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Introduction and Overview of Manufacturing

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Making things has been an essential activity of human civilizations since before recorded history. Today, the term *manufacturing* is used for this activity. For technological and economic reasons, manufacturing is important to the welfare of the United States and most other developed and developing nations. *Technology* can be defined as the application of science to provide society and its members with those things that are needed or desired. Technology affects our daily lives, directly and indirectly, in many ways. Consider the list of products in Table 1.1. They represent various technologies that help our society and its members to live better. What do all these products have in common? They are all manufactured. These technological wonders would not be available to our society if they could not be manufactured. Manufacturing is the critical factor that makes technology possible.

Economically, manufacturing is an important means by which a nation creates material wealth. In the United States, the manufacturing industries account for only about 12% of gross domestic product (GDP). A country's natural resources, such as agricultural lands, mineral deposits, and oil reserves, also create wealth. In the U.S., agriculture, mining, and similar industries account for less than 5% of GDP (agriculture alone is only about 1%). Construction and public utilities make up around 5%. The rest is service industries, which include retail, transportation, banking, communication, education, and government. The service sector accounts for more than 75% of U.S. GDP. Government (federal, state, and local) accounts for more of GDP than the manufacturing sector; however, government services do not create wealth. In the modern global economy, a nation must have a strong manufacturing base (or it must have significant natural resources) if it is to provide a strong economy and a high standard of living for its people.

TABLE • 1.1 Products representing various technologies, most of which affect nearly all of us.

Athletic shoes	E-book reader	One-piece molded plastic patio chair
Automatic teller machine	Fax machine	Optical scanner
Automatic dishwasher	Hand-held electronic calculator	Personal computer (PC)
Ballpoint pen	High density PC diskette	Photocopying machine
Camcorder	Home security system	Pull-tab beverage cans
Cell phone	Hybrid gas-electric automobile	Quartz crystal wrist watch
Compact disc (CD)	Industrial robot	Self-propelled mulching lawnmower
Compact disc player	Ink-jet color printer	Smart phone
Compact fluorescent light bulb	LCD and Plasma TVs	Supersonic aircraft
Contact lenses	Magnetic resonance imaging (MRI) machine for medical diagnosis	Tablet computer
Digital camera	Medicines	Tennis racket of composite materials
Digital video disc (DVD)	Microwave oven	Video games
Digital video disc player		Washing machine and dryer

This opening chapter considers some general topics about manufacturing. What is manufacturing? How is it organized in industry? What are the materials, processes, and systems by which it is accomplished?

What Is Manufacturing?

The word **manufacture** is derived from two Latin words, **manus** (hand) and **factus** (make); the combination means made by hand. The English word manufacture is several centuries old, and “made by hand” accurately described the manual methods used when the word was first coined.¹ Most modern manufacturing is accomplished by automated and computer-controlled machinery (Historical Note 1.1).

Historical Note 1.1 *History of manufacturing*

The history of manufacturing can be separated into two subjects: (1) the discovery and invention of materials and processes to make things, and (2) the development of the systems of production. The materials and processes to make things predate the systems by several millennia. Some of the processes—casting, hammering (forging), and grinding—date back 6000 or more. The early fabrication of implements and weapons was accomplished more as crafts and trades than manufacturing as it is known today. The ancient Romans had what might be called factories to produce

weapons, scrolls, pottery and glassware, and other products of the time, but the procedures were largely based on handicraft.

The systems aspects of manufacturing are examined here, and the materials and processes are discussed in Historical Note 1.2. **Systems of manufacturing** refer to the ways of organizing people and equipment so that production can be performed more efficiently. Several historical events and discoveries stand out as having had a major impact on the development of modern manufacturing systems.

¹As a noun, the word **manufacture** first appeared in English around 1567 A.D. As a verb, it first appeared around 1683 A.D.

Certainly one significant discovery was the principle of **division of labor**—dividing the total work into tasks and having individual workers each become a specialist at performing only one task. This principle had been practiced for centuries, but the economist Adam Smith (1723–1790) is credited with first explaining its economic significance in *The Wealth of Nations*.

The **Industrial Revolution** (circa 1760–1830) had a major impact on production in several ways. It marked the change from an economy based on agriculture and handicraft to one based on industry and manufacturing. The change began in England, where a series of machines were invented and steam power replaced water, wind, and animal power. These advances gave British industry significant advantages over other nations, and England attempted to restrict export of the new technologies. However, the revolution eventually spread to other European countries and the United States. Several inventions of the Industrial Revolution greatly contributed to the development of manufacturing: (1) **Watt's steam engine**—a new power-generating technology for industry; (2) **machine tools**, starting with John Wilkinson's boring machine around 1775 (Historical Note 21.1); (3) the **spinning jenny, power loom**, and other machinery for the textile industry that permitted significant increases in productivity; and (4) the **factory system**—a new way of organizing large numbers of production workers based on division of labor.

While England was leading the industrial revolution, an important concept was being introduced in the United States: **interchangeable parts** manufacture. Much credit for this concept is given to Eli Whitney (1765–1825), although its importance had been recognized by others [10]. In 1797, Whitney negotiated a contract to produce 10,000 muskets for the U.S. government. The traditional way of making guns at the time was to custom-fabricate each part for a particular gun and then hand-fit the parts together by filing. Each musket was unique, and the time to make it was considerable. Whitney believed that the components could be made accurately enough to permit parts assembly without fitting. After several years of development in his Connecticut factory, he traveled to Washington in 1801 to demonstrate the principle. He laid out components for 10 muskets before government officials, including Thomas Jefferson, and proceeded to select parts randomly to assemble the guns. No special filing or fitting was required, and all of the guns worked perfectly. The secret behind his achievement was the collection of special machines, fixtures, and gages that he had developed in his factory. Interchangeable parts manufacture

required many years of development before becoming a practical reality, but it revolutionized methods of manufacturing. It is a prerequisite for mass production. Because its origins were in the United States, interchangeable parts production came to be known as the **American System** of manufacture.

The mid- and late 1800s witnessed the expansion of railroads, steam-powered ships, and other machines that created a growing need for iron and steel. New steel production methods were developed to meet this demand (Historical Note 6.1). Also during this period, several consumer products were developed, including the sewing machine, bicycle, and automobile. To meet the mass demand for these products, more efficient production methods were required. Some historians identify developments during this period as the **Second Industrial Revolution**, characterized in terms of its effects on manufacturing systems by (1) mass production, (2) scientific management movement, (3) assembly lines, and (4) electrification of factories.

In the late 1800s, the **scientific management** movement was developing in the United States in response to the need to plan and control the activities of growing numbers of production workers. The movement's leaders included Frederick W. Taylor (1856–1915), Frank Gilbreth (1868–1924), and his wife Lillian (1878–1972). Scientific management included several features [3]: (1) **motion study**, aimed at finding the best method to perform a given task; (2) **time study**, to establish work standards for a job; (3) extensive use of **standards** in industry; (4) the **piece rate system** and similar labor incentive plans; and (5) use of data collection, record keeping, and cost accounting in factory operations.

Henry Ford (1863–1947) introduced the **assembly line** in 1913 at his Highland Park, Michigan plant. The assembly line made possible the mass production of complex consumer products. Use of assembly line methods permitted Ford to sell a Model T automobile for as little as \$500, thus making ownership of cars feasible for a large segment of the U.S. population.

In 1881, the first electric power generating station had been built in New York City, and soon electric motors were being used as a power source to operate factory machinery. This was a far more convenient power delivery system than steam engines, which required overhead belts to distribute power to the machines. By 1920, electricity had overtaken steam as the principal power source in U.S. factories. The twentieth century was a time of more technological advances than in all other centuries combined. Many of these developments resulted in the **automation** of manufacturing.

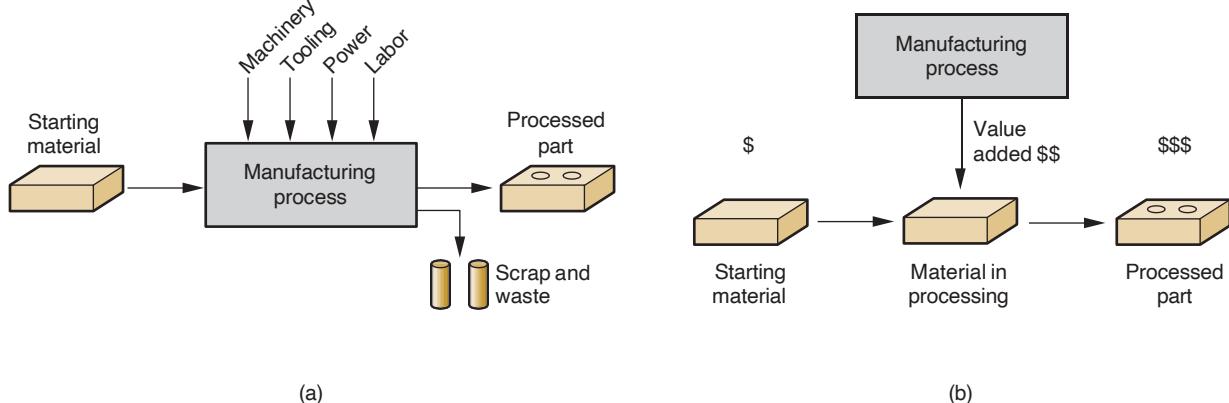


FIGURE 1.1 Two ways to define manufacturing: (a) as a technical process, and (b) as an economic process.

1.1.1 MANUFACTURING DEFINED

As a field of study in the modern context, manufacturing can be defined two ways, one technologic, and the other economic. Technologically, **manufacturing** is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labor, as depicted in Figure 1.1(a). Manufacturing is almost always carried out as a sequence of operations. Each operation brings the material closer to the desired final state.

Economically, **manufacturing** is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as depicted in Figure 1.1(b). The key point is that manufacturing **adds value** to the material by changing its shape or properties, or by combining it with other materials that have been similarly altered. The material has been made more valuable through the manufacturing operations performed on it. When iron ore is converted into steel, value is added. When sand is transformed into glass, value is added. When petroleum is refined into plastic, value is added. And when plastic is molded into the complex geometry of a patio chair, it is made even more valuable.

Figure 1.2 shows a product on the left and the starting workpiece from which the circular frame of the product was produced on the right. The starting workpiece is

FIGURE 1.2 A mechanical heart valve on the left and the titanium workpiece from which the frame is machined on the right. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)



a titanium billet, and the product consists of a carbon wafer assembled to the hook that protrudes from the right of the frame. The product is an artificial heart valve costing thousands of dollars, well worth it for patients who need one. (By the way, the surgeon who installs it charges several more thousand dollars.) The titanium billet costs a small fraction of the selling price. It measures about 25 mm (1 in) in diameter. The frame was machined (a material removal process, Section 1.3.1) from the starting billet. Machining time was about one hour. Note the added value provided by this operation. Note also the waste in the unit operation, as depicted in Figure 1.1(a); the finished frame has only about 5% of the mass of the starting workpiece (although the titanium swarf can be recycled).

The words manufacturing and production are often used interchangeably. The author's view is that production has a broader meaning than manufacturing. To illustrate, one might speak of "crude oil production," but the phrase "crude oil manufacturing" seems out of place. Yet when used in the context of products such as metal parts or automobiles, either word seems okay.

