temperature for transformation to coarse pearlite and holding until transformation is complete. This method, called isothermal annealing, is illustrated in Fig. 2.10. It may save considerable time over the full-annealing

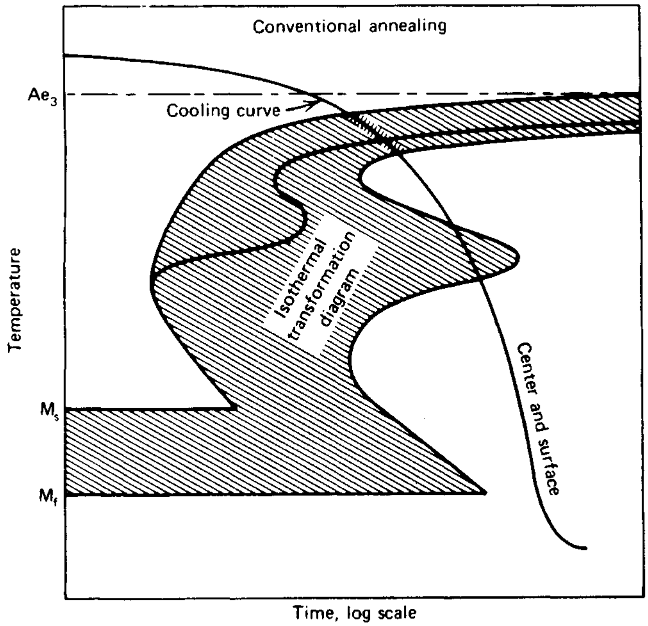

Fig. 2.9 Transformation diagram for full annealing; the product is ferrite and pearlite (from Ref. 1).

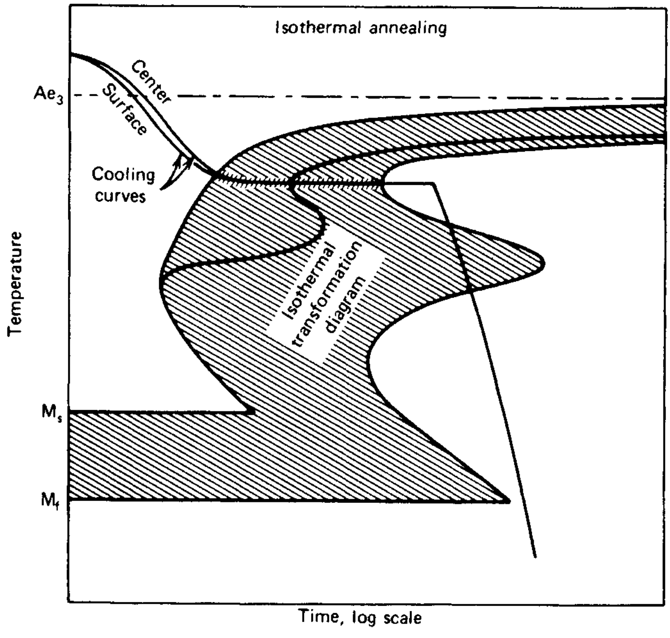

Fig. 2.10 Transformation diagram for isothermal annealing; the product is ferrite and pearlite (from Ref. 1).

process described previously, since neither the time from the austenitizing temperature to the transformation temperature, nor from the transformation temperature to room temperature, is critical; these may be shortened as desired. If extreme softness of the coarsest pearlite is not necessary, the transformation may be carried out at the nose of the IT curve, where the transformation is completed rapidly and the operation further expedited: the pearlite in this case is much finer and harder.

Isothermal annealing can be conveniently adapted to continuous annealing, usually in specially designed furnaces, when it is commonly referred to as cycle annealing.

2.4.9 Spheroidization Annealing

Coarse pearlite microstructures are too hard for optimum machinability in the higher carbon steels. Such steels are customarily annealed to develop spheroidized microstructures by tempering the as-rolled, slowly cooled, or normalized materials just below the lower critical temperature range. Such an operation is known as subcritical annealing. Full spheroidization may require long holding times at the subcritical temperature and the method may be slow, but it is simple and may be more convenient than annealing above the critical temperature.

The annealing procedures described above to produce pearlite can, with some modifications, give spheroidized microstructures. If free carbide remains after austenitizing, transformation in the temperature range where coarse pearlite ordinarily would form proceeds to spheroidized rather than pearlite microstructures. Thus, heat treatment to form spheroidized microstructures can be carried out like heat treatment for pearlite, except for the lower austenitizing temperatures. Spheroidization annealing may thus involve a slow cooling similar to the full-annealing treatment used for pearlite, or it may be a treatment similar to isothermal annealing. An austenitizing temperature not more than 55°C above the lower critical temperature is customarily used for this supercritical annealing.

2.4.10 Process Annealing

Process annealing is the term used for subciritical annealing of cold-worked materials. It customarily involves heating at a temperature high enough to cause recrystallization of the cold-worked material and to soften the steel. The most important example of process annealing is the box annealing of cold-rolled low-carbon sheet steel. The sheets are enclosed in a large box that can be sealed to permit the use of a controlled atmosphere to prevent oxidation. Annealing is usually carried out between 590 and 700°C. The operation usually takes ~24 hr, after which the charge is cooled slowly within the box; the entire process takes ~40 hr.

2.4.11 Carburizing

In carburizing, low-carbon steel acquires a high-carbon surface layer by heating in contact with carbonaceous materials. On quenching after carburizing, the high-carbon skin hardens, whereas the low-carbon core remains comparatively soft. The result is a highly wear-resistant exterior over a very tough interior. This material is particularly suitable for gears, camshafts, etc. Carburizing is most commonly carried out by packing the steel in boxes with carbonaceous solids, sealing to exclude the atmosphere, and heating to about 925°C for a period of time depending on the depth desired; this method is called pack carburizing. Alternatively, the steel may be heated in contact with carburizing gases in which case the process is called gas carburizing; or, least commonly, in liquid baths of carburizing salts, in which case it is known as liquid carburizing.

2.4.12 Nitriding

The nitrogen case-hardening process, termed nitriding, consists of subjecting machined and (preferably) heat-treated parts to the action of a nitrogenous medium, commonly ammonia gas, under conditions whereby surface hardness is imparted without requiring any further treatment. Wear resistance, retention of hardness at high temperatures, and resistance to certain types of corrosion are also imparted by nitriding.

