MANUFACTURING PROCESSES

Manufacturing processes can be broadly classified as follows:

1. *Casting, Foundry, or Molding Processes.* A permanent or a nonpermanent mold is prepared, and molten metal is poured into this prepared "cavity." The metal later solidifies and retains the shape of the mold cavity. In many cases the castings may have to be machined to conform to desired specifications and tolerances. Plastics and composites utilize molding processes, such as *injection molding.*
2. *Forming or Metalworking Processes.* This could be the next step after a casting or molding process is completed. The basic purpose is to modify the shape and size of the material. Examples are rolling, forging, extrusion, and bending.
3. *Machining or Material-Removal Processes.* In some cases, this could be the final process before commencing assembly operations. The objective is to remove certain designated, unwanted areas from a given part to yield the final desired "finished" shape. For example, a cutting tool may be used to cut a thread in a bolt. Traditionally, there are seven basic machining processes: shaping, drilling, turning, milling, sawing, broaching, and abrasive machining. Different machine tools have been developed to accomplish these tasks. For example, a lathe accomplishes the process of turning, and a drill press is used to drill holes. It is obviously convenient to perform several of these operations using a single workpiece setup. Equipment to accomplish such tasks are called *machining centers.*
4. *Nontraditional Machining Processes.* The traditional cutting tool in a lathe for example, removes a certain amount of material from the product and this results in a chip. There are several nontraditional chipless machining processes: chemical machining (as in photoengraving), chemical etching, physical vapor deposition (PVD), electropolishing or electroplating, thermochemical machining (TCM), electrochemical machining (ECM), electrodischarge machining (EDM), electron-beam machining (EBM), laser-beam machining (LBM), ultrasonic machining (USM), water-jet machining, plasma-arc welding (PAW), plasma-arc cutting (PAC), and plasma-jet machining.
5. *Assembly or Joining and Fastening Processes.* These include mechanical fastening (with bolts, nuts, rivets, screws, etc.), soldering and brazing, welding, adhesive bonding, and press, snap, and shrink fittings.
6. *Finishing or Surface Treatment Processes.* Some products may need this operation, whereas others totally skip this operation. Finishing ensures that all the burrs left by machining are removed so that the product is prepared appropriately and is ready for shipment or assembly. Sometimes a protective or decorative coating may be used in a finishing operation. Surface treatment may include chemical cleaning with solvents, painting, plating, buffing, and galvanizing.
7. *Heat Treatment Processes.* These processes are included only in certain cases, where the mechanical and metallurgical properties must be altered to meet specific needs. These processes subject metal parts to heating and cooling at predetermined rates.
8. *Miscellaneous Processes.* These include many processes that may not have been covered under the previous categories: inspection, testing, palletizing, packaging, material handling, storage, and shipping fall under this heading.

UNCONVENTIONAL OR NONTRADITIONAL MANUFACTURING PROCESSES

Conventional manufacturing processes always utilize a tool, which is harder than the workpiece, to remove unwanted material. A function box as shown in Fig. 1 can represent a manufacturing operation. The box has an input and an output. The "controlling factor" and the "manufacturing process" are supposed to represent how the operation is accomplished. Because harder tools are required to process tougher workpieces, a variety of new technologies have been developed. Some are discussed here.

Electrodischarge Machining (EDM)

The principle used is creating a high-frequency electric spark to erode the workpiece. A simple R–C circuit or a high-frequency impulse voltage generator provides high frequencies (250 kHz, for example) and high voltages to cause an electron avalanche in a dielectric medium. Figure 2 is a schematic representation of the EDM process. The idea is to create an ionized path and a rapid increase in the plasma temperature to something like 20,000°F. Transient heat transfer is subsequently accomplished to the tool and to the work piece. A thin surface layer of the metal is ionized. Surface finishes as thin as 2 μin. can be accomplished in this manner. EDM erodes both the tool and the workpiece. Therefore, it requires trial and error to optimize the tool–workpiece combination. Material removal rates of 2 cubic inches per hour have been achieved using a supply-input power of 10 kW. Electrodischarge grinding (EDG) is another modern manufacturing process that follows the same principle.