1.1.2 MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity performed by companies that sell products to customers. The type of manufacturing done by a company depends on the kinds of products it makes.

Manufacturing Industries Industry consists of enterprises and organizations that produce or supply goods and services. Industries can be classified as primary, secondary, or tertiary. **Primary industries** cultivate and exploit natural resources, such as agriculture and mining. **Secondary industries** take the outputs of the primary industries and convert them into consumer and capital goods. Manufacturing is the principal activity in this category, but construction and power utilities are also included. **Tertiary industries** constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 1.2.

TABLE • 1.2 Specific industries in the primary, secondary, and tertiary categories.

Primary	Secondary		Tertiary (service)	
Agriculture	Aerospace	Food processing	Banking	Insurance
Forestry	Apparel	Glass, ceramics	Communications	Legal
Fishing	Automotive	Heavy machinery	Education	Real estate
Livestock	Basic metals	Paper	Entertainment	Repair and maintenance
Quarries	Beverages	Petroleum refining	Financial services	
Mining	Building materials	Pharmaceuticals	Government	Restaurant
Petroleum	Chemicals	Plastics (shaping)	Health and medical	Retail trade
	Computers	Power utilities	Hotel	Tourism
	Construction	Publishing	Information	Transportation
	Consumer appliances	Textiles		Wholesale trade
	Electronics	Tire and rubber		
	Equipment	Wood and furniture		
	Fabricated metals			

This book is concerned with the secondary industries in Table 1.2, which include the companies engaged in manufacturing. However, the International Standard Industrial Classification (ISIC) used to compile Table 1.2 includes several industries whose production technologies are not covered in this text; for example, beverages, chemicals, and food processing. In this book, manufacturing means production of **hardware**, which ranges from nuts and bolts to digital computers and military weapons. Plastic and ceramic products are included, but apparel, paper, pharmaceuticals, power utilities, publishing, and wood products are excluded.

Manufactured Products Final products made by the manufacturing industries can be divided into two major classes: consumer goods and capital goods. **Consumer goods** are products purchased directly by consumers, such as cars, personal computers, TVs, tires, and tennis rackets. **Capital goods** are those purchased by companies to produce goods and/or provide services. Examples of capital goods include aircraft, computers, communication equipment, medical apparatus, trucks and buses, railroad locomotives, machine tools, and construction equipment. Most of these capital goods are purchased by the service industries. It was noted in the introduction that manufacturing accounts for about 12% of gross domestic product and services about 75% of GDP in the United States. Yet the manufactured capital goods purchased by the service sector are the enablers of that sector. Without the capital goods, the service industries could not function.

In addition to final products, other manufactured items include the materials, components, tools, and supplies used by the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings and extrusions, cutting tools, dies, molds, and lubricants. Thus, the manufacturing industries consist of a complex infrastructure with various categories and layers of intermediate suppliers with whom the final consumer never deals.

This book is generally concerned with **discrete items**—individual parts and assembled products rather than items produced by **continuous processes**. A metal stamping is a discrete item, but the sheet-metal coil from which it is made is continuous (almost). Many discrete parts start out as continuous or semicontinuous products, such as extrusions and electrical wire. Long sections made in almost continuous lengths are cut to the desired size. An oil refinery is a better example of a continuous process.

Production Quantity and Product Variety The quantity of products made by a factory has an important influence on the way its people, facilities, and procedures are organized. Annual production quantities can be classified into three ranges: (1) **low** production, quantities in the range 1 to 100 units per year; (2) **medium** production, from 100 to 10,000 units annually; and (3) **high** production, 10,000 to millions of units. The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the kinds of products, these boundaries may shift by an order of magnitude or so.

Production quantity refers to the number of units produced annually of a particular product type. Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. Product variety refers to different product designs or types that are produced in the plant. Different products have different shapes and

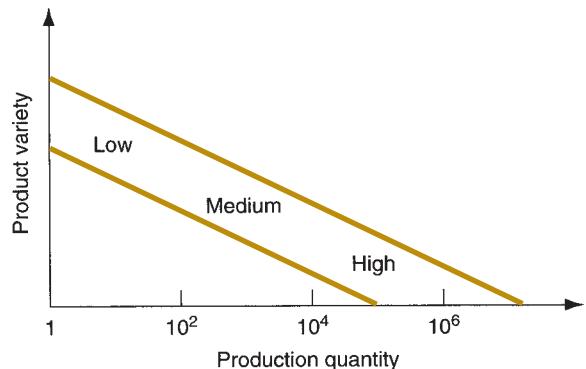


FIGURE 1.3 Relationship between product variety and production quantity in discrete product manufacturing.

sizes; they perform different functions; they are intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. When the number of product types made in the factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. If a factory's product variety is high, then its production quantity is likely to be low; but if production quantity is high, then product variety will be low, as depicted in Figure 1.3. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.3.

Although product variety has been identified as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity because details on how much the designs differ are not captured simply by the number of different designs. Differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Within each product type, there are differences among specific models.

The extent of the product differences may be small or great, as illustrated in the automotive industry. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are virtually the same. In different plants, the company builds heavy trucks. The terms "soft" and "hard" might be used to describe these differences in product variety. **Soft product variety** occurs when there are only small differences among products, such as the differences among car models made on the same production line. In an assembled product, soft variety is characterized by a high proportion of common parts among the models. **Hard product variety** occurs when the products differ substantially, and there are few common parts, if any. The difference between a car and a truck exemplifies hard variety.

1.1.3 MANUFACTURING CAPABILITY

A manufacturing plant consists of a set of **processes** and **systems** (and people, of course) designed to transform a certain limited range of **materials** into products of increased value. These three building blocks—materials, processes, and systems—constitute the subject of modern manufacturing. There is a strong interdependence among these factors. A company engaged in manufacturing cannot do everything.

It must do only certain things, and it must do those things well. **Manufacturing capability** refers to the scope of technical and physical capabilities and limitations of a manufacturing company and each of its plants. Manufacturing capability has three dimensions: (1) technological processing capability, (2) physical size and weight of product, and (3) production capacity.

Technological Processing Capability The technological processing capability of a plant (or company) is its available set of manufacturing processes. Certain plants perform machining operations, others roll steel billets into sheet stock, and others build automobiles. A machine shop cannot roll steel, and a rolling mill cannot build cars. The underlying feature that distinguishes these plants is the processes they can perform. Technological processing capability is closely related to material type. Certain manufacturing processes are suited to certain materials, whereas other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in certain material types. Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies must concentrate on the design and manufacture of products that are compatible with their technological processing capability.

Physical Product Limitations A second aspect of manufacturing capability is imposed by the physical product. A plant with a given set of processes is limited in terms of the size and weight of the products that can be accommodated. Large, heavy products are difficult to move. To move these products about, the plant must be equipped with cranes of the required load capacity. Smaller parts and products made in large quantities can be moved by conveyor or other means. The limitation on product size and weight extends to the physical capacity of the manufacturing equipment as well. Production machines come in different sizes. Larger machines must be used to process larger parts. The production and material handling equipment must be planned for products that lie within a certain size and weight range.

Production Capacity A third limitation on a plant's manufacturing capability is the production quantity that can be produced in a given time period (e.g., month or year). This quantity limitation is commonly called **plant capacity**, or **production capacity**, defined as the maximum rate of production that a plant can achieve under assumed operating conditions. The operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and so on. These factors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?

Plant capacity is usually measured in terms of output units, such as annual tons of steel produced by a steel mill, or number of cars produced by a final assembly plant. In these cases, the outputs are homogeneous. In cases in which the output units are not homogeneous, other factors may be more appropriate measures, such as available labor hours of productive capacity in a machine shop that produces a variety of parts.

Materials, processes, and systems are the basic building blocks of manufacturing and the three broad subject areas of this book. This introductory chapter provides an overview of these three subjects before embarking on a detailed coverage in the remaining chapters.

1.2 Materials in Manufacturing

Most engineering materials can be classified into one of three basic categories: (1) metals, (2) ceramics, and (3) polymers. Their chemistries are different, their mechanical and physical properties are different, and these differences affect the manufacturing processes that can be used to produce products from them. In addition to the three basic categories, there are (4) **composites**—nonhomogeneous mixtures of the other three basic types rather than a unique category. The classification of the four groups is pictured in Figure 1.4. This section provides a survey of these materials. Chapters 6 through 9 cover the four material types in more detail.

1.2.1 METALS

Metals used in manufacturing are usually **alloys**, which are composed of two or more elements, with at least one being a metallic element. Metals and alloys can be divided into two basic groups: (1) ferrous, and (2) nonferrous.

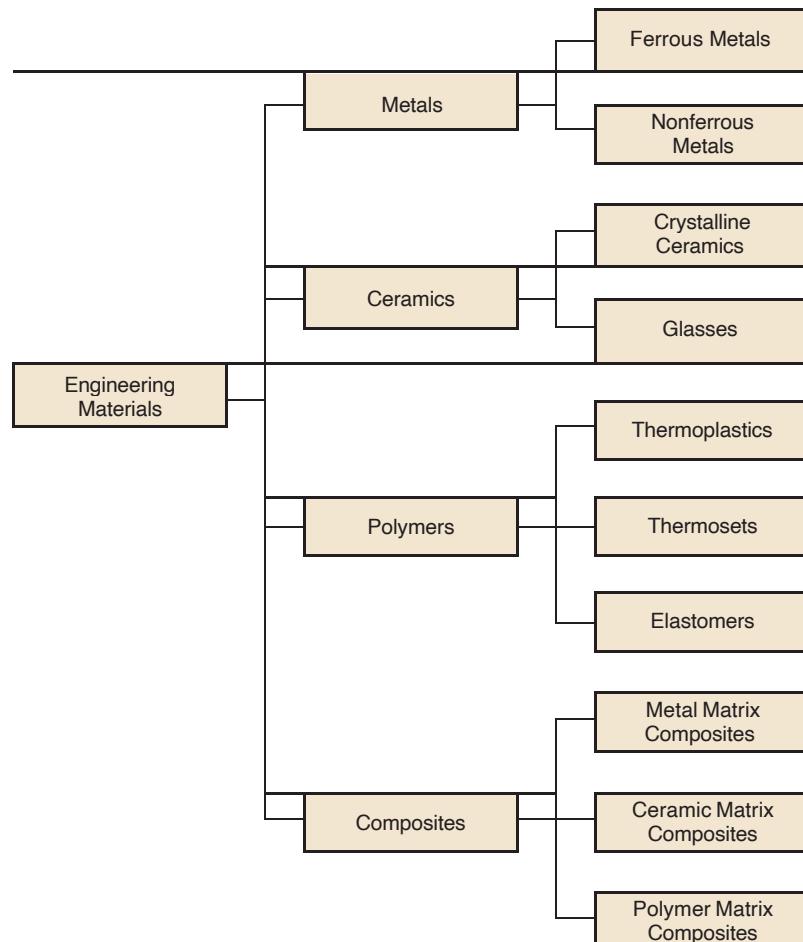


FIGURE 1.4
Classification of the
four engineering
materials.

Ferrous Metals Ferrous metals are based on iron; the group includes steel and cast iron. These metals constitute the most important group commercially, more than three-fourths of the metal tonnage throughout the world. Pure iron has limited commercial use, but when alloyed with carbon, iron has more uses and greater commercial value than any other metal. Alloys of iron and carbon form steel and cast iron.