2.5 CARBON STEELS

The plain carbon steels represent by far the largest volume produced, with the most diverse applications of any engineering material, including castings, forgings, tubular products, plates, sheet and strip, wire and wire products, structural shapes, bars, and railway materials (rails, wheels, and axles). Carbon steels are made by all modern steelmaking processes and, depending on their carbon content and intended purpose, may be rimmed, semikilled, or fully killed.[11-15]

The American Iron and Steel Institute has published standard composition ranges for plain carbon steels, which in each composition range are assigned an identifying number according to a method of classification (see Table 2.3). In this system, carbon steels are assigned to one of three series: 10xx (nonresulfurized), 11xx (resulfurized), and 12xx (rephosphorized and resulfurized). The 10xx steels are made with low phosphorus and sulfur contents, 0.04% max and 0.050% max, respectively. Sulfur in amounts as high as 0.33% max may be added to the 11xx and as high as 0.35% max to

Table 2.3 Standard Numerical Designations of Plain Carbon and Constructional Alloy Steels (AISI-SAE Designations)[1]

Series Designation[a]	Types	Series Desig- nation[a]	Types
10xx	Nonresulfurized carbon-steel grades	47xx	1.05% Ni–0.45% Cr–0.20% Mo
11xx	Resulfurized carbon-steel grades	48xx	3.5% Ni–0.25% Mo
12xx	Rephosphorized and resulfurized Carbon-steel grades	50xx	0.28 or 0.40% Cr
13xx	1.75% Mn	51xx	0.80, 0.90, 0.95, 1.00, or 1.05% Cr
23xx	3.50% Ni	5xxxx	1.00% C–0.50, 1.00, or 1,45% Cr
25xx	5.00% Ni	61xx	0.80 or 0.95% Cr–0.10 or 0.15% V
31xx	1.25% Ni–0.65% Cr	86xx	0.55% Ni–0.50 or 0.65% Cr–0.20% Mo
33xx	3.5% Ni–1.55% Cr	87xx	0.55% Ni–0.50% Cr–0.25% Mo
40xx	0.25% Mo	92xx	0.85% Mn–2.00% Si
41xx	0.50 or 0.95% Cr–0.12 or 0.20% Mo	93xx	3.25% Ni–1.20% Cr–0.12% Mo
43xx	1.80% Ni–0.50 or 0.80% Cr–0.25% Mo	98xx	1.00% Ni–0.80% Cr–0.25% Mo
46xx	1.55 or 1.80% Ni–0.20 or 0.25% Mo		

[a] The first figure indicates the class to which the steel belongs; 1xxx indicates a carbon steel, 2xxx a nickel steel, and 3xxx a nickel-chromium steel. In the case of alloy steels, the second figure generally indicates the approximate percentage of the principal alloying element. Usually, the last two or three figures (represented in the table by x) indicate the average carbon content in points or hundredths of 1 wt %. Thus, a nickel steel containing a 3.5% nickel and 0.30% carbon would be designated as 2330.

the 12xx steels to improve machinability. In addition, phosphorus up to 0.12% max may be added to the 12xx steels to increase stiffness.

In identifying a particular steel, the letters x are replaced by two digits representing average carbon content; for example, an AISI No. 1040 steel would have an average carbon content of 0.40%, with a tolerance of ±0.03%, giving a range of 0.37 to 0.43% carbon.

2.5.1 Properties

The properties of plain carbon steels are governed principally by carbon content and microstructure. The fact that properties can be controlled by heat treatment has been discussed in Section 2.1. Most plain carbon steels, however, are used without heat treatment.

The properties of plain carbon steels may be modified by residual elements other than the carbon, manganese, silicon, phosphorus, and sulfur that are always present, as well as gases, especially oxygen, nitrogen, and hydrogen, and their reaction products. These incidental elements are usually acquired from scrap, deoxidizers, or the furnace atmosphere. The gas content depends mostly on melting, deoxidizing, and pouring procedures; consequently, the properties of plain carbon steels depend heavily on the manufacturing techniques.

The average mechanical peoperties of as-rolled 2.5-cm bars of carbon steels as a function of carbon contents are shown in Fig. 2.11. This diagram is an illustration of the effect of carbon content when microstructure and grain size are held approximately constant.

2.5.2 Microstructure and Grain Size

The carbon steels with relatively low hardenability are predominantly pearlitic in the cast, rolled, or forged state. The constituents of the hypoeutectoid steels are, therefore, ferrite and pearlite, and of the hypereutectoid steels, cementite and pearlite. As discussed earlier, the properties of such pearlitic steels depend primarily on the interlamellar spacing of the pearlite and the grain size. Both hardness and ductility increase as the interlamellar spacing or the pearlite-transformation temperature decreases, whereas the ductility increases with decreasing grain size. The austenite-transformation behavior in carbon steel is determined almost entirely by carbon and manganese content; the effects of

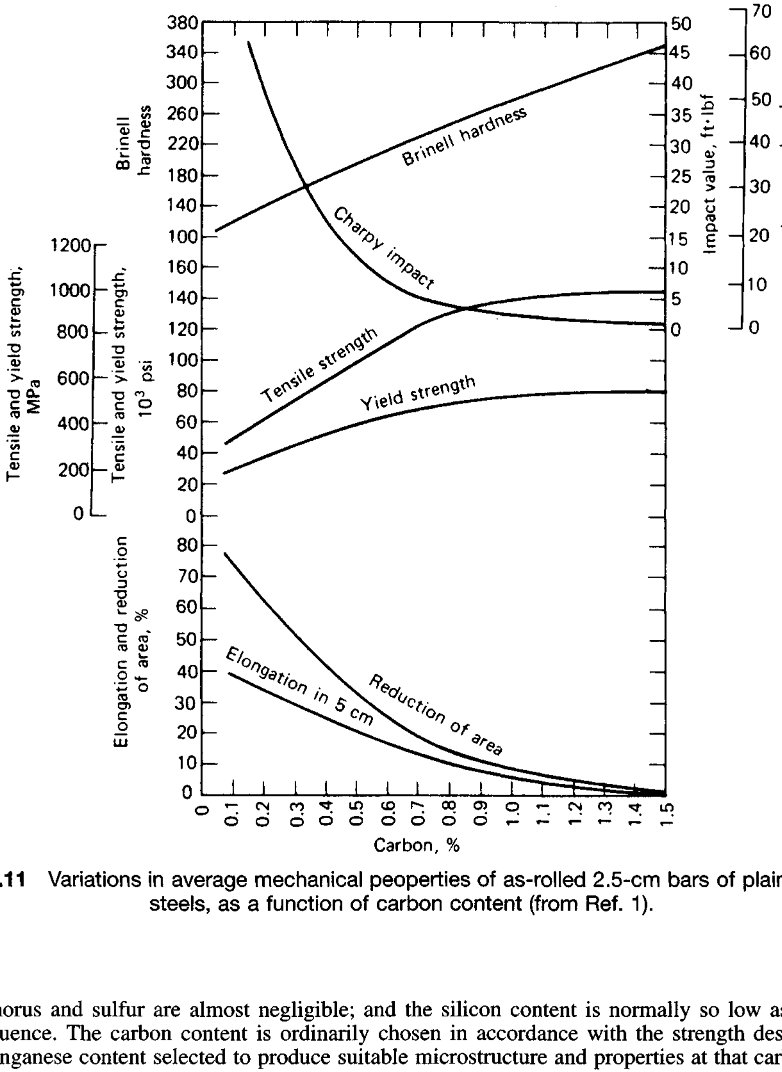

Fig. 2.11 Variations in average mechanical peoperties of as-rolled 2.5-cm bars of plain carbon steels, as a function of carbon content (from Ref. 1).

phosphorus and sulfur are almost negligible; and the silicon content is normally so low as to have no influence. The carbon content is ordinarily chosen in accordance with the strength desired, and the manganese content selected to produce suitable microstructure and properties at that carbon level under the given cooling conditions.