Electrochemical Machining

The electrochemical machining (ECM) process is based on Faraday's electrolytic law relating to anodic dissolution of metals. In this case the workpiece is connected to the positive of a dc source and made the anode. The tool is the cathode and is connected to the negative terminal. Electronic current

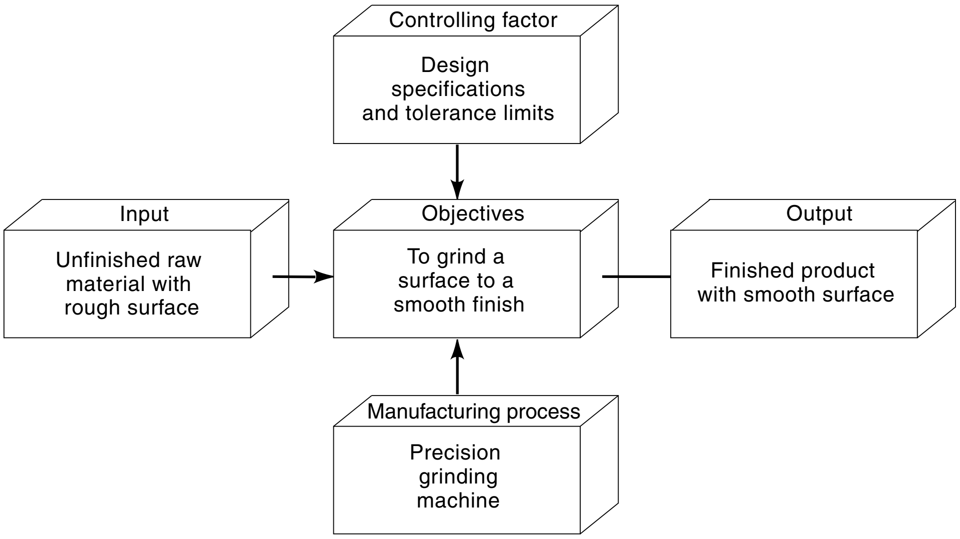

Figure 1. Representation of a manufacturing operation.

flows from cathode to anode and this effect is advantageously utilized to remove burrs or to drill a hole. It is estimated that 10,000 A of current remove steel at the rate of 1 in.^{3} per minute.

Ultrasonic Machining

In ultrasonic machining (USM) a transducer is used in conjunction with a tool that vibrates at low amplitudes but at high frequencies (25 kHz, for example). The principle is to remove material by microchipping and erosion. This is facilitated by an abrasive slurry contained between the workpiece and tool. The vibration of the tip of the tool results in imparting a very high velocity to the fine abrasive grains. Thus, the motion of the grinding grits is normal to the work surface, as shown in Fig. 3. In a conventional operation, the motion of grinding grits is tangential to the work surface. This produces a cutting type of miniature chips. Sometimes this process is also called ultrasonic grinding (USG). Ultrasonic welding (USW) is another manufacturing process that utilizes the same principle for welding.

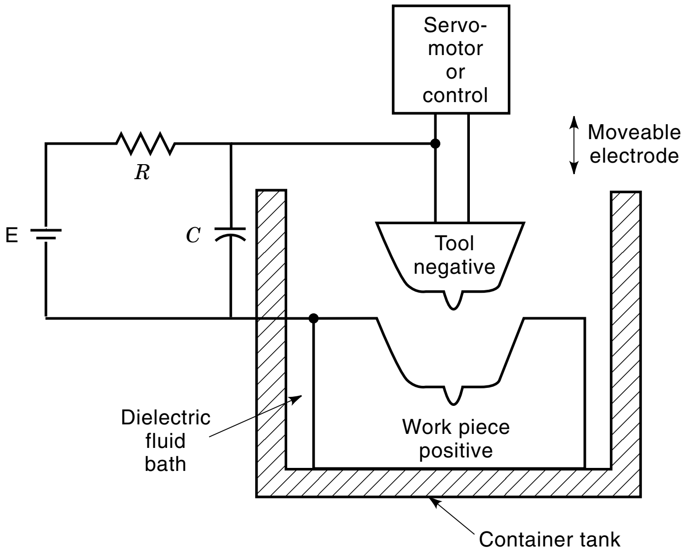

Figure 2. In the EDM process a powerful spark erodes the workpiece to a desired configuration.