Steel can be defined as an iron–carbon alloy containing 0.02% to 2.11% carbon. It is the most important category within the ferrous metal group. Its composition often includes other alloying elements as well, such as manganese, chromium, nickel, and molybdenum, to enhance the properties of the metal. Applications of steel include construction (bridges, I-beams, and nails), transportation (trucks, rails, and rolling stock for railroads), and consumer products (automobiles and appliances).

Cast iron is an alloy of iron and carbon (2% to 4%) used in casting (primarily sand casting). Silicon is also present in the alloy (in amounts from 0.5% to 3%), and other elements are often added also, to obtain desirable properties in the cast part. Cast iron is available in several different forms, of which gray cast iron is the most common; its applications include blocks and heads for internal combustion engines.

Nonferrous Metals Nonferrous metals include the other metallic elements and their alloys. In almost all cases, the alloys are more important commercially than the pure metals. The nonferrous metals include the pure metals and alloys of aluminum, copper, gold, magnesium, nickel, silver, tin, titanium, zinc, and other metals.

1.2.2 CERAMICS

A ceramic is defined as a compound containing metallic (or semimetallic) and nonmetallic elements. Typical nonmetallic elements are oxygen, nitrogen, and carbon. Ceramics include a variety of traditional and modern materials. Traditional ceramics, some of which have been used for thousands of years, include: **clay** (abundantly available, consisting of fine particles of hydrous aluminum silicates and other minerals used in making brick, tile, and pottery); **silica** (the basis for nearly all glass products); and **alumina** and **silicon carbide** (two abrasive materials used in grinding). Modern ceramics include some of the preceding materials, such as alumina, whose properties are enhanced in various ways through modern processing methods. Newer ceramics include: **carbides**—metal carbides such as tungsten carbide and titanium carbide, which are widely used as cutting tool materials; and **nitrides**—metal and semimetal nitrides such as titanium nitride and boron nitride, used as cutting tools and grinding abrasives.

For processing purposes, ceramics can be divided into crystalline ceramics and glasses. Different methods of manufacturing are required for the two types. Crystalline ceramics are formed in various ways from powders and then fired (heated to a temperature below the melting point to achieve bonding between the powders). The glass ceramics (namely, glass) can be melted and cast, and then formed in processes such as traditional glass blowing.

1.2.3 POLYMERS

A polymer is a compound formed of repeating structural units called **mers**, whose atoms share electrons to form very large molecules. Polymers usually consist of carbon plus one or more other elements such as hydrogen, nitrogen, oxygen, and chlorine. Polymers are divided into three categories: (1) thermoplastic polymers, (2) thermosetting polymers, and (3) elastomers.

Thermoplastic polymers can be subjected to multiple heating and cooling cycles without substantially altering the molecular structure of the polymer. Common thermoplastics include polyethylene, polystyrene, polyvinylchloride, and nylon. **Thermosetting polymers** chemically transform (cure) into a rigid structure upon cooling from a heated plastic condition; hence the name thermosetting. Members of this type include phenolics, amino resins, and epoxies. Although the name “thermosetting” is used, some of these polymers cure by mechanisms other than heating. **Elastomers** are polymers that exhibit significant elastic behavior; hence the name elastomer. They include natural rubber, neoprene, silicone, and polyurethane.

1.2.4 COMPOSITES

Composites do not really constitute a separate category of materials; they are mixtures of the other three types. A **composite** is a material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to those of its constituents. The term **phase** refers to a homogeneous mass of material, such as an aggregation of grains of identical unit cell structure in a solid metal. The usual structure of a composite consists of particles or fibers of one phase mixed in a second phase, called the **matrix**.

Composites are found in nature (e.g., wood), and they can be produced synthetically. The synthesized type is of greater interest here, and it includes glass fibers in a polymer matrix, such as fiber-reinforced plastic; polymer fibers of one type in a matrix of a second polymer, such as an epoxy-Kevlar composite; and ceramic in a metal matrix, such as a tungsten carbide in a cobalt binder to form a cemented carbide cutting tool.

Properties of a composite depend on its components, the physical shapes of the components, and the way they are combined to form the final material. Some composites combine high strength with light weight and are suited to applications such as aircraft components, car bodies, boat hulls, tennis rackets, and fishing rods. Other composites are strong, hard, and capable of maintaining these properties at elevated temperatures, for example, cemented carbide cutting tools.

1.3 Manufacturing Processes

A **manufacturing process** is a designed procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. A manufacturing process is usually carried out as a **unit operation**, which means that it is a single step in the sequence of steps required to transform the starting material into a final product. Manufacturing operations can be divided into two basic types: (1) processing operations and (2) assembly operations. A **processing operation** transforms a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete work parts, but certain processing operations are also applicable to assembled items (e.g., painting a spot-welded car body). An **assembly operation** joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process (e.g., a welded assembly is called a **weldment**). A classification of manufacturing processes is presented in Figure 1.5. Some of the basic processes used in modern manufacturing date from antiquity (Historical Note 1.2).

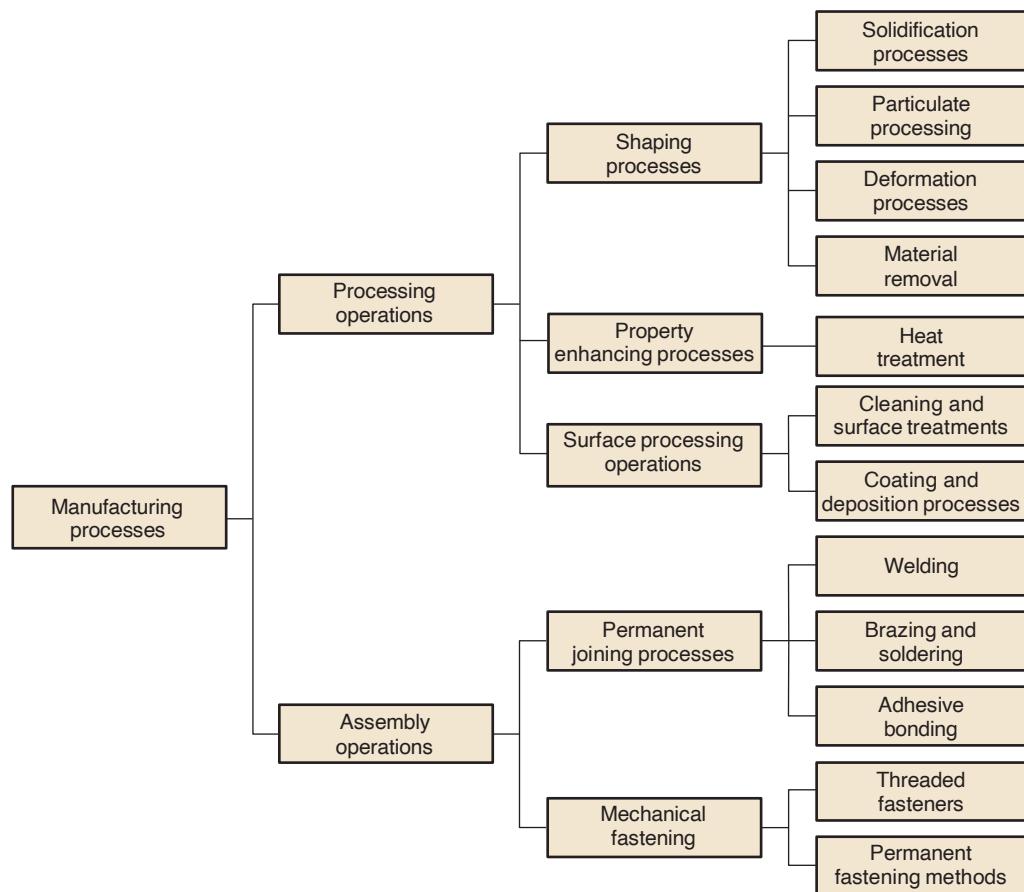


FIGURE 1.5
Classification of manufacturing processes.

Historical Note 1.2 Manufacturing materials and processes

Although most of the historical developments that form Gold was found by early humans in relatively pure form the modern practice of manufacturing have occurred in nature; it could be **hammered** into shape. Copper only during the last few centuries (Historical Note 1.1), was probably the first metal to be extracted from ores, several of the basic fabrication processes date as far back as the Neolithic period (circa 8000–3000 B.C.E.). It was during this period that processes such as the following were developed: carving and other **woodwork-ing**, hand forming and **firing** of clay pottery, **grinding** and **polishing** of stone, **spinning** and **weaving** of textiles, and **dyeing** of cloth.

Metallurgy and metalworking also began during the Neolithic period, in Mesopotamia and other areas around the Mediterranean. It either spread to, or developed independently in, regions of Europe and Asia.

Iron was also first smelted during the Bronze Age. Meteorites may have been one source of the metal,

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but iron ore was also mined. Temperatures required to reduce iron ore to metal are significantly higher than for copper, which made furnace operations more difficult. Other processing methods were also more difficult for the same reason. Early blacksmiths learned that when certain irons (those containing small amounts of carbon) were sufficiently **heated** and then **quenched**, they became very hard. This permitted grinding a very sharp cutting edge on knives and weapons, but it also made the metal brittle. Toughness could be increased by reheating at a lower temperature, a process known as **tempering**. What we have described is, of course, the **heat treatment** of steel. The superior properties of steel caused it to succeed bronze in many applications (weaponry, agriculture, and mechanical devices). The period of its use has subsequently been named the **Iron Age** (starting around 1000 B.C.). It was not until much later, well into the nineteenth century, that the demand for steel grew significantly and more modern steelmaking techniques were developed (Historical Note 6.1).

The beginnings of machine tool technology occurred during the Industrial Revolution. During the period 1770–1850, machine tools were developed for most of the conventional **material removal processes**, such as **boring**, **turning**, **drilling**, **milling**, **shaping**, and **planing** (Historical Note 21.1). Many of the individual processes predate the machine tools by centuries; for example, drilling and sawing (of wood) date from ancient times, and turning (of wood) from around the time of Christ.

Assembly methods were used in ancient cultures to make ships, weapons, tools, farm implements,

machinery, chariots and carts, furniture, and garments. The earliest processes included **binding** with twine and rope, **riveting** and **nailing**, and **soldering**. Around 2000 years ago, **forge welding** and **adhesive bonding** had been developed. Widespread use of screws, bolts, and nuts as fasteners—so common in today's assembly—required the development of machine tools that could accurately cut the required helical shapes (e.g., Maudsley's screw cutting lathe, 1800). It was not until around 1900 that **fusion welding** processes started to be developed as assembly techniques (Historical Note 28.1).

Natural rubber was the first polymer to be used in manufacturing (if we exclude wood, which is a polymer composite). The **vulcanization** process, discovered by Charles Goodyear in 1839, made rubber a useful engineering material (Historical Note 8.2). Subsequent developments included plastics such as cellulose nitrate in 1870, Bakelite in 1900, polyvinylchloride in 1927, polyethylene in 1932, and nylon in the late 1930s (Historical Note 8.1). Processing requirements for plastics led to the development of **injection molding** (based on die casting, one of the metal casting processes) and other polymer shaping techniques.