2.5.3 Microstructure of Cast Steels

Cast steel is generally coarse grained, since austenite forms at high temperature and the pearlite is usually coarse, in as much as cooling through the ciritical range is slow, particularly if the casting is cooled in the mold. In hypoeutectoid steels, ferrite ordinarily precipitates at the original austenite grain boundaries during cooling. In hypereutectoid steels, cementite is similarly precipitated. Such mixtures of ferrite or cementite and coarse pearlite have poor strength and ductility properties, and heat treatment is usually necessary to obtain suitable microstructures and properties in cast steels.

2.5.4 Hot Working

Many carbon steels are used in the form of as-rolled finished sections. The microstructure and properties of these sections are determined largely by composition, rolling procedures, and cooling conditions. The rolling or hot working of these sections is ordinarily carried out in the temperature range in which the steel is austentic, with four principal effects: Considerable homogenization occurs during the heating for rolling, tending to eliminate dendrite segregation present in the ingot; the dendritic structure is broken up during rolling; recrystallization takes place during rolling, with final austenitic grain size determined by the temperature at which the last passes are made (the finishing temperature); and dendrites and inclusions are reoriented, with markedly improved ductility, in the rolling direction.

Thus, homogeneity and grain size of the austenite is largely determined by the rolling technique. However, the recrystallization characteristics of the austenite and, therefore, the austenite grain size characteristic at a given finishing temperature, may be affected markedly by the steelmaking technique, particularly with regard to deoxidation.

The distribution of the ferrite or cementite and the nature of the pearlite are determined by the cooling rate after rolling. Since the usual practice is air cooling, the final microstructure and the properties of as-rolled sections depend primarily on composition and section size.

2.5.5 Cold Working

The manufacture of wire, sheet, strip, and tubular products often includes cold working, with effects that may be eliminated by annealing; however, some products, particularly wire, are used in the cold-worked condition. The most pronounced effects of cold working are increased strength and hardness and decreased ductility. The effect of cold working on the tensile strength of plain carbon steel is shown in Fig. 2.12.

Upon reheating cold-worked steel to the recrystallization temperature (400°C) or above, depending on composition, extent of cold work, and other variables, the original microstructure and properties may be restored.

2.5.6 Heat Treatment

Although most wrought (rolled or forged) carbon steels are used without a final heat treatment, it may be employed to improve the microstructure and properties for specific applications.

Annealing is applied when better machinability or formability is required than would be obtained with the as-rolled microstructure. A complete annealing is generally employed to form coarse pearlite,

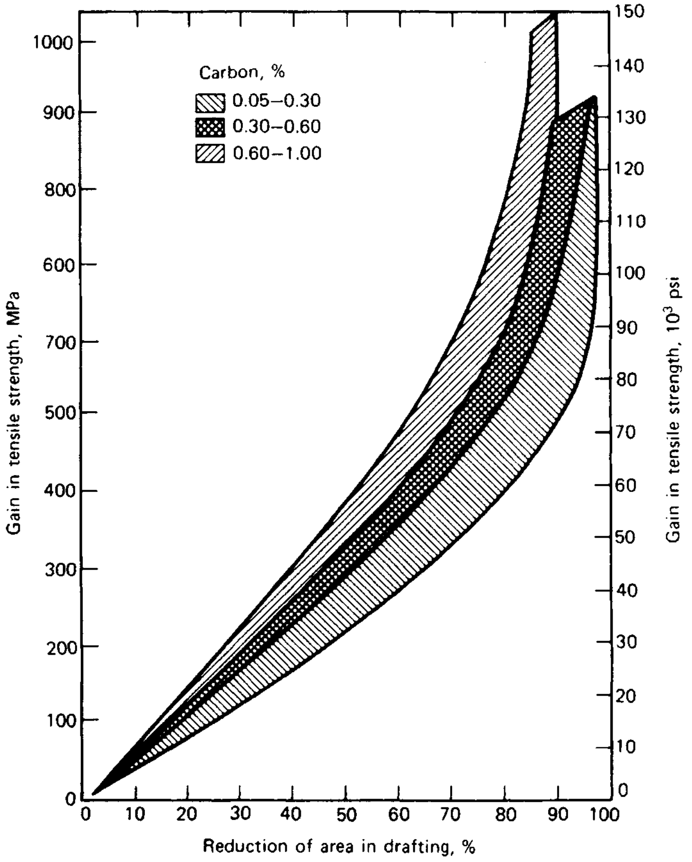

Fig. 2.12 Increase of tensile strength of plain carbon steel with increased cold working (from Ref. 1).

although a subcritical annealing or spheroidizing treatment is occasionally used. Process annealing for optimum formability is universal with cold-rolled strip and sheet and cold-worked tubing.

The grain size of as-rolled products depends largely on the finishing temperature but is difficult to control. A final normalizing treatment from a relatively low temperature may establish a fine, uniform grain size for applications in which ductility and toughness are critical.

Quenching and tempering of plain carbon steels are being more frequently applied. In one type of treatment, the steel is heat treated to produce tempered martensite, but because of relatively low hardenability, the operation is limited to section sizes of not more than 10-13 mm. In the other type, large sections of plain carbon steels are quenched and tempered to produce fine pearlite microstructures with much better strength and ductility than those of the coarse pearlite microstructures in as-rolled or normalized products.

Thin sections of carbon steels ($\leq$ 5 mm) are particularly suitable for the production of parts requiring toughness at high hardness by austempering.

2.5.7 Residual Elements

In addition to the carbon, manganese, phosphorus, sulfur, and silicon that are always present, carbon steels may contain small amounts of gases, such as hydrogen, oxygen, or nitrogen, introduced during the steelmaking process; nickel, copper, molybdenum, chromium, and tin, which may be present in the scrap, and aluminum, titanium, vanadium, or zirconium, which may be introduced during deoxidation.

Oxygen and nitrogen cause the phoenomenon called aging, mainfested as a spontaneous increase in hardness at room temperature and believed to be a precipitation effect.

An embrittling effect, the mechanism of which is not completely understood, is caused by a hydrogen content of more than ~3 ppm. As discussed earlier, the content of hydrogen and other gases can be reduced by vacuum degassing.

Alloying elements such as nickel, chromium, molybdenum, and copper, which may be introduced with scrap, do, of course, increase the hardenability although only slightly since the concentrations are ordinarily low. However, the heat-treating characteristics may change, and for applications in which ductility is important, as in low-carbon steels for deep drawing, the increased hardness imparted by these elements may be harmful.