Powder Metallurgy

A crude form of powder metallurgy may have existed in Egypt as early as 3000 B.C. This process gained popularity during the late nineteenth century. Powder metallurgy is a manufacturing process wherein finely-powdered materials are blended and pressed into a desired shape by a process known as compacting. Then the compacted mass is heated at a controlled temperature to bond the contacting surfaces of the particles, a process called sintering. Thus the final product is manufactured in the shape required. In addition, it also possesses the desired properties and characteristics. Further, the product often needs no machining or finishing. There is almost no wastage of material. Porosity and permeability of the product are easily controlled. To be cost effective, powder metallurgy (abbreviated P/M) requires high production volume. Quality-grade metal powders, precision punches, compacting dies, and specialized sintering equipment are all very expensive, and

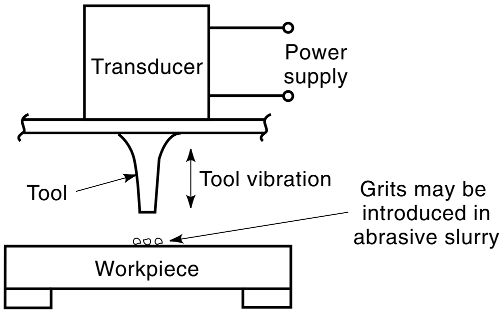

Figure 3. In ultrasonic grinding, motion of the grinding grits is perpendicular to the surface of the workpiece.

these contribute to high costs. Nevertheless, casting by traditional means may not be feasible for some high temperature alloys. Forging or hot extrusion, on the other hand, may result in poor tolerances and cause unnecessary die wear. Machining obviously generates waste material during processing. Powder metallurgy produces a wide range and variety of goods of diverse shape and size with good and acceptable tolerance limits. Modern manufacturing methods utilizing highly automated equipment produce several types of consumer items, toys, and automotive parts by the million. Because labor cost per part is low, powder metallurgy offers a viable alternative and is often preferred. Powder metallurgy is also preferred in cases where parts are produced in small quantities. Stringent specifications, tolerances, and desired metallurgical properties sometimes dictate the use of powder metallurgy. Small parts made from nickel-based super alloys, beryllium processing, certain types of self-lubricating bearings, and metallic filters are some examples where powder metallurgy is applied.

Laser Beam Machining (LBM), Welding, and Cutting

The principle used here is focusing the high-density energy of a laser (Light Amplification by Stimulated Emission of Radiation) beam to melt and evaporate portions of the workpiece in a controlled manner. A schematic representation is shown in Fig. 4. Extreme caution has to be exercised while using lasers because they can cause permanent retinal damage to the eyes. LBM is widely used in electronics and automotive parts manufacturing where precision drilling of holes (0.005 mm or 0.0002 in.) is required. Reflectivity and thermal conductivity of the workpiece surface play a major role in LBM. Excimer lasers are very popular for drilling holes and marking plastics and ceramics. Pulsed carbon dioxide lasers are commonly used for cutting ceramics and metals. Neodymium : Yttrium-aluminum-garnet (Nd : YAG) lasers and ruby lasers are used for welding metals.

Electron Beam Machining (EBM), Welding, and Cutting

Unlike laser beam machining, electron beam machining requires a vacuum. Dc voltages as high as 200 kV are used to accelerate electrons to speeds comparable to the speed of light. These high-speed electrons impinge on the surface of the workpiece and generate heat which accomplishes the desired manufacturing operation, say, for example, drilling a hole or cutting a pattern in a precious metal. Caution must be exercised while using EBM because electrons, high voltages, vacuum, and metal surface all combine to generate hazardous X rays. Higher material removal rates (compared with EDM or LBM) are achieved by plasma-arc cutting (PAC). In this case ionized gases (plasma beams) are used which are particularly useful when cutting materials like stainless steel, and where very high temperatures (17,000°F) are needed.