Electronics products have imposed unusual demands on manufacturing in terms of miniaturization. The evolution of the technology has been to package more and more devices into a smaller area—in some cases millions of transistors onto a flat piece of semiconductor material that is only 12 mm (0.50 in) on a side. The history of electronics processing and packaging dates from around 1960 (Historical Notes 33.1, 34.1, and 34.2).

1.3.1 PROCESSING OPERATIONS

A processing operation uses energy to alter a work part's shape, physical properties, or appearance to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but the human workers are generally employed to control the machines, oversee the operations, and load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 1.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed work part exits the process. Most production operations produce waste or scrap, either as a natural aspect of the process (e.g., removing material as in machining) or in the form of occasional defective pieces. It is an important objective in manufacturing to reduce waste in either of these forms.

More than one processing operation is usually required to transform the starting material into final form. The operations are performed in the particular sequence required to achieve the geometry and condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations, (2) property-enhancing operations, and (3) surface processing operations. **Shaping operations** alter the geometry of the starting work material by various methods. Common shaping processes include casting, forging, and machining. **Property-enhancing operations** add value to the material by improving its physical properties without changing its shape. Heat treatment is the most common example. **Surface processing operations** are performed to clean, treat, coat, or deposit material onto the exterior surface of the work. Common examples of coating are plating and painting. Shaping processes are covered in Parts III through VI, corresponding to the four main categories of shaping processes in Figure 1.5. Property-enhancing processes and surface processing operations are covered in Part VII.

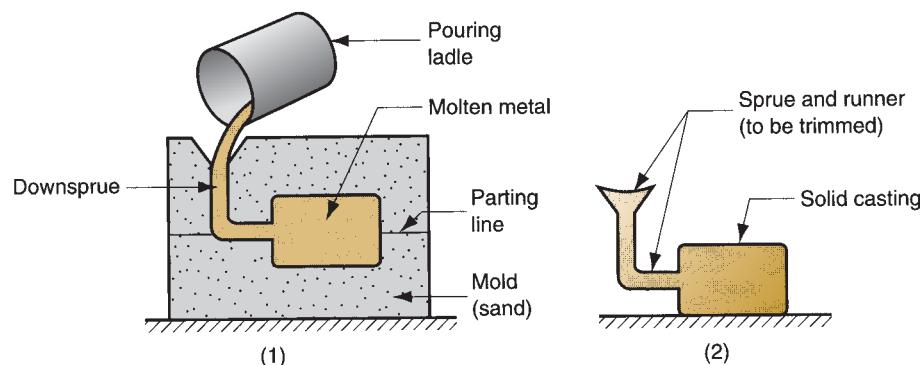
Shaping Processes Most shape processing operations apply heat, mechanical force or a combination of these to effect a change in geometry of the work material. There are various ways to classify the shaping processes. The classification used in this book is based on the state of the starting material, by which there are four categories:

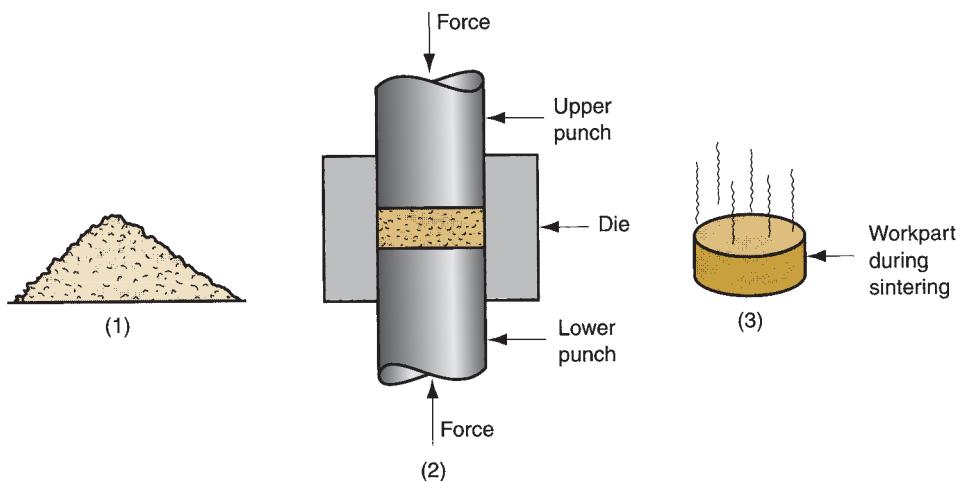
(1) **solidification processes**, in which the starting material is a heated *liquid* or *semifluid* that cools and solidifies to form the part geometry; (2) **particulate processing**, in which the starting material is a *powder*, and the powders are formed and heated into the desired geometry; (3) **deformation processes**, in which the starting material is a *ductile solid* (commonly metal) that is deformed to shape the part; and (4) **material removal processes**, in which the starting material is a *solid* (ductile or brittle), from which material is removed so that the resulting part has the desired geometry.

In the first category, the starting material is heated sufficiently to transform it into a liquid or highly plastic (semifluid) state. Nearly all materials can be processed in this way. Metals, ceramic glasses, and plastics can all be heated to sufficiently high temperatures to convert them into liquids. With the material in a liquid or semifluid form, it can be poured or otherwise forced to flow into a mold cavity and allowed to solidify, thus taking a solid shape that is the same as the cavity. Most processes that operate this way are called casting or molding. **Casting** is the name used for metals, and **molding** is the common term used for plastics. This category of shaping process is depicted in Figure 1.6. Figure 11.1 shows a cast iron casting, and a collection of plastic molded parts is displayed in Figure 13.20.

In **particulate processing**, the starting materials are powders of metals or ceramics. Although these two materials are quite different, the processes to shape them in particulate processing are quite similar. The common technique in powder

FIGURE 1.6 Casting and molding processes start with a work material heated to a fluid or semifluid state. The process consists of (1) pouring the fluid into a mold cavity and (2) allowing the fluid to solidify, after which the solid part is removed from the mold.



**FIGURE 1.7**

Particulate processing:
(1) the starting material
is powder; the usual
process consists of
(2) pressing and
(3) sintering.

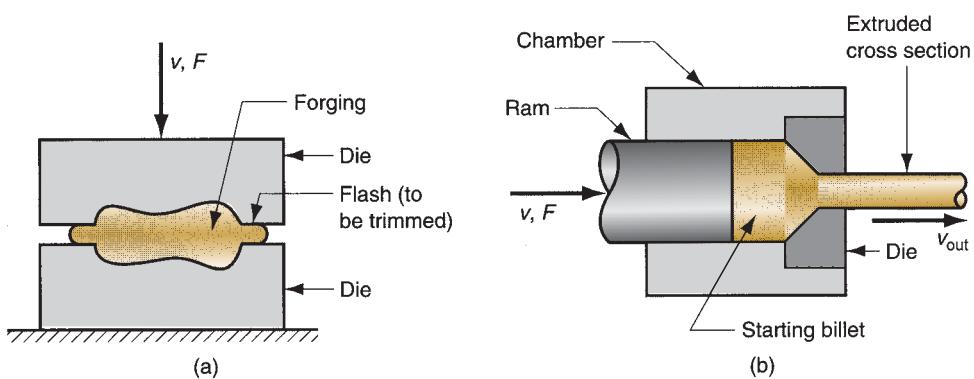
metallurgy involves pressing and sintering, illustrated in Figure 1.7, in which the powders are first squeezed into a die cavity under high pressure and then heated to bond the individual particles together. Examples of parts produced by powder metallurgy are shown in Figure 15.1.

In the **deformation processes**, the starting work part is shaped by the application of forces that exceed the yield strength of the material. For the material to be formed in this way, it must be sufficiently ductile to avoid fracture during deformation. To increase ductility (and for other reasons), the work material is often heated before forming to a temperature below the melting point. Deformation processes are associated most closely with metalworking and include operations such as **forging** and **extrusion**, shown in Figure 1.8. Figure 18.19 shows a forging operation performed by a drop hammer.

Also included within the deformation processes category is **sheet metalworking**, which involves bending, forming, and shearing operations performed on starting blanks and strips of sheet metal. Several sheet metal parts, called stampings because they are made on a stamping press, are illustrated in Figure 19.35.

Material removal processes are operations that remove excess material from the starting workpiece so that the resulting shape is the desired geometry. The most important processes in this category are **machining** operations such as **turning**,

FIGURE 1.8 Some common deformation processes: (a) **forging**, in which two halves of a die squeeze the work part, causing it to assume the shape of the die cavity; and (b) **extrusion**, in which a billet is forced to flow through a die orifice, thus taking the cross-sectional shape of the orifice.



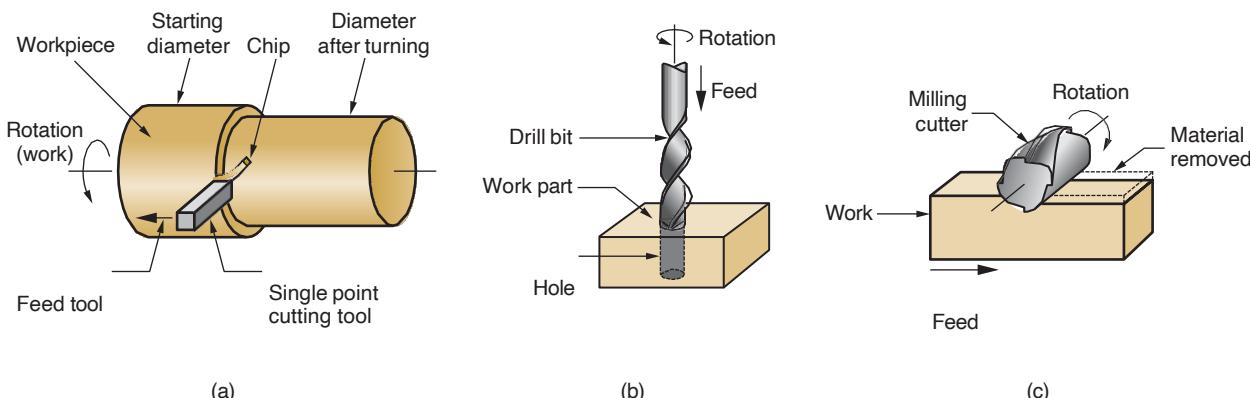


FIGURE 1.9 Common machining operations: (a) **turning**, in which a single-point cutting tool removes metal from a rotating workpiece to reduce its diameter; (b) **drilling**, in which a rotating drill bit is fed into the work to create a round hole; and (c) **milling**, in which a work part is fed past a rotating cutter with multiple edges.

drilling, and **milling**, shown in Figure 1.9. These cutting operations are most commonly applied to solid metals, performed using cutting tools that are harder and stronger than the work metal. The front cover of this book shows a turning operation.

Grinding is another common material removal process. Other processes in this category are known as **nontraditional processes** because they use lasers, electron beams, chemical erosion, electric discharges, and electrochemical energy to remove material rather than cutting or grinding tools.

It is desirable to minimize waste and scrap in converting a starting work part into its subsequent geometry. Certain shaping processes are more efficient than others in terms of material conservation. Material removal processes (e.g., machining) tend to be wasteful of material, simply by the way they work. The material removed from the starting shape is waste, at least in terms of the unit operation. Other processes, such as certain casting and molding operations, often convert close to 100% of the starting material into final product. Manufacturing processes that transform nearly all of the starting material into product and require no subsequent machining to achieve final part geometry are called **net shape processes**. Other processes require minimum machining to produce the final shape and are called **near net shape processes**.