Tin, even in low amounts, is harmful in steels for deep drawing; for most applications, however, the effect of tin in the quantities ordinarily present is negligible.

Aluminum is generally desirable as a grain refiner and tends to reduce the susceptibility of carbon steel to aging associated with strain. Unfortunately, it tends to promote graphitization and is, therefore, undesirable in steels used at high temperatures. The other elements that may be introduced as deoxidizers, such as titanium, vanadium, or zirconium, are ordinarily present in such small amounts as to be ineffective.

2.6 DUAL-PHASE SHEET STEELS

Dual-phase steels derive their name from their unique microstructure of a mixture of ferrite and martensite phases. This microstructure is developed in hot- and cold-rolled sheet by using a combination of steel composition and heat treatment that changes an initial microstructure of ferrite and pearlite (or iron carbide) to ferrite and martensite.[16-22]

Normally, high-strength hot-rolled sheets are manufactured by hot rolling and cooling on a hot-strip mill, which produces a microstructure of ferrite and pearlite. On heating to ~750–850°C, a microstructure of ferrite and austenite is produced, and by cooling at an appropriate rate (which depends on steel composition or hardenability), the austenite is transformed to a very hard martensite phase contained within the soft, ductile ferrite matrix. The final ferrite–martensite microstructure, which may contain 5–30% martensite (increasing amounts increase the strength), may be considered as a composite; the strength may therefore be estimated, according to a simple law of mixtures, from the strengths and volume fractions of the individual phases.

The properties of a steel (0.11% C, 1.6%, Mn, 0.60% Si, 0.04% V) in the hot-rolled (ferrite and pearlite) and in the heat-treated (ferrite-martensite double-phase) state are given below (to convert MPa to psi, multiply by 145):

	Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation (%)
Hot rolled	480	4275	24
Dual phase	345	4516	32

Although the tensile (ultimate) strength of the steel is little affected by heat treating, the yield strength is substantially reduced and the ductility markedly improved. The low yield strength allows for the easy initiation of plastic deformation during press forming of dual-phase sheet material.

However, dual-phase steels have the unique capacity to strain harder rapidly so that after a few percent deformation (3–5%) the yield strength exceeds 550 MPa (80,000 psi).

Dual-phase steels have found application in automotive bumpers and wheels where high ductility is requried to form the complex shapes. The development of very high strength of ~550 MPa (80,000 psi) allows thinner, lighter weight sheet to be used, instead of steels having strengths of only 200–350 MPa (30,000–50,000 psi). However, the heat-treating step increases production costs.

2.7 ALLOY STEELS

As a class, alloy steels may be defined as steels having enhanced properties owing to the presence of one or more special elements or larger proportions of elements (such as silicon and manganese) than are ordinarily present in carbon steel. Steels containing alloying elements are classified into high-strength low-alloy (HSLA) steels; AISI alloy steels; alloy tool steels; stainless steels; heat-resistant steels; and electrical steels (silicon steels). In addition, there are numerous steels, some with proprietary compositions, with exceptional properties developed to meet unusually severe requirements. The relatively small production of such steels does not reflect their engineering importance.[23,24]

2.7.1 Functions of Alloying Elements

In the broadest sense, alloy steels may contain up to ~50% of alloying elements which directly enhance properties. Examples are the increased corrosion resistance of high chromium steels, the enhanced electric properties of silicon steels, the improved strength of the HSLA steels, and the improved hardenability and tempering characteristics of the AISI alloy steels.

2.7.2 Thermomechanical Treatment

The conventional method of producing high-strength steels has been to add alloy elements such as Cr, Ni, and Mo to the liquid steel. The resulting alloy steels are often heat treated after rolling to develop the desired strength without excessive loss of toughness (resistance to cracking upon impact). In the 1970s, a less expensive method was developed to produce HSLA steels with improved toughness and yield strength ranging from 400 to 600 MPa (60,000 to 85,000 psi). In this thermomechanical treatment, the working of the steel is controlled while its temperature is changing and it is being hot rolled between 1300 and 750°C to its final thickness.[25–29] The HSLA steels that are commonly strengthened by thermomechanical treatment, also called controlled rolling, generally contain 0.05–0.20% carbon, 0.40–1.60% manganese, 0.05–0.50% silicon, plus 0.01–0.30% of one or more of the following elements: aluminum, molybdenum, niobium, titanium, and vanadium. Thermomechanical treatment usually involves a substantial degree of rolling, such as a 50–75% decrease in thickness in the last rolling passes; temperature maintained between 750 and 950°C; and a controlled rate of cooling after hot rolling. This procedure gives a very fine steel grain size and imparts strength and toughness. Steels so treated are increasingly used in automobiles and oil and gas pipelines.

2.7.3 High-Strength Low-Alloy (HSLA) Steels

HSLA steels are categorized according to mechanical properties, particularly the yield point; for example, within certain thickness limits they have yield points ranging from 310 to 450 MPa (45,000 to 65,000 psi) as compared with 225 to 250 MPa (33,000 to 36,000 psi) for structural carbon steel. This classification is in contrast to the usual classification into plain carbon or structural-carbon steels, alloy steels, and stainless steels on the basis of alloying elements.

The superior mechanical properites of HSLA steels are obtained by the addition of alloying elements (other than carbon), singly and in combination. Each steel must meet similar minimum mechanical requirements. They are available for structural use as sheets, strips, bars, and plates, and in various other shapes. They are not to be considered as special-purpose steels or requiring heat treatment.

To be of commercial interest, HSLA steels must offer economic advantages. They should be much stronger and often tougher than structural carbon steel. In addition, they must have sufficient ductility, formability, and weldability to be fabricated by customary techniques. Improved resistance to corrosion is often required. The abrasion resistance of these steels is somewhat higher than that of structural carbon steel containing 0.15–0.20% carbon. Superior mechanical properties permits the use of HSLA steels in structures with a higher unit working stress; this generally permits reduced section thickness with corresponding decrease in weight. Thus, HSLA steels may be substituted for structural carbon steel without change in section, resulting in a stronger and more duable structure without weight increase.

2.7.4 AISI Alloy Steels

The American Iron and Steel Institute defines alloy steels as follows: "By common custom steel is considered to be alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65%; silicon, 0.60%; copper, 0.60%; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels: aluminum, boron, chromium up to 3.99%, cobalt, columbium (niobium), molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect."[30] Steels that contain 4.00% or more of chromium are included by convention among the special types of alloy steels known as stainless steels subsequently discussed.[31–37]

Steels that fall within the AISI definition have been standardized and classified jointly by AISI and SAE as shown in Table 2.3. They represent by far the largest alloy steel production and are generally known as AISI alloy steels. They are also commonly referred to as constructional alloy steels.

The effect of the alloying elements on AISI steels is indirect since alloying elements control microstructure through their effect on hardenability. They permit the attainment of desirable microstructures and properties over a much wider range of sizes and sections than is possible with carbon steels.