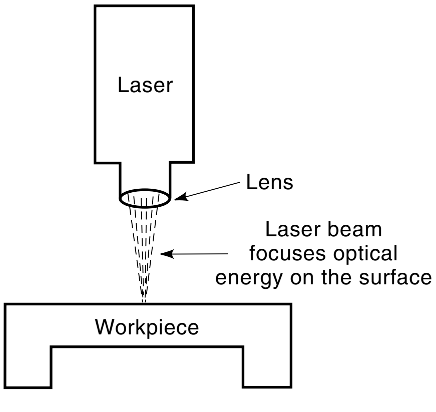

Figure 4. The principle behind the laser-beam-machining (LBM) process. The reflectivity and thermal conductivity of the workpiece influence LBM effectiveness.

Injection Molding

This type of fabrication is very popular for manufacturing complex-shaped plastic components. This method is similar to "die casting." In both, molten thermoplastic resin or some low melting point alloy is injected into a die. Then it is allowed to cool and harden. Modern day industry uses a wide variety of plastics and polymers. The idea implemented is to convert the plastic raw material directly into a finished product in a single operation. The process selected for fabricating these modern day plastics depends mainly on one criterion, whether the polymer is thermoplastic or thermosetting. Thermoplastic resins and polymers can be heated to a fluid state, so that they can be poured into a die or injected into a mold. In the case of thermosetting polymers, the polymerization process and the shape-forming process are achieved simultaneously because, once the polymerization has taken place, no further deformation is possible. Some of the methods available are casting, extrusion, thermoforming, etc. In addition, a variety of molding techniques are extensively used with plastics and polymers. Injection molding, reaction injection molding (RIM), rotational molding, foam molding, transfer molding, cold molding, compression molding, and hot-compression molding are some of the manufacturing processes most commonly used by the plastics industry.

Rapid Prototyping

Space age technologies and the computer revolution have required the manufacturing industry to produce prototypes of parts and components economically at a faster pace. This has resulted in the development of *rapid prototyping* techniques, also called *desktop manufacturing* or *free-form fabrication.* The idea is to manufacture an initial full-scale model of a product. The part is made directly from a three-dimensional CAD drawing. One of the methods is called *stereolithography,* a process based on curing and hardening a photocurable liquid polymer to the desired shape, using an ultraviolet laser source. Some of this equipment costs as much as half-a-million dollars. However, in many instances, this method is much cheaper than conventional prototyping, and the manufacturing industry has quickly recognized the importance and economic impact of these new technologies. Some of the other techniques used are selective laser sintering, three-dimensional printing, ballistic particle manufacturing, photochemical etching, and laminated object manufacturing. Almost all of these methods use CAD systems, and many cost in the region of hundreds of thousands of dollars. Some metals are used, but rapid prototyping with plastics and polymers, such as polystyrene, epoxy, polyester, PVC, and nylon, is more common.

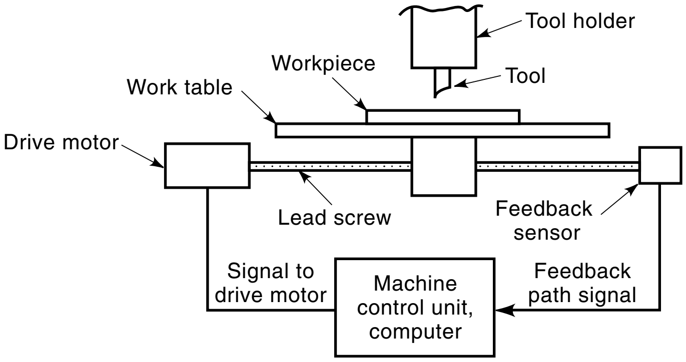

Figure 5. Improved quality and reduced manufacturing time are some of the advantages of using computers and closed-loop feedback systems.

Assembly or Joining and Fastening Processes

In most cases, this joining process is inevitable because the product cannot be manufactured in one single piece or one single operation. For example, a pressure cooker lid may be made from aluminum, but it has a plastic handle. In addition, the replaceable sealing ring is made from rubber. In other words, selected products may have to be replaced frequently, according to a routine maintenance schedule. In some cases it might be more economical to manufacture, transport, and assemble individual components at the customer's site. The functionality of different components may dictate that the desired properties be different. Besides traditional mechanical fastening, a variety of joining and fastening processes are available. If the material is "weldable," then the engineer has a wide selection depending on the application and needs. Under the category of welding one can list shielded metal arc welding, submerged arc welding, gas metal arc welding, flux-cored arc welding, electrogas welding, electrosag welding, gas tungsten arc welding, plasma-arc welding, laser-beam welding, electron-beam welding, inertia friction welding, linear friction welding, resistance spot welding, resistance seam welding, resistance projection welding, flash butt welding, stud arc welding, percussion welding, explosion welding, and diffusion welding.