Property-Enhancing Processes The second major type of part processing is performed to improve mechanical or physical properties of the work material. These processes do not alter the shape of the part, except unintentionally in some cases. The most important property-enhancing processes involve **heat treatments**, which include various annealing and strengthening processes for metals and glasses. **Sintering** of powdered metals is also a heat treatment that strengthens a pressed powder metal work part. Its counterpart in ceramics is called **firing**.

Surface Processing Surface processing operations include (1) cleaning, (2) surface treatments, and (3) coating and thin film deposition processes. **Cleaning** includes both chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface. **Surface treatments** include mechanical working such as shot peening and sand blasting, and physical processes such as diffusion and ion implantation. **Coating** and **thin film deposition** processes apply a coating of material to the exterior surface of the work part. Common coating processes include **electroplating**,

anodizing of aluminum, organic **coating** (call it **painting**), and porcelain enameling. Thin film deposition processes include **physical vapor deposition** and **chemical vapor deposition** to form extremely thin coatings of various substances.

Several surface-processing operations have been adapted to fabricate semiconductor materials into integrated circuits for microelectronics. These processes include chemical vapor deposition, physical vapor deposition, and oxidation. They are applied to very localized areas on the surface of a thin wafer of silicon (or other semiconductor material) to create the microscopic circuit.

1.3.2 ASSEMBLY OPERATIONS

The second basic type of manufacturing operation is **assembly**, in which two or more separate parts are joined to form a new entity. Components of the new entity are connected either permanently or semipermanently. Permanent joining processes include **welding**, **brazing**, **soldering**, and **adhesive bonding**. They form a joint between components that cannot be easily disconnected. Certain **mechanical assembly** methods are available to fasten two (or more) parts together in a joint that can be conveniently disassembled. The use of screws, bolts, and other **threaded fasteners** are important traditional methods in this category. Other mechanical assembly techniques form a more permanent connection; these include **rivets**, **press fitting**, and **expansion fits**. Special joining and fastening methods are used in the assembly of electronic products. Some of the methods are identical to or are adaptations of the preceding processes, for example, soldering. Electronics assembly is concerned primarily with the assembly of components such as integrated circuit packages to printed circuit boards to produce the complex circuits used in so many of today's products. Joining and assembly processes are discussed in Part VIII, and the specialized assembly techniques for electronics are described in Chapter 34.

1.3.3 PRODUCTION MACHINES AND TOOLING

Manufacturing operations are accomplished using machinery and tooling (and people). The extensive use of machinery in manufacturing began with the Industrial Revolution. It was at that time that metal cutting machines started to be developed and widely used. These were called **machine tools**—power-driven machines used to operate cutting tools previously operated by hand. Modern machine tools are described by the same basic definition, except that the power is electrical rather than water or steam, and the level of precision and automation is much greater today. Machine tools are among the most versatile of all production machines. They are used to make not only parts for consumer products, but also components for other production machines. Both in a historic and a reproductive sense, the machine tool is the mother of all machinery.

Other production machines include **presses** for stamping operations, **forge hammers** for forging, **rolling mills** for rolling sheet metal, **welding machines** for welding, and **insertion machines** for inserting electronic components into printed circuit boards. The name of the equipment usually follows from the name of the process.

Production equipment can be general purpose or special purpose. **General purpose equipment** is more flexible and adaptable to a variety of jobs. It is commercially available for any manufacturing company to invest in. **Special purpose equipment** is usually designed to produce a specific part or product in very large quantities. The economics

TABLE • 1.3 Production equipment and tooling used for various manufacturing processes.

Process	Equipment	Special tooling (function)
Casting	^a	Mold (cavity for molten metal)
Molding	Molding machine	Mold (cavity for hot polymer)
Rolling	Rolling mill	Roll (reduce work thickness)
Forging	Forge hammer or press	Die (squeeze work to shape)
Extrusion	Press	Extrusion die (reduce cross-section)
Stamping	Press	Die (shearing, forming sheet metal)
Machining	Machine tool	Cutting tool (material removal) Fixture (hold work part) Jig (hold part and guide tool)
Grinding	Grinding machine	Grinding wheel (material removal)
Welding	Welding machine	Electrode (fusion of work metal) Fixture (hold parts during welding)

^aVarious types of casting setups and equipment (Chapter 11).

of mass production justify large investments in special purpose machinery to achieve high efficiencies and short cycle times. This is not the only reason for special purpose equipment, but it is the dominant one. Another reason may be because the process is unique and commercial equipment is not available. Some companies with unique processing requirements develop their own special purpose equipment.

Production machinery usually requires **tooling** that customizes the equipment for the particular part or product. In many cases, the tooling must be designed specifically for the part or product configuration. When used with general purpose equipment, it is designed to be exchanged. For each work part type, the tooling is fastened to the machine and the production run is made. When the run is completed, the tooling is changed for the next work part type. When used with special purpose machines, the tooling is often designed as an integral part of the machine. Because the special purpose machine is likely being used for mass production, the tooling may never need changing except for replacement of worn components or for repair of worn surfaces.

The type of tooling depends on the type of manufacturing process. In Table 1.3, we list examples of special tooling used in various operations. Details are provided in the chapters that discuss these processes.

.4 Production Systems

To operate effectively, a manufacturing firm must have systems that allow it to efficiently accomplish its type of production. Production systems consist of people, equipment, and procedures designed for the combination of materials and processes that constitute a firm's manufacturing operations. Production systems can be divided into two categories: (1) production facilities and (2) manufacturing support systems, as shown in Figure 1.10.² **Production facilities** refer to the physical equipment and the arrangement of equipment in the factory. **Manufacturing support systems** are

² This diagram also indicates the major topic areas covered in this book.

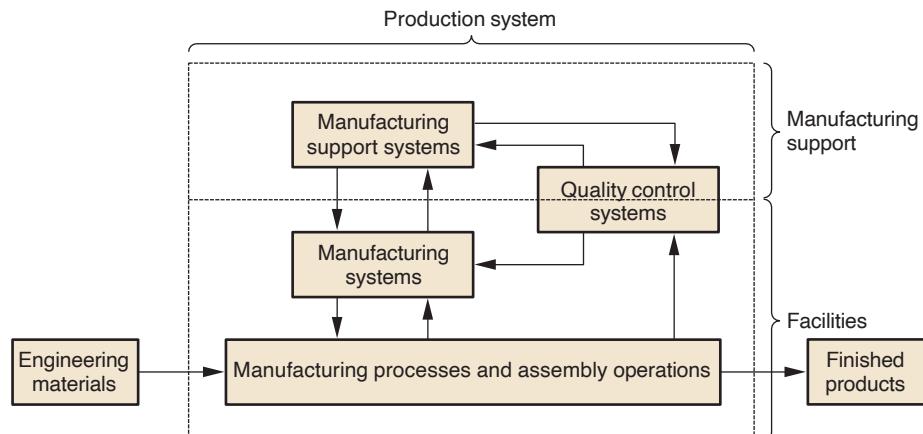


FIGURE 1.10 Model of the production system and overview of major topics in the book.

the procedures used by the company to manage production and solve the technical and logistics problems encountered in ordering materials, moving work through the factory, and ensuring that products meet quality standards. Both categories include people. People make these systems work. In general, direct labor workers are responsible for operating the manufacturing equipment; and professional staff workers are responsible for manufacturing support.

1.4.1 PRODUCTION FACILITIES

Production facilities consist of the factory and the production, material handling, and other equipment in the factory. The equipment comes in direct physical contact with the parts and/or assemblies as they are being made. The facilities “touch” the product. Facilities also include the way the equipment is arranged in the factory—the ***plant layout***. The equipment is usually organized into logical groupings. In this book they are called ***manufacturing systems***, such as an automated production line, or a machine cell consisting of an industrial robot and two machine tools.

A manufacturing company attempts to design its manufacturing systems and organize its factories to serve the particular mission of each plant in the most efficient way. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given combination of product variety and production quantity, as discussed in Section 1.1.2. Different types of facilities are required for each of the three ranges of annual production quantities.

Low-Quantity Production In the low-quantity range (1–100 units/year), the term ***job shop*** is often used to describe the type of production facility. A job shop makes low quantities of specialized and customized products. The products are typically complex, such as space capsules, prototype aircraft, and special machinery. The equipment in a job shop is general purpose, and the labor force is highly skilled.

A job shop must be designed for maximum flexibility to deal with the wide product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move, it typically remains in a single location during its fabrication or assembly. Workers and processing equipment are brought to the product, rather than moving the product to the equipment. This type of layout is referred to as a ***fixed-position layout***, shown in Figure 1.11(a). In a pure situation, the product

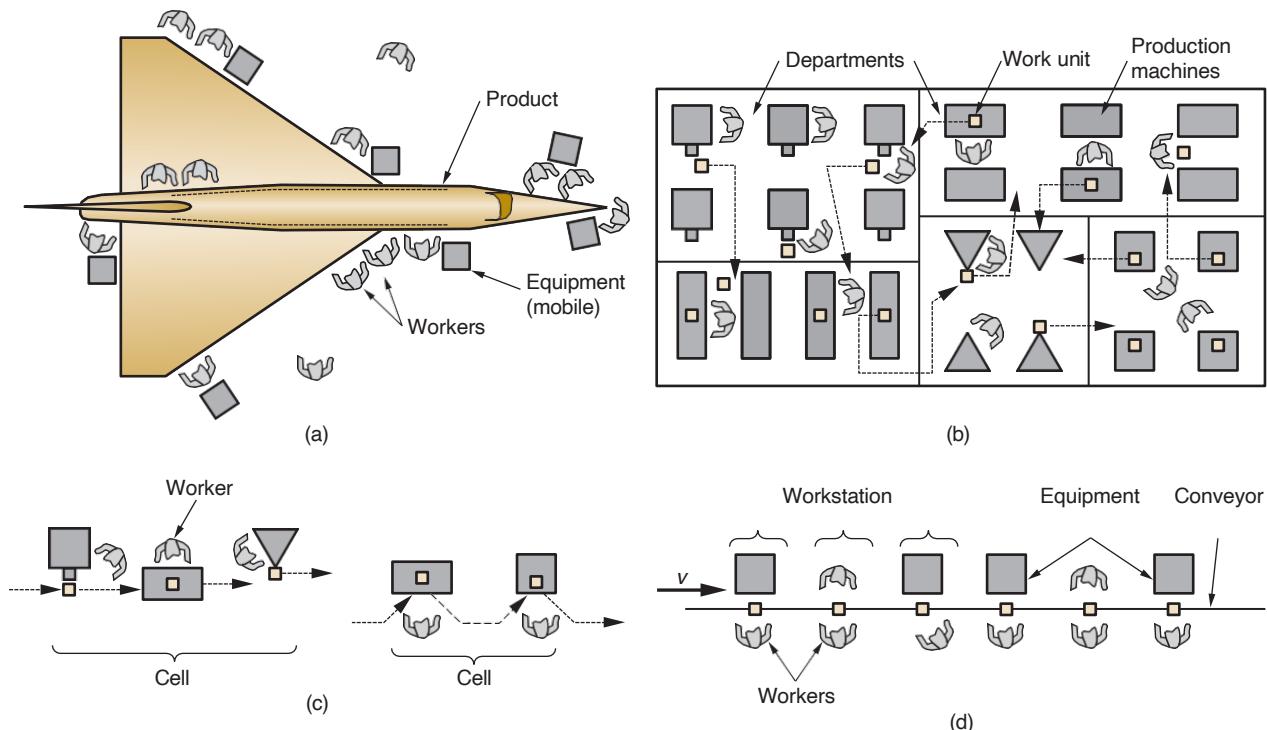


FIGURE 1.11 Various types of plant layout: (a) fixed-position layout, (b) process layout, (c) cellular layout, and (d) product layout.

remains in a single location during its entire production. Examples of such products include ships, aircraft, locomotives, and heavy machinery. In actual practice, these items are usually built in large modules at single locations, and then the completed modules are brought together for final assembly using large-capacity cranes.