2.7.5 Alloy Tool Steels

Alloy tool steels are classified roughly into three groups: Low-alloy tool steels, to which alloying elements have been added to impart hardenability higher than that of plain carbon tool steels; accordingly, they may be hardened in heavier sections or with less drastic quenches to minimize distortion; intermediate-alloy tool steels usually contain elements such as tungsten, molybdenum, or vanadium, which form hard, wear-resistant carbides; high-speed tool steels contain large amounts of carbide-forming elements that serve not only to furnish wear-resisting carbides, but also promote the phenomenon known as secondary hardening and thereby increase resistance to softening at elevated temperatures.

2.7.6 Stainless Steels

Stainless steels are more resistant to rusting and staining than plain carbon and low-alloy steels.[38–46] This superior corrosion resistance is due to the addition of chromium. Although other elements, such as copper, aluminum, silicon, nickel, and molybdenum, also increase corrosion resistance, they are limited in their usefulness.

No single nation can claim credit for the development of the stainless steels; Germany, the United Kingdom, and the United States share alike in their developoment. In the United Kingdom in 1912, during the search for steel that would resist fouling in gun barrels, a corrosion-resistant composition was reported of 12.8% chromium and 0.24% carbon. It was suggested that this composition be used for cutlery. In fact, the composition of AISI type 420 steel (12–14% chromium, 0.15% carbon) is similar to that of the first corrosion-resistant steel.

The higher chromium–iron alloys were developed in the United States from the early 20th century on, when the effect of chromium on oxidation resistance at 1090°C was fist noticed. Oxidation resistance increased markedly as the chromium content was raised above 20%. Even now and with steels containing appreciable quantities of nickel, 20% chromium seems to be the minimum amount necessary for oxidation resistance at 1090°C.

The austenitic iron–chromium–nickel alloys were developed in Germany around 1910 in a search for materials for use in pyrometer tubes. Further work led to the versatile 18% chromium–8% nickel steels, so-called 18–8, which are widely used today.

The chromium content seems to be the controlling factor and its effect may be enhanced by additions of molybdenum, nickel, and other elements. The mechanical properties of the stainless steels, like those of the plain carbon and lower-alloy steels, are functions of structure and composition. Thus, austenitic steels possess the best impact properties at low temperatures and the highest strength at high temperatures, whereas martensitic steels are the hardest at room temperature. Thus, stainless steels, which are available in a variety of structures, exhibit a range of mechanical properties which, combined with their excellent corrosion resistance, makes these steels highly versatile from the standpoint of design.

The standard AISI and SAE types are identified in Table 2.4.

2.7.7 Martensitic Stainless Steels

Martensitic stainless steels are iron–chromium alloys that are hardenable by heat treatment. They include types 403, 410, 414, 416, 420, 431, 440A, 440B, 440C, 501, and 502 (see Table 2.4). The most widely used is type 410, containing 11.50–13.50% chromium and <0.15% carbon. In the annealed condition, this grade may be drawn or formed. It is an air-hardening steel, affording a wide range of properties by heat treatment. In sheet or strip form, type 410 is used extensively in the petroleum industry for ballast trays and liners. It is also used for parts of furnaces operating below 650°C, and for blades and buckets in steam turbines.

Type 420, with ~0.35% carbon and a resultant increased hardness, is used for cutlery. In bar form, it is used for valves, valve stems, valve seats, and shafting where corrosion and wear resistance are needed. Type 440 may be employed for surgical instruments, especially those requiring a durable

Table 2.4 Standard Stainless and Heat-Resisting Steel Products[1]

AISI Type Number	SAE Type[a] Number	Chemical Composition, %			
		Carbon	Chromium	Nickel	Other
201	30201	0.15 max	16.00–18.00	3.50–5.50	Mn 5.50–7.50[b] P 0.06 max[c] N 0.25 max
202	30202	0.15 max	17.00–19.00	4.00–6.00	Mn 7.50–10.00 P 0.06 max N 0.25 max
301	30301	0.15 max	16.00–18.00	6.00–8.00	
302	30302	0.15 max	17.00–19.00	8.00–10.00	
302B	30302B	0.15 max	17.00–19.00	8.00–10.00	Si 2.00–3.00[d] P 0.20 max S 0.15 min[e]
303	30303	0.15 max	17.00–19.00	8.00–10.00	Mo 0.60 max
303Se	30303Se	0.15 max	17.00–19.00	8.00–10.00	P 0.20 max S 0.06 max Se 0.15 min
303SeA		0.08 max	17.25–18.75	11.50–13.00	Se 0.15–0.35
304	30304	0.08 max	18.00–20.00	8.00–10.00	
304L		0.030 max	18.00–20.00	8.00–10.00	
305	30305	0.12 max	17.00–19.00	10.00–13.00	
307		0.07–0.15	19.50–21.50	9.00–10.50	Mo residual only
308	30308	0.08 max	1900–21.00	10.00–12.00	
308 Mod		0.07–0.15	19.50–21.50	9.00–10.50	Mo residual only
309	30309	0.20 max	22.00–24.00	12.00–15.00	
309S	30309S	0.08 max	22.00–24.00	12.00–15.00	
309SCb		0.08 max	22.00–24.00	12.00–15.00	NbTa min. 10 times carbon Ta 0.10 max
309SCbTa		0.08 max	22.00–24.00	12.00–15.00	NbTa min. 10 times carbon
310	30310	0.25 max	24.00–26.00	19.00–22.00	
314	30314	0.25 max	23.00–26.00	19.00–22.00	
316	30316	0.08 max	16.00–18.00	10.00–14.00	Mo 2.00–3.00
316L	30316L	0.030 max	16.00–18.00	10.00–14.00	Mo 2.00–3.00
317	30317	0.08 max	18.00–20.00	11.00–15.00	Mo 3.00–4.00
318		0.10 max	16.00–18.00	10.00–14.00	Mo 2.00–3.00 NbTa min. 10 times carbon
D319		0.07 max	17.50–19.50	11.00–15.00	Mn 2.00 max Si 1.00 max Mo 2.25–3.00
321	30321	0.08 max	17.00–19.00	9.00–12.00	Ti min. 5 times carbon
330		0.25 max	14.00–16.00	33.00–36.00	
347	30347	0.08 max	17.00–19.00	9.00–13.00	NbTa min. 10 times carbon
348	30348	0.08 max	17.00–19.00	9.00–13.00	NbTa min, 10 times carbon Ta 0.10 max Co 0.20 max
403	51403	0.15 max	11.50–13.00		
405	51405	0.08 max	11.50–14.50		Al 0.10–0.30
410	51410	0.15 max	11.50–13.50		
410Mo		0.15 max	11.50–13.50		Mo 0.40–0.60
414	51414	0.15 max	11.50–13.50	1.25–2.50	
416	51416	0.15 max	12.00–14.00		P 0.06 max S 0.15 min Mo 0.60 max
410Se	51410Se	0.15 max	12.00–14.00		P 0.06 mas S 0.06 max Se 0.15 min
420	51420	>0.15	12.00–14.00		