In many cases welding may not be the proper choice. For example, alloys containing zinc or copper are considered unweldable. Aluminum alloys are weldable only at a very high temperature. Brazing and soldering processes use much lower temperatures compared to welding. Further, soldering temperatures are lower than those used for brazing. Brazing is a joining operation wherein a filler material is placed between the surfaces to be joined and the temperature is raised to melt the filler material but not the workpieces. As such, a brazed joint possesses higher strength. It is believed that brazing dates as far back as 3000 B.C. Brazing methods are identified by the various heating methods employed. Torch brazing, furnace brazing, induction brazing, resistance brazing, dip brazing, infrared brazing, and diffusion brazing are noteworthy. Brazing is conducted at relatively high temperatures. For example, stainless steel and nickel-copper alloys need high brazing temperatures on the order of 1120°C. At the other extreme, titanium can be brazed at 730°C, using silver alloys.

Soldering is similar to brazing but requires lower temperatures. In this case, the filler material melts below 450°C and again, as in brazing, the base metal does not melt. A general purpose soldering alloy widely used in electronics assembly

Figure 6. Water-jet cutting machine. Courtesy of Stäubli Unimation, Duncan S.C.

operations melts at 188°C and is made of 60% tin and 40% lead. However, special soldering alloys are made of silver-lead, silver-tin, or silver-bismuth. Silver–lead and silver–cadmium soldering alloys are used when strength at higher temperatures is required. Gold, silver, and copper are easy to solder. Stainless steel and aluminum are difficult to solder and need special fluxes that modify the surfaces. Automated soldering of electronic components to printed circuit boards at high speeds is accomplished with wave soldering equipment. Other methods include torch soldering, furnace soldering, iron soldering with a soldering iron, induction soldering, resistance soldering, dip soldering, infrared soldering, and ultrasonic soldering. Soldering is commonly associated with electronics assembly operations, such as printed circuit assembly.

Adhesive bonding has been gaining increased acceptance by manufacturing engineers since World War II. Common examples are bookbinding, labeling, packaging, and plywood manufacturing. The three basic types of adhesives are natural adhesives (examples, starch, soya flour), inorganic adhesives (example, sodium silicate) and synthetic organic adhesives (examples, thermoplastics and thermosetting polymers).

AUTOMATED MANUFACTURING PROCESSES

Manufacturing operations have been carried out on traditional machines, such as lathes and drill presses, for a long time. This lacked flexibility and required skilled craftsmanship, trained mechanics, and was labor-intensive. Besides, "repeatability" of operations or production of exactly identical parts was extremely difficult because of human involvement.

Figure 7. The Merlin® Gantry Robot in an industrial setting Courtesy of American Robot Corporation, Oakdale, PA.

Automation is derived from the Greek word *automatos,* which means self-acting. Automation is broadly defined as the process of performing certain preselected sequences of operations with very little labor or human intervention. Numerically controlled machine tools were developed only recently in the 1950s. This breakthrough came almost two centuries after the industrial revolution! The postwar era gave automated manufacturing processes a gigantic boost that was long overdue. The latter part of the twentieth century saw some of the outstanding technological developments, such as integrated circuits, high-speed computers, programmable controllers, lasers, robots, vision systems, artificial intelligence, and expert systems. Figure 5 shows how sensors, feedback control systems, computers and computer numerically controlled (CNC) machine tools help in automating a manufacturing process.