The individual components of these large products are often made in factories in which the equipment is arranged according to function or type. This arrangement is called a ***process layout***. The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.11(b). Different parts, each requiring a different operation sequence, are routed through the departments in the particular order needed for their processing, usually in batches. The process layout is noted for its flexibility; it can accommodate a great variety of operation sequences for different part configurations. Its disadvantage is that the machinery and methods to produce a part are not designed for high efficiency.

Medium Quantity Production In the medium-quantity range (100–10,000 units annually), two different types of facility are distinguished, depending on product variety. When product variety is hard, the usual approach is ***batch production***, in which a batch of one product is made, after which the manufacturing equipment is changed over to produce a batch of the next product, and so on. The production rate of the equipment is greater than the demand rate for any single product type, and so the same equipment can be shared among multiple products. The changeover between production runs takes time—time to change tooling and set up the machinery. This setup time is lost production time, and this is a disadvantage of batch manufacturing. Batch production is commonly used for make-to-stock situations, in which

items are manufactured to replenish inventory that has been gradually depleted by demand. The equipment is usually arranged in a process layout, as in Figure 1.11(b).

An alternative approach to medium-range production is possible if product variety is soft. In this case, extensive changeovers between one product style and the next may not be necessary. It is often possible to configure the manufacturing system so that groups of similar products can be made on the same equipment without significant lost time because of setup. The processing or assembly of different parts or products is accomplished in cells consisting of several workstations or machines. The term ***cellular manufacturing*** is often associated with this type of production. Each cell is designed to produce a limited variety of part configurations; that is, the cell specializes in the production of a given set of similar parts, according to the principles of ***group technology*** (Section 39.5). The layout is called a ***cellular layout***, depicted in Figure 1.11(c).

High Production The high-quantity range (10,000 to millions of units per year) is referred to as ***mass production***. The situation is characterized by a high demand rate for the product, and the manufacturing system is dedicated to the production of that single item. Two categories of mass production can be distinguished: quantity production and flow line production. ***Quantity production*** involves the mass production of single parts on single pieces of equipment. It typically involves standard machines (e.g., stamping presses) equipped with special tooling (e.g., dies and material handling devices), in effect dedicating the equipment to the production of one part type. Typical layouts used in quantity production are the process layout and cellular layout.

Flow line production involves multiple pieces of equipment or workstations arranged in sequence, and the work units are physically moved through the sequence to complete the product. The workstations and equipment are designed specifically for the product to maximize efficiency. The layout is called a ***product layout***, and the workstations are arranged into one long line, as in Figure 1.11(d), or into a series of connected line segments. The work is usually moved between stations by mechanized conveyor. At each station, a small amount of the total work is completed on each unit of product.

The most familiar example of flow line production is the assembly line, associated with products such as cars and household appliances. The pure case of flow line production occurs when there is no variation in the products made on the line. Every product is identical, and the line is referred to as a ***single model production line***. To successfully market a given product, it is often beneficial to introduce feature and model variations so that individual customers can choose the exact merchandise that appeals to them. From a production viewpoint, the feature differences represent a case of soft product variety. The term ***mixed-model production line*** applies to these situations in which there is soft variety in the products made on the line. Modern automobile assembly is an example. Cars coming off the assembly line have variations in options and trim representing different models and in many cases different nameplates of the same basic car design.

1.4.2 MANUFACTURING SUPPORT SYSTEMS

To operate its facilities efficiently, a company must organize itself to design the processes and equipment, plan and control the production orders, and satisfy product quality requirements. These functions are accomplished by manufacturing support systems—people and procedures by which a company manages its production

operations. Most of these support systems do not directly contact the product, but they plan and control its progress through the factory. Manufacturing support functions are often carried out in the firm by people organized into departments such as the following:

- **Manufacturing engineering.** The manufacturing engineering department is responsible for planning the manufacturing processes—deciding what processes should be used to make the parts and assemble the products. This department is also involved in designing and ordering the machine tools and other equipment used by the operating departments to accomplish processing and assembly.
- **Production planning and control.** This department is responsible for solving the logistics problem in manufacturing—ordering materials and purchased parts, scheduling production, and making sure that the operating departments have the necessary capacity to meet the production schedules.
- **Quality control.** Producing high-quality products should be a top priority of any manufacturing firm in today's competitive environment. It means designing and building products that conform to specifications and satisfy or exceed customer expectations. Much of this effort is the responsibility of the QC department.

.5 Manufacturing Economics

In Section 1.1.1, manufacturing was defined as a transformation process that adds value to a starting work material. In Section 1.1.2, we noted that manufacturing is a commercial activity performed by companies that sell products to customers. It is appropriate to consider some of the economic aspects of manufacturing, and that is the purpose of this section. Our coverage consists of (1) production cycle time analysis and (2) manufacturing cost models.

1.5.1 PRODUCTION CYCLE TIME ANALYSIS

“Time is money”, as the saying goes. The total time to make a product is one of the components that determine its total cost and the price that can be charged for it. The total time is the sum of all of the individual cycle times of the unit operations needed to manufacture the product. As defined in Section 1.3, a unit operation is a single step in the sequence of steps required to make the final product. The **cycle time** of a unit operation is defined as the time that one work unit spends being processed or assembled. It is the time interval between when one work unit begins the operation and the next unit begins. A typical production cycle time consists of the actual processing time plus the work handling time, for example, loading and unloading the part in the machine. In some processes, such as machining, time is also required to periodically change the tooling used in the operation when it wears out. In equation form,

$$T_c = T_o + T_h + T_t \quad (1.1)$$

where T_c = cycle time of the unit operation, min/pc; T_o = actual processing time in the operation, min/pc; T_h = work handling time, min/pc; and T_t = tool handling time if that applies in the operation, min/pc. As indicated, the tool handling time usually occurs periodically, not every cycle, so the time per workpiece must be determined by dividing the actual time associated with changing the tool by the number of pieces

between tool changes. It should be mentioned that many production operations do not include a tool change, so that term is omitted from Equation (1.1) in those cases.

Batch and job shop production are common types of manufacturing. The time to produce a batch of parts in a unit operation consists of the time to set up for the batch plus the actual run time. This can be summarized as follows:

$$T_b = T_{su} + QT_c \quad (1.2)$$

where T_b = total time to complete the batch, min/batch; T_{su} = setup time, min/batch; Q = batch quantity, number of pieces (pc); and T_c = cycle time as defined in Equation (1.1), min/pc. To obtain a realistic value of the average production time per piece, the setup time is spread over the batch quantity, as follows:

$$T = \frac{T_{su}}{Q} + T_c = \frac{T_{su}}{Q} + \overline{QT_c} = \overline{\overline{Q}} \quad (1.3)$$

where T_p = average production time per piece, min/pc; and the other terms are defined above.

If the batch size is one part, then Equations (1.2) and (1.3) are still applicable, and $Q = 1$. In high production (mass production), these equations can also be used, but the value of Q is so large that the setup time loses significance: As $Q \rightarrow \infty$, $T_{su}/Q \rightarrow 0$.

The average production time per piece in Equation (1.3) can be used to determine the actual average production rate in the operation:

$$R_p = \frac{60}{T_p} \quad (1.4)$$

where R_p = average hourly production rate, pc/hr. This production rate includes the effect of setup time. During the production run (after the machine is set up), the production rate is the reciprocal of the cycle time:

$$R_c = \frac{60}{T_c} \quad (1.5)$$

where R_c = hourly cycle rate, cycles/hr or pc/hr. These equations indicate that the cycle rate will always be larger than the actual production rate unless the setup time is zero ($R_c > R_p$).

1.5.2 MANUFACTURING COST MODELS

In this section, the cycle time analysis is used to estimate the costs of production, which include not only the cost of time but also material and overhead. The cost of time consists of labor and equipment costs, which are applied to the average production time per piece as cost rates (e.g., \$/hr). Thus, our cost model for production cost per piece can be stated as follows:

$$C_{pc} = C_m + (C_L + C_{eq})T_p + C_t \quad (1.6)$$

where C_{pc} = cost per piece, \$/pc; C_m = starting material cost, \$/pc; C_L = labor cost rate, \$/min; C_{eq} = equipment cost rate, \$/min; C_t = cost of tooling that is used in the unit operation, \$/pc; and T_p = average production time per piece, min/pc. If applicable, the cost of tooling C_t must be determined by dividing the actual cost of the tooling by the number of pieces between tool changes.

Overhead Costs The two cost rates, C_L and C_{eq} , include overhead costs, which consist of all of the expenses of operating the company other than material, labor, and equipment. Overhead costs can be divided into two categories: (1) factory overhead and (2) corporate overhead. Factory overhead consists of the costs of running the factory excluding materials, direct labor, and equipment. This overhead category includes plant supervision, maintenance, insurance, heat and light, and so forth. A worker who operates a piece of equipment may earn an hourly wage of \$15/hr, but when fringe benefits and other overhead costs are figured in, the worker may cost the company \$30/hr. Corporate overhead consists of company expenses not related to the factory, such as sales, marketing, accounting, legal, engineering, research and development, office space, utilities, and health benefits.³ These functions are required in the company, but they are not directly related to the cost of manufacturing. On the other hand, for pricing the product, they must be added in, or else the company will lose money on every product it sells.

J Black [1] offers some estimates of the typical costs associated with manufacturing a product, presented in Figure 1.12. Several observations are worth making here. First, total manufacturing costs constitute only 40% of the product's selling price. Corporate overhead expenses (Engineering, Research and development, Administration, sales, marketing, etc.) add up to almost as much as manufacturing cost. Second, parts and materials are 50% of total manufacturing cost, so that is about 20% of selling price. Third, direct labor is only about 12% of manufacturing cost, so that is less than 5% of selling price. Factory overhead, which includes the categories Plant and machinery, depreciation, energy at 26% and Indirect labor at 12%, adds up to more than three times Direct labor cost.

The issue of overhead costs can become quite complicated. A more complete treatment can be found in [7] and most introductory accounting textbooks. Our approach in this book is simply to include an appropriate overhead expense in our labor and equipment cost rates. For example, the labor cost rate is

$$C = \frac{R_H}{L} (1 + R_{LOH}) \quad (1.7)$$

L LOH
60

where C_L = labor cost rate, \$/min; R_H = worker's hourly wage rate, \$/hr; and R_{LOH} = labor overhead rate, %.