Table 2.4 ***(Continued)***

AISI Type Number	SAE Type[a] Number	Chemical Composition, %			
		Carbon	Chromium	Nickel	Other
420F	51420F	>0.15	12.00–14.00		S[f]
430	51430	0.12 max	14.00–18.00		
430F	51430F	0.12 max	14.00–18.00		P 0.06 max S 0.15 min Mo 0.60 max
430Ti		0.10 max	16.00–18.00		Ti 0.30–0.70
431	51431	0.20 max	15.00–17.00	1.25–2.50	
434A		0.05–0.10	15.00–17.00		Cu 0.75–1.10
442	51442	0.25 max	18.00–23.00		
446	51446	0.20 max	23.00–27.00		N 0.25 max
501	51501	>0.10	4.00–6.00		Mo 0.40–0.65
502	51502	0.10 max	4.00–6.00		Mo 0.40–0.65

[a] SAE chemical composition (ladle) ranges may differ slightly in certain elements from AISI limits.

[b] Manganese: All steels of AISI Type 300 series—2.00% max. All steels of AISI Type 400 and 500 series—1.00% max except 416, 416Se, 430F, and 430Se (1.25% max) and Type 446 (1.5% max).

[c] Phosphorus: All steels of AISI Type 200 series—0.060% max. All steels of AISI Type 300 series—0.045% max except Types 303 and 303Se (0.20% max). All steels of AISI Type 400 and 500 series—0.040% max except Types 416, 416Se, 430F, and 430FSe (0.060% max).

[d] Silicon: All steels of AISI Type 200, 300, 400 and 500 series—1.00% max except where otherwise indicated.

[e] Sulfur: All steels of AISI Type 200, 300, 400, and 500 series—0.30% max except Types 303, 416, and 430F (0.15% min) and Types 303Se, 416Se, and 430FSe (0.060% max).

[f] No restriction.

cutting edge. The necessary hardness for different applications can be obtained by selecting grade A, B, or C, with increasing carbon content in that order.

Other martensitic grades are types 501 and 502, the former with > 0.10% and the latter < 0.10% carbon; both contain 4.6% chromium. These grades are also air hardening, but do not have the corrosion resistance of the 12% chromium grades. Type 501 and 502 have wide application in the petroleum industry for hot lines, bubble towers, valves, and plates.

2.7.8 Ferrite Stainless Steels

These steels are iron–chromium alloys that are largely ferritic and not hardenable by heat treatment (ignoring the 475°C embrittlement). They include types 405, 430, 430F, and 446 (see Table 2.4).

The most common ferritic grade is type 430, containing 0.12% carbon or less and 14–18% chromium. Because of its higher chromium content, the corrosion resistance of type 430 is superior to that of the martensitic grades. Furthermore, type 430 may be drawn, formed, and, with proper techniques, welded. It is widely used for automotive and architectural trim. It is employed in equipment for the manufacture and handling of nitric acid to which it is resistant. Type 430 does not have high creep strength but is suitable for some types of service up to 815°C and thus has application in combustion chambers for domestic heating furnaces.

The high chromium content of type 446 (23–27% chromium) imparts excellent heat resistance, although its high-temperature strength is only slightly better than that of carbon steel. Type 446 is used in sheet or strip form up to 1150°C. This grade does not have the good drawing characteristics of type 430, but it may be formed. Accordingly, it is widely used for furnace parts such as muffles, burner sleeves, and annealing baskets. Its resistance to nitric and other oxidizing acids makes it suitable for chemical-processing equipment.

2.7.9 Austenitic Stainless Steels

These steels are iron-chromium–nickel alloys not hardenable by heat treatment and predominantly austenitic. They include types 301, 302, 302B, 303, 304, 304L, 305, 308, 309, 310, 314, 316, 316L, 317, 321, and 347. In some recently developed austenitic stainless steels, all or part of the nickel is replaced by manganese and nitrogen in proper amounts, as in one proprietary steel and types 201 and 202 (see Table 2.4).

The most widely used austenitic stainless steel is type 302, known as 18–8; it has excellent corrosion resistance and, because of its austenitic structure, excellent ductility. It may be deep drawn or strongly formed. It can be readily welded, but carbide precipitation must be avoided in and near the weld by cooling rapidly enough after welding. Where carbide precipitation presents problems, types 321, 347, or 304L may be used. The applications of type 302 are wide and varied, including kitchen equipment and utensils; dairy installations; transportation equipment; and oil-, chemical-, paper-, and food-processing machinery.

The low nickel content of type 301 causes it to harden faster than type 302 because of reduced austenite stability. Accordingly, although type 301 can be drawn successfully, its drawing properties are not as good as those of type 302. For the same reason, type 301 can be cold rolled to very high strength.

Type 301, because of its lower carbon content, is not as prone as type 302 to give carbide precipitation problems in welding. In addition, its somewhat higher chromium content makes it slightly more resistant to corrosion. It is used to withstand severe corrosive conditions in the paper, chemical, and other industries.

The austenitic stainless steels are widely used for high-temperature service.

Types 321 and 347, with additions of titanium and niobium, respectively, are used in welding applications and high-temperature service under corrosive conditions. Type 304L may be used as an alternative for types 321 and 347 in welding and stress-relieving applications below 426°C.

The addition of 2–4% molybdenum to the basic 18–8 composition produces types 316 and 317 with improved corrosion resistance. These grades are employed in the textile, paper, and chemical industries where strong sulfates, chlorides, and phosphates and reducing acids such as sulfuric, sulfurous, acetic, and hydrochloric acids are used in such concentrations that the use of corrosion-resistant alloys is mandatory. Types 316 and 317 have the highest creep and rupture strengths of any commercial stainless steels.

The austenitic stainless steels most resistant to oxidation are types 309 and 310. Because of their high chromium and nickel contents, these steels resist scaling at temperatures up to 1090 and 1150°C and, consequently, are used for furnace parts and heat exchangers. They are somewhat harder and not as ductile as the 18–8 types, but they may be drawn and formed. They can be welded readily and have increasing use in the manufacture of jet-propulsion motors and industrial-furnace equipment.

For applications requiring good machinability, type 303 containing sulfur or selenium may be used.

2.7.10 High-Temperature Service, Heat-Resisting Steels

The term high-temperature service comprises many types of operations in many industries. Conventional high-temperature equipment includes steam boilers and turbines, gas turbines, cracking stills, tar stills, hydrogenation vessels, heat-treating furnaces, and fittings for diesel and other internal-combustion engines. Numerous steels are available from which to select the one best suited for each of the foregoing applications. Where unusual conditions occur, modification of the chemical composition may adapt an existing steel grade to service conditions. In some cases, however, entirely new alloy combinations must be developed to meet service requirements. For example, the aircraft and missile industries have encountered design problems of increased complexity, requiring metals of great high-temperature strength for both power plants and structures, and new steels are constantly under development to meet these requirements.[47,48]

A number of steels suitable for high-temperature service are given in Table 2.5.