Manufacturing processes are cost effective only when they are designed, planned, and executed efficiently. Process plan-

Figure 8. Clean room applications include wafer handling and sputtering. Courtesy of Stäubli Unimation, Duncan S.C.

ning is labor-intensive and time-consuming because the "process planner" has to selectively choose the methods and sequences required for the production and assembly operations. The planner also selects the necessary machine tools, fixtures, and dies. This tedious task is made simple by using computer-aided process planning (CAPP), a powerful tool that views the complete manufacturing operation as one integrated system. There are two types of CAPP systems, *the derivative system* (wherein the idea is to follow a standard process stored in the computer files) and *the generative system* (wherein the process is automatically generated based on some sort of "logic"). CAPP obviously requires expensive, sophisticated software that works appropriately with CAD/CAM systems. Some of the benefits include reduced planning costs, decreased "lead times," and improved product quality. Computers have helped in inventory management and other areas. Group technology (GT), cellular material-requirements planning (MRP), manufacturing resource planning (MRP-II) are some of the areas destined to gain wider acceptance and usage during the twenty-first century. Coordinate measuring machines (CMM), lasers, vision systems, ultrasonics, and other noncontact measurement techniques are helping to streamline inspection and quality control.

Programmable automation has several advantages. Some are listed here:

1. improves product quality
2. eliminates dangerous jobs and hazardous working conditions
3. increases the safety of operating personnel
4. eliminates human error by reducing human involvement.
5. minimizes cycle times
6. minimizes effort
7. enhances productivity
8. relieves skilled labor shortages
9. relieves boredom
10. stabilizes production
11. reduces labor costs
12. reduces waste of material
13. reduces manufacturing costs
14. maintains consistency of product uniformity
15. increases product diversification and product flexibility
16. designs more repeatable processes, just-in-time (J.I.T.)
17. increases punctuality and conformity to stipulated delivery dates
18. improves management of in stock material and improves inventory control
19. motivates work force whose capabilities are more challenged
20. improves compliance with OSHA regulations and reduces accidents

Environmentally safe manufacturing processes are obviously very desirable, and *Water-jet machinging* (WJM) falls under this category. The force resulting from the momentum change of a stream of water can be advantageously utilized to create an efficient and clean cutting operation. Pressures ranging between 500 and 1200 MPa (1 Pascal = 1 Newton/meter^2 and 1 pound per square inch = 6891 Pa) are used to direct a jet of water to act like a saw. Water-jet machining, which is also called *hydrodynamic machinging,* can be very conveniently used to effectively cut plastics and composites. The food processing industry uses. WJM for slicing a variety of food products. Whether it is a strong and solid material like brick or wood, or a soft and flexible material such as vinyl or foam, hydrodynamic machining offers the engineer an advantageous choice for the selected manufacturing operation, because WJM eliminates the need for certain requirements, such as, for example, pre-drilled holes. A water-jet cutting machine can be seen in Fig. 6.

Robots have made a significant impact on the manufacturing shop floor, relieving humans from dull, dirty, and dangerous environments. They have been manufacturing high quality goods with minimal waste and at reduced costs. Robots are continuing to play a dominant role in streamlining several manufacturing processes. An example of a gantry robot installation is shown in Fig. 7.

Robots have helped the electronics manufacturing industry in a variety of ways. An example of a Robot being used in a semiconductor manufacturing processes is shown in Fig. 8.

Figure 9. Odex-III with telescoping leg design. Courtesy of Odetics, Inc., Anaheim, CA.

Here, the robot helps in a *clean room* application handling a silicon wafer. Silicon processing for the electronics industry may include the following: epitaxial growth, cleaning, deposition, and lithography using masks, inspection, measurement, etching and doping.

Industry is currently using *manufacturing cells* that operate without direct human intervention. Remotely controlled robots have been designed to work in hazardous environments or locations that are inaccessible to conventional wheeled or tracked vehicles. "Walking" robots, such as the Odex-III with its telescoping leg design, can maneuver in confined spaces and "climb" steep stairs (see Fig. 9). The twenty-first century will see great progress in the area of manufacturing processes.

The factory of the future will be a fully automated facility wherein several processes such as material handling, machining, assembly, inspection, and packaging, will all be accomplished using sophisticated sensor/vision equipped robots and computer controlled machine tools. The focus is on re-directing an unskilled direct labor force toward more creative jobs, such as robot–computer programming or information processing. The highly competitive global marketplace demands the development and successful implementation of sophisticated manufacturing processes that can be termed world class.

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