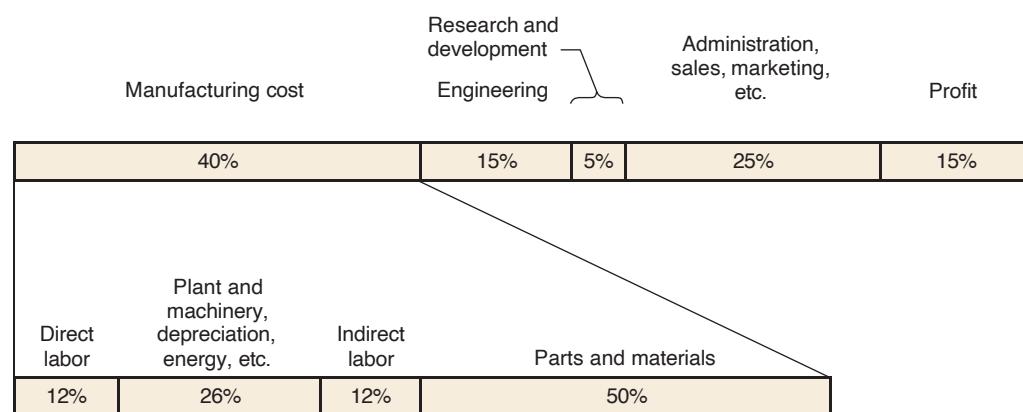


FIGURE 1.12
Typical breakdown of costs for a manufactured product [1].

³Health benefits, if available from the company, are fringe benefits that apply to all regular employees, and so they would be included in the direct labor overhead in the factory as well as the corporate offices.

Equipment Cost Rate The cost of production equipment used in the factory is a **fixed cost**, meaning that it remains constant for any level of production output. It is a capital investment that is made in the hope that it will pay for itself by producing a revenue stream that ultimately exceeds its cost. The company puts up the money to purchase the equipment as an initial cost, and then the equipment pays back over a certain number of years until it is replaced or disposed of. This is different from direct labor and material costs, which are **variable costs**, meaning they are paid for as they are used. Direct labor cost is a cost per time (\$/min), and Material cost is a cost per piece (\$/pc).

In order to determine an equipment cost rate, the initial cost plus installation cost of the equipment must be amortized over the number of minutes it is used during its lifetime. The equipment cost rate is defined by the following:

$$C_{eq} = \frac{IC}{60NH} (1 + R_{OH}) \quad (1.8)$$

where C_{eq} = equipment cost rate, \$/min; IC = initial cost of the equipment, \$; N = anticipated number of years of service; H = annual number of hours of operation, hr/yr; and R_{OH} = applicable overhead rate for the equipment, %.

Example 1.1 Equipment cost rate

A production machine is purchased for an initial cost plus installation of \$500,000. Its anticipated life = 7 years. The machine is planned for a two-shift operation, eight hours per shift, and five days per week. Assume 50 weeks per year. The applicable overhead rate on this type of equipment = 35%. Determine the equipment cost rate.

Solution: The number of hours of operation per year $H = 50(2)(5)(8) = 4000$ hr/yr. Using Equation (1.8), we have

$$C_{eq} = \frac{500,000}{60(7)(4000)} (1 + 0.35) = \$0.402/\text{min} == \$24.11/\text{hr}$$

Example 1.2 Cycle time and cost per piece

The production machine in Example 1.1 is used to produce a batch of parts that each has a starting material cost = \$2.35. Batch quantity = 100. The actual processing time in the operation = 3.72 min. Time to load and unload each workpiece = 1.60 min. Tool cost = \$4.40, and each tool can be used for 20 pieces before it is changed, which takes 2.0 min. Before production can begin, the machine must be set up, which takes 2.5 hr. Hourly wage rate of the operator = \$16.50/hr, and the applicable labor overhead rate = 40%. Determine (a) the cycle time for the piece, (b) average production rate when setup time is figured in, and (c) cost per piece.

Solution: (a) For Equation (1.1), processing time $T_o = 3.72$ min, part handling time $T_h = 1.50$ min, and tool handling time $T_t = 2.00$ min/20 = 0.10 min.

$$T_c = 3.72 + 1.60 + 0.10 = 5.42 \text{ min/pc}$$

(b) The average production time per piece including the effect of setup time is

$$T_p = \frac{2.5(60)}{100} + 5.42 = 6.92 \text{ min/pc}$$

Hourly production rate is the reciprocal of T_p , correcting for time units:

$$R_p = \frac{60}{6.92} = 8.67 \text{ pc/hr}$$

(c) The equipment cost rate from Example 1.1 is $C_{eq} = \$0.402/\text{min} (\$24.11/\text{hr})$. The labor rate is calculated as follows:

$$C_L = \frac{16.50}{60} (1 + 0.40) = \$0.385/\text{min} (\$23.10/\text{hr})$$

Cost of tooling $C_t = 4.40/20 = \$0.22/\text{pc}$

Finally, cost per piece is calculated as

$$C_{pc} = 2.35 + (0.385 + 0.402)(6.92) + 0.22 = \$8.02/\text{pc}$$

Equipment reliability and scrap rate of parts are sometimes issues in production. Equipment reliability is represented by the term **availability** (denoted by the symbol A), which is simply the proportion uptime of the equipment. For example, if $A = 97\%$, then for every 100 hours of machine operation, we would expect on average that the machine would be running for 97 hours and be down for maintenance and repairs for 3 hours. Scrap rate refers to the proportion of parts produced that are defective. Let q denote the scrap rate. In batch production, more than the specified batch quantity are often produced to compensate for the losses due to scrap. Let Q = the required quantity of parts to be delivered and Q_o = the starting quantity. The following equation can be used to determine how many starting parts are needed on average to satisfy an order for Q finished parts:

$$Q_o = \frac{Q}{1 - q} \quad (1.9)$$

Example 1.3 Scrap rate

A customer has ordered a batch of 1,000 parts to be produced by a machine shop. Historical data indicates that the scrap rate on this type of part = 4%. How many parts should the machine shop plan to make in order to account for this scrap rate?

Solution: Given $Q = 1,000$ parts and $q = 4\% = 0.04$, then the starting quantity is determined as follows:

$$Q_o = \frac{1000}{1 - 0.04} = \frac{1000}{0.96} = 1041.7 \text{ rounded to } \mathbf{1042 \text{ starting parts}}$$

Of course, in modern manufacturing practice, every effort is made to minimize scrap rate, with the goal being zero defects. Availability and scrap rate also figure into calculations of production rate and part cost, as demonstrated in Example 1.4.

Example 1.4 Cycle time and cost per piece

A high-production operation manufactures a part for the automotive industry. Starting material cost = \$1.75, and cycle time = 2.20 min. Equipment cost rate = \$42.00/hr, and labor cost rate = \$24.00/hr, including overhead costs in both cases. Availability of the production machine in this job = 97%, and the scrap rate of parts produced = 5%. Because this is a long-running job, setup time is ignored, and there is no tooling cost to be considered. (a) Determine the production rate and finished part cost in this operation. (b) If availability could be increased to 100% and scrap rate could be reduced to 0, what would be the production rate and finished part cost?

Solution: (a) Production rate, including effect of availability

$$R_p = \frac{60}{p} (0.97) = 26.45 \text{ pc/hr}$$

However, because of the 5% scrap rate, the production rate of acceptable parts is

$$R_p = 26.45(1 - 0.05) = 25.13 \text{ pc/hr}$$

Because of availability and scrap rate, the part cost is

$$C_{pc} = \frac{1.75}{(1 - 0.05)} + \frac{60}{(24 + 42)} \left(\frac{2.20}{(0.97)} \right) = \$4.47/\text{pc}$$

$$(b) \text{ If } A = 100\% \text{ and } q = 0, \quad R_p = \frac{60}{2.20} = 27.27 \text{ pc/hr.}$$

$$\text{Part cost } C_{pc} = 1.75 + (42 + 24)(2.20/60) = \$4.17/\text{pc.}$$

This is an 8.5% increase in production rate and a 6.7% reduction in cost.

.6

Recent Developments in Manufacturing

Manufacturing materials, processes, and systems have been the object of development for thousands of years (Historical Notes 1.1 and 1.2). In this section, we want to focus on developments that are of more recent vintage, say within the last 25 to 50 years. The discussion is organized around the following topic areas: (1) microelectronics, (2) computerization of manufacturing, (3) flexible manufacturing, (4) microfabrication and nanotechnology, (5) lean production and Six Sigma, (6) globalization, and (7) environmentally conscious manufacturing.

Microelectronics Microelectronics involves electronic devices that are fabricated on a microscopic scale. Examples include **integrated circuits**, which consist of components such as transistors, diodes, and resistors that have been fabricated and electrically connected on a small flat chip, usually made of silicon. The remarkable feature about today's microelectronics devices is the huge number of components that can be contained onto the chip. The capability to fabricate integrated circuits dates from the early 1960s and has advanced to the point where the current technology is called **giga-scale integration**, meaning that chips are being produced consisting of billions of components. Microelectronics has become so pervasive that a large

proportion of the common items used today are based on this technology. Two thirds of the products listed in Table 1.1 are either called electronics products or their function and operation depend on electronics. In this book, the fabrication of integrated circuits is covered in Chapter 33 and electronics assembly in Chapter 34.

Computerization of Manufacturing The first digital computers date from the mid-1940s, but their applications in manufacturing came quite a few years later. In the mid-1960s *direct numerical control* was developed, in which mainframe computers were employed to remotely control machine tools in factories. As computer technology developed, enabled by advances in microelectronics, the cost of computers and data processing was reduced, leading to the widespread use of personal computers, not only in the office but also in the factory for tasks ranging from control of individual equipment on the shop floor to control of the information required to manage the entire enterprise. The Internet has allowed manufacturing companies to communicate among their own geographically distributed plants and offices, and it has also provided access to customers and suppliers around the world. In this book, several aspects of computerization of manufacturing are included in Parts X and XI on manufacturing systems (Chapters 37 and 38) and manufacturing support systems (Chapters 39 and 40).

Flexible Manufacturing During most of the twentieth century, the emphasis in the manufacturing industries in the United States was on mass production to satisfy the consumer demands of a rapidly growing population. Mass production is still widely used in the United States and throughout the world, but computerization has enabled manufacturing companies to develop systems that are able to cope with product variations. The reader encountered several instances of this manufacturing flexibility in Section 1.4.1 in the discussion of production facilities. Cellular manufacturing and mixed-model assembly lines are two examples of manually operated manufacturing systems that are capable of producing a variety of parts or products without the time-consuming downtime for changeover. The automobile industry, in particular, is designing its final assembly lines so that ever-greater model variations can be accommodated on a single line to meet changing and unpredictable demand patterns. Computerization has also allowed flexibility to be designed into automated systems, examples of which are the flexible manufacturing systems discussed in Section 38.6.

Closely related to flexible manufacturing is *mass customization*, which involves a production system that is capable of producing individualized products for each customer. The customer specifies the model and options, and the product is made to those specifications. Mass customization is discussed in Section 38.6.3.