The design of load-bearing structures for service at room temperature is generally based on the yield strength or for some applications on the tensile strength. The metal behaves essentially in an elastic manner, that is, the structure undergoes an elastic deformation immediately upon load appli-

Table 2.5 Alloy Composition of High-Temperature Steels[1]

Ferritic Steels	Austenitic Steels	AISI Type
0.5% Mo	18% Cr-8% Ni	304
0.5% Cr-0.5% Mo	18% Cr-8% Ni with Mo	316
1% Cr-0.5% Mo	18% Cr-8% Ni with Ti	321
2% Cr-0.5% Mo	18% Cr-8% Ni with Nb	347
2.25% Cr-1% Mo	25% Cr-12% Ni	309
3% Cr-0.5% Mo-1.5% Si	25% Cr-20% Ni	310
5% Cr-0.5% Mo-1.5% Si		
5% Cr-0.5% Mo. with Nb added		
5% Cr-0.5% Mo, with Ti added		
9% Cr-1% Mo		
12% Cr		410
17% Cr		430
27% Cr		446

cation and no further deformation occurs with time; when the load is removed, the structure returns to its original dimensions.

At high temperature, the behavior is different. A structure designed according to the principles employed for room-temperature service continues to deform with time after load application, even though the design data may have been based on tension tests at the temperature of interest. This deformation with time is called creep, since at the design stresses at which it first was recognized it occurred at a relatively low rate.

In spite of the fact that plain carbon steel has lower resistance to creep than high-temperature alloy steels, it is widely used in such applications up to 540°C, where rapid oxidation commences and a chromium-bearing steel must be employed. Low-alloy steels containing small amounts of chromium and molybdenum have higher creep strengths than carbon steel and are employed where materials of higher strength are needed. Above ~540°C, the amount of chromium required to impart oxidation resistance increases rapidly. The 2% chromium steels containing molybdenum are useful up to ~620°C, whereas 10–14% chromium steels may be employed up to ~700–760°C. Above this temperature, the austenitic 18–8 steels are commonly used; their oxidation resistance is considered adequate up to ~815°C. For service between 815 and 1090°C, steels containing 25% chromium and 20% nickel, or 27% chromium are used.

The behavior of steels at high temperature is quite complex, and only a few design considerations have been mentioned here.

2.7.11 Quenched and Tempered Low-Carbon Constructional Alloy Steels

A class of quenched and tempered low-carbon constructional alloy steels has been very extensively used in a wide variety of applications such as pressure vessels, mining and earth-moving equipment, and large steel structures.[49–51]

As a general class, these steels are referred to as low-carbon martensites to differentiate them from constructional alloy steels of higher carbon content, such as AISI alloy steels, that develop high-carbon martensite upon quenching. They are characterized by a relatively high strength, with minimum yield strengths of 690 MPa (100,000 psi), toughness down to –45°C, and weldability with joints showing full joint efficiency when welded with low-hydrogen electrodes. They are most commonly used in the form of plates, but also sheet products, bars, structural shapes, forgings, or semifinished products.

Several steel-producing companies manufacture such steels under various tradenames; their compositions are proprietary.

2.7.12 Maraging Steels

A group of high-nickel martenisitic steels called maraging steels contain so little carbon that they are referred to as carbon-free iron–nickel martensites.[52,53]

Iron–carbon martensite is hard and brittle in the as-quenched condition and becomes softer and more ductile when tempered. Carbon-free iron–nickel martensite, on the other hand, is relatively soft and ductile and becomes hard, strong, and tough when subjected to an aging treatment at 480°C.

The first iron–nickel martensitic alloys contained ~0.01% carbon, 20 or 25% nickel, and 1.5–2.5% aluminum and titanium. Later an 18% nickel steel containing cobalt, molybdenum, and titanium was developed, and still more recently a series of 12% nickel steels containing chromium and molybdenum came on the market.

By adjusting the content of cobalt, molybdenum, and titanium, the 18% nickel steel can attain yield strengths of 1380–2070 MPa (200,000–300,000 psi) after the aging treatment. Similarly, yield strengths fo 12% nickel steel in the range of 1035–1380 MPa (150,000–200,000 psi) can be developed by adjusting its composition.

2.7.13 Silicon-Steel Electrical Sheets

The silicon steels are characterized by relatively high permeability, high electrical resistance, and low hysteresis loss when used in magnetic circuits. First patented in the United Kingdom around 1900, the silicon steels permitted the development of more powerful electrical equipment and have furthered the rapid growth of the electrical power industry. Steels containing 0.5–5% silicon are produced in sheet form for the laminated magnetic cores of electrical equipment and are referred to as electrical sheets.[54–56]

The grain-oriented steels, containing ~3.25% silicon, are used in the highest efficiency distribution and power transformers and in large turbine generators. They are processed in a special way to give them directional properties related to orientation of the crystals making up the structure of the steel in a preferred direction.

The nonoriented steels are subdivided into low-silicon steels, containing ~0.5–1.5% silicon, used mainly in rotors and stators of motors and generators. Steels containing ~1% silicon are used for reactors, relays, and small intermittent-duty transformers.

Intermediate-silicon steels (2.5–3.5% Si) are used in motors and generators of average to high efficiency and in small- to medium-size intermittent-duty transformers, reactors, and motors.

High-silicon steels (~3.75–5.00% Si) are used in power transformers and high-efficiency motors, generators, and transformers, and in communications equipment.

REFERENCES

1. H. E. McGannon, (ed.), *The Making, Shaping and Treating of Steel*, 9th ed., U.S. Steel Corporation, Pittsburgh, PA, 1971.
2. *Applications of Modern Metallographic Techniques*, STP 480, American Society for Testing Materials, Philadelphia, PA, 1970.
3. W. C. Leslie, *The Physical Metallurgy of Steels*, Hemisphere Publishing, McGraw-Hill, New York, 1981
4. E. C. Bain and H. W. Paxton, *Alloying Elements in Steel*, American Society for Metals, Metals Park, OH, 1961.
5. *Heat Treatment '79*, Metals Society Publication 261, Metals Society, London, 1980.
6. K. E. Thelning, *Steel and Its Heat Treatment: Bofors Handbook*, Butterworths, Boston, 1975.
7. D. V. Doane and J. S. Kirkaldy, *Hardenability Concepts with Applications to Steel*, The Metallurgical Society–AIME, Warrendale, PA, 1978.
8. C. A. Siebert, D. V. Doane, and D. H. Breen, *The Hardenability of Steels*, American Society for Metals, Metals Park, OH, 1977.
9. G. Krauss, *Principles of Heat Treatment of Steel*, American Society for Metals, Metals Park, OH, 1980.
10. M. Atkins, *Atlas of Continuous Cooling Transformations Diagrams for Engineering Steels*, British Steel Corp., Sheffield, UK, 1978.
11. J. S. Blair, *The Profitable Way: Carbon Sheet Steel Specifying and Purchasing Handbook* General Electric Technology Marketing, Schenectady, NY, 1978.
12. J. S. Blair, *The Profitable Way: Carbon Strip Steel Specifying and Purchasing Handbook*, General Electric Technology Marketing, Schenectady, NY, 1978.
13 J. D. Jevons, *The Metallurgy of Deep Drawing and Pressing*, Wiley, New York, 1942.
14. *Low Carbon Structural Steels for the Eighties*, Institution of Metallurgists, London, 1977.
15. J. S. Blair, *The Profitable Way: Carbon Plate Steel Specifying and Purchasing Handbook*, General Electric Technology Marketing, Schenectady, NY, 1978.
16. R. A. Kot and J. W. Morris (eds.), *Structure and Properties of Highly Formable Dual-Phase Steels*, The Metallurgical Society–AIME, Warrendale, PA, 1979.
17. A. T. Davenport (ed.), *Formable HSLA and Dual-Phase Steels*, The Metallurgical Society–AIME, Warrendale, PA, 1979.
18. A. B. Rothwell and J. M. Gray (eds.), *Welding of HSLA (Microalloyed) Structural Steels*, American Society for Metals, Metals Park, OH, 1978.
19. R. A. Kot and B. L. Bramfitt, *Fundamentals of Dual-Phase Steels*, The Metallurgical Society–AIME, Warrendale, PA, 1981.
20. P. E. Repas, *Iron Steelmaker* **7**, 12 (1980).
21. M. D. Baughman, K. L. Fetters, G. Perrault, Jr., and K. Toda, *Iron Steel Eng.* **56**, 52 (1979).
22. A. P. Coldren and G. T. Eldis, *J. Met.* **32**, 41 (1980).
23. B. P. Bardes (ed.), *Metals Handbook*, 9th ed., American Society for Metals, Metals Park, OH, 1978, Vol. 1, p. 127.
24. *Nickel Alloy Steels Data Book*, International Nickel Co., Inc., New York, 1967.
25. *Micro Alloying 75: Proceedings of an International Symposium on High-Strength Low-Alloy Steels*, Union Carbide Corp., New York, 1977.
26. F. B. Pickering, *Physical Metallurgy and the Design of Steels*, Applied Science Publishers, London, 1978.
27. G. R. Speich and D. S. Dabkowski, in *The Hot Deformation of Austenite*, J. B. Ballance (ed.), The Metallurgical Society–AIME, Warrendale, PA, 1977.
28. *Iron Age* **214**, MP9 (Dec. 9, 1974).
29. A. T. Davenport, D. R. DiMicco, and D. W. Dickinson, *J. Met.* **32**, 28 (1980).
30. *Steel Products Manual: Strip Steel*, American Iron and Steel Institute, Washington, DC, 1978.
31. *Alloy Cross Index*, Mechanical Properties Data Center, Battelle's Columbus Laboratories, Columbus, OH, 1981.
32. P. M. Unterweiser, *Worldwide Guide to Equivalent Irons and Steels*, American Society for Metals, Metals Park, OH, 1979.
33. *Unified Numbering System for Metals and Alloys*, Society of Automotive Engineers, Warrendale, PA, 1977.

34. *Handbook of Comparative World Steel Standards*, International Technical Information Institute, Tokyo, Japan, 1980.

35. R. B. Ross, *Metallic Materials Specification Handbook*, E. and F. N. Spon Ltd., New York, 1980.

36. C. W. Wegst, *Key to Steel (Stahlschluessel)*, Verlag Stahlschluessel Wegst KG, Marbach/Neckar, Federal Republic of Germany, 1974.

37. M. J. Wahll and R. F. Frontani, *Handbook of Soviet Alloy Compositions*, Metals and Ceramics Information Center, Battelle's Columbus Laboratories, Columbus, OH, 1976.

38. *Source Book on Stainless Steels*, American Society for Metals, Metals Park, OH, 1976.

39. K. G. Brickner and co-workers, *Selection of Stainless Steels*, American Society for Metals, Metals Park, OH, 1968.

40. D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, McGraw-Hill, New York, 1977.

41. W. F. Simmons and R. B. Gunia, *Compilation and Index of Trade Names, Specifications, and Producers of Stainless Alloys and Superalloys*, Data Series, DS45A, American Society for Testing Materials, Philadelphia, PA, 1972.

42. G. E. Rowan and co-workers, *Forming of Stainless Steels*, American Society for Metals, Metals Park, OH, 1968.

43. R. A. Lula (ed.), *Toughness of Ferritic Stainless Steels*, STP 706, American Society for Testing Materials, Philadelphia, PA, 1980.

44. C. R. Brinkman and H. W. Garvin (eds.), *Properties of Austenitic Stainless Steels and Their Weld Metals*, STP 679, American Society for Testing Materials, Philadelphia, PA, 1978.

45. J. J. Demo (ed.), *Structure, Constitution, and General Characteristics of Wrought Ferritic Stainless Steels*, STP 619, American Society for Testing Materials, Philadelphia, PA, 1977.

46. F. B. Pickering (ed.), *The Metallurgical Evolution of Stainless Steels*, American Society for Metals, Metals Park, OH, 1979.

47. E. F. Bradley (ed.), *Source Book on Materials for Elevated-Temperature Application*, American Society for Metals, Metals Park, OH, 1979.

48. G. V. Smith (ed.), *Ductility and Toughness Considerations in Elevated Temperature Service*, American Society of Mechanical Engineers, New York, 1978.

49. R. L. Brockenbrough and B. G. Johnston, *USS Steel Design Manual*, ADUSS 27-3400-03, U.S. Steel Corp., Pittsburgh, PA, 1974.

50. J. H. Gross, *Trans. ASME: J. Pressure Vessel Technology* **96**, 9 (1974).

51. *Annual Book of ASTM Standards, Part 4—Steel*, American Society for Testing Materials, Philadelphia, PA, 1982, p. 465.

52. S. Floreen and G. R. Speich, *Trans. ASM* **57**, 714 (1964).

53. *Third Maraging Steel Project Review*, AD 425 299, Air Force Systems Command Technical Documentary Report No. RTD-TDR-63-4048, Nov. 1963, available from National Technical Information Service of the United States Department of Commerce, Springfield, VA.

54. A. E. DeBarr, *Soft Magnetic Materials Used in Industry*, Reinhold, New York, 1953.

55. F. Brailsford, *Magnetic Materials*, Wiley, New York, 1960.

56. R. M. Bozorth, *Ferromagnetism*, Van Nostrand, New York, 1951.

57. R. J. King, "Steel," in *Kirk-Olthmer Encyclopedia of Chemical Technology*, 3rd ed., Wiley, New York, 1983, Vol. 21.