Microfabrication and Nanotechnology Another recent development in manufacturing, closely related to microelectronics, is the introduction of materials and products whose dimensions are sometimes so small that they cannot be seen by the naked eye. In extreme cases, the items cannot even be seen under an optical microscope. Products that are so miniaturized require special fabrication technologies. *Microfabrication* refers to the processes needed to make parts and products whose feature sizes are in the micrometer range ($1 \text{ mm} = 10^{-3} \text{ mm} = 10^{-6} \text{ m}$). Examples include ink-jet printing heads, compact discs (CDs and DVDs), and microsensors used in automotive applications (e.g., air-bag deployment sensors). *Nanotechnology* refers to materials and products whose feature sizes are in the nanometer scale

($1 \text{ nm} = 10^{-3} \text{ mm} = 10^{-6} \text{ m} = 10^{-9} \text{ m}$), a scale that approaches the size of atoms and molecules. Ultra-thin coatings for catalytic converters, flat screen TV monitors, and cancer drugs are examples of products based on nanotechnology. The technological and economic importance of microscopic and nanoscopic materials and products is expected to increase in the future, and processes are needed to produce them commercially. Chapters 35 and 36 are devoted to these technologies.

Lean Production and Six Sigma These are two programs aimed at improving efficiency and quality in manufacturing. They address demands by customers for products they buy to be both low in cost and high in quality. Lean production and Six Sigma are being widely adopted by companies, especially in the United States.

Lean production is based on the Toyota Production System developed by Toyota Motors in Japan. Its origins date from the 1950s and 1960s when Toyota began using unconventional approaches to improve quality, reduce inventories, and increase flexibility in its operations. **Lean production** can be defined simply as “doing more work with fewer resources.”⁴ It means that fewer workers and less equipment are used to accomplish more production in less time, and yet achieve higher quality in the final product. The underlying objective of lean production is the elimination of various forms of waste, such as producing defective parts, excessive inventories, and workers waiting. Lean production is described in Sections 39.4 and 39.5 in our chapter on process planning and production control.

Six Sigma was started in the 1980s at Motorola Corporation in the United States. The objective was to reduce variability in the company’s processes and products to increase customer satisfaction. Today, **Six Sigma** can be defined as “a quality-focused program that utilizes worker teams to accomplish projects aimed at improving an organization’s operational performance.”⁵ Six Sigma is discussed in more detail in Section 40.4.2.

Globalization and Outsourcing The world is becoming more and more integrated, creating an international economy in which barriers once established by national boundaries have been reduced or eliminated. This has enabled a freer flow of goods and services, capital, technology, and people among regions and countries. Globalization is the term that describes this trend, which was recognized in the late 1980s and is now a dominant economic reality. Of interest here is that once underdeveloped nations such as China, India, and Mexico have developed their manufacturing infrastructures and technologies to a level such that they are now important producers in the global economy. These countries have large populations, and therefore large workforces, and low labor costs. Hourly wages are significantly higher in the United States than in these countries, making it difficult for domestic U.S. companies to compete in many products that require high labor content. Examples include garments, furniture, toys, and electronic consumer products. The result has been a loss of manufacturing jobs in the United States and a gain of related work to these countries.

Outsourcing is closely related to globalization. In manufacturing, **outsourcing** refers to the use of outside contractors to perform work that was traditionally

⁴M. P. Groover, *Work Systems and the Methods, Measurement, and Management of Work* [8], p. 514. The term *lean production* was coined by researchers at the Massachusetts Institute of Technology who studied the production operations at Toyota and other automobile companies in the 1980s.

⁵Ibid, p. 541.

accomplished in-house. Outsourcing can be done in several ways, including the use of local suppliers. In this case the jobs remain in the United States. Alternatively, U.S. companies can outsource to foreign countries, so that parts and products once made in the United States are now made outside the country. In this case U.S. jobs are displaced. Two possibilities can be distinguished: (1) *offshore outsourcing*, which refers to production in China or other overseas locations and transporting the items by cargo ship to the United States, and (2) *near-shore outsourcing*, which means the items are made in Canada, Mexico, or Central America and shipped by rail or truck into the United States.

Outsourcing has resulted in the growth of *contract manufacturers*, companies that specialize in producing parts, subassemblies, and/or products for other companies. Contract manufacturers have developed expertise and efficiencies in certain manufacturing operations, which means they can likely produce the contracted items at prices that are lower than the production costs of the customer company if it were the producer. Contract manufacturers include both domestic (U.S.) and foreign companies.⁶ Reasons why a company might prefer to use the services of a contract manufacturer include: (1) the company benefits from cost savings because it does not have to pay the factory expenses associated with production, (2) the company can focus its resources on design and marketing of products rather than manufacturing, and (3) the company may benefit from skills possessed by the contract manufacturer but not by itself. On the other hand, there are risks associated with contract manufacturing by the customer company. In turning over its product designs it loses control over its intellectual property, which might result in the contract manufacturer becoming a competitor. The distinction between a contract manufacturer and a supplier is perhaps subtle. A *supplier* is usually thought of as a company that provides materials and components for a customer who is engaged in production of a product, whereas a contract manufacturer accomplishes the whole production of the product. It may use suppliers itself.

China is of particular interest in this discussion of globalization and outsourcing because of (1) its fast-growing economy (it now boasts the second largest gross domestic product in the world), (2) the importance of manufacturing in that economy, and (3) the extent to which U.S. companies have outsourced work to China. To take advantage of the low labor rates, many U.S. companies have moved much of their production to China (and other east Asian countries). Despite the logistics problems and costs of shipping the goods back into the United States, the result has been lower costs and higher profits for the outsourcing companies, as well as lower prices and a wider variety of available products for American consumers. The downside has been the loss of well-paying manufacturing jobs in the United States. Another consequence of U.S. outsourcing to China has been a reduction in the relative contribution of the manufacturing sector to GDP. In the 1990s, the manufacturing industries accounted for about 20% of GDP in the United States. Today, that contribution is only about 12%. At the same time, the manufacturing sector in China has grown (along with the rest of its economy), now accounting for about 35% of Chinese GDP.

Recently, there have been signs that outsourcing of production to China by American companies may be declining, and that manufacturing jobs are being brought back to the U.S. There are several reasons for this trend, which is called

⁶The largest contract manufacturer at the time of this writing is Hon Hai Precision Industries (a.k.a. Foxconn, headquartered in Taiwan, but many of its factories are located in China). It ranked 60th in the Fortune Global 500 with sales of \$95 billion in 2010 (*Fortune*, July 25, 2011).

reshoring. First, wage rates in China are increasing as the government attempts to evolve from an export-driven economy to a consumer-oriented economy, similar to the United States. Higher Chinese wage rates mean less advantage for U.S. companies to offshore jobs to China. Second, logistics costs and delays involved in transporting products from China to North America are significant, especially as oil prices increase. Accordingly, some companies, in their analyses of costs and benefits, have decided to produce in the United States, reopening old factories or building new ones. On the other hand, U.S. companies producing goods for the Chinese market still have good reasons to keep their operations going in that country, just as Japanese and German automobile makers have established plants in the United States.

Environmentally Conscious Manufacturing An inherent feature of virtually all manufacturing processes is waste (Section 1.3.1). The most obvious examples are material removal processes, in which chips are removed from a starting workpiece to create the desired part geometry. Waste in one form or another is a by-product of nearly all production operations. Another unavoidable aspect of manufacturing is that power is required to accomplish any given process. Generating that power requires fossil fuels (at least in the United States and China), the burning of which results in pollution of the environment. At the end of the manufacturing sequence, a product is created that is sold to a customer. Ultimately, the product wears out and is disposed of, perhaps in some landfill, with the associated environmental degradation. More and more attention is being paid by society to the environmental impact of human activities throughout the world and how modern civilization is using our natural resources at an unsustainable rate. Global warming is presently a major concern. The manufacturing industries contribute to these problems.

Environmentally conscious manufacturing refers to programs that seek to determine the most efficient use of materials and natural resources in production and minimize the negative consequences on the environment. Other terms for these programs include **green manufacturing** and **sustainable manufacturing**. They all boil down to two basic approaches: (1) design products that minimize their environmental impact and (2) design processes that are environmentally friendly.

Product design is the logical starting point in environmentally conscious manufacturing. The term **design for environment** (DFE) is used for the techniques that attempt to consider environmental impact during product design prior to production. Considerations in DFE include (1) selecting materials that require minimum energy to produce, (2) selecting processes that minimize waste of materials and energy, (3) designing parts that can be recycled or reused, (4) designing products that can be readily disassembled to recover the parts, (5) designing products that minimize the use of hazardous and toxic materials, and (6) giving attention to how

the product will be disposed of at the end of its useful life.

To a great degree, decisions made during design dictate the materials and processes that are used to make the product. These decisions limit the options available to the manufacturing departments to achieve sustainability. However, various approaches can be applied to make plant operations more environmentally friendly. They include

(1) adopting good housekeeping practices—keeping the factory clean, (2) preventing pollutants from escaping into the environment (rivers and atmosphere), (3) minimizing waste of materials in unit operations, (4) recycling rather than discarding waste materials, (5) using net shape processes, (6) using renewable energy sources when feasible, (7) maintaining production equipment so that it operates at maximum efficiency, and (8) investing in equipment that minimizes power requirements.

The Nature of Materials

Chapter Contents

2.1 Atomic Structure and the Elements

2.2 Bonding between Atoms and Molecules

2.3 Crystalline Structures

2.3.1 Types of Crystal Structures

2.3.2 Imperfections in Crystals

2.3.3 Deformation in Metallic Crystals

2.3.4 Grains and Grain Boundaries in Metals

2.4 Noncrystalline (Amorphous) Structures

2.5 Engineering Materials

An understanding of materials is fundamental in the study of manufacturing processes. In Chapter 1, manufacturing was defined as a transformation process. It is the material that is transformed; and it is the behavior of the material when subjected to the particular forces, temperatures, and other physical parameters of the process that determines the success of the operation. Certain materials respond well to certain types of manufacturing processes and poorly or not at all to others. What are the characteristics and properties of materials that determine their capacity to be transformed by the different processes?

Part I of this book consists of four chapters that address this question. The current chapter considers the atomic structure of matter and the bonding between atoms and molecules. It also shows how atoms and molecules in engineering materials organize themselves into two structural forms: crystalline and noncrystalline. It turns out that the basic engineering materials—metals, ceramics, and polymers—can exist in either form, although a preference for a particular form is usually exhibited by a given material. For example, metals almost always exist as crystals in their solid state. Glass (e.g., window glass), a ceramic, assumes a noncrystalline form. Some polymers are mixtures of crystalline and amorphous structures.

Chapters 3 and 4 discuss the mechanical and physical properties that are relevant in manufacturing. Of course, these properties are also important in product design. Chapter 5 is concerned with several part and product

attributes that are specified during product design and must be achieved in manufacturing: dimensions, tolerances, and surface finish. Chapter 5 also describes how these attributes are measured.

2. Atomic Structure and the Elements

The basic structural unit of matter is the atom. Each atom is composed of a positively charged nucleus, surrounded by a sufficient number of negatively charged electrons so that the charges are balanced. The number of electrons identifies the atomic number and the element of the atom. There are slightly more than 100 elements (not counting a few extras that have been artificially synthesized), and these elements are the chemical building blocks of all matter.

Just as there are differences among the elements, there are also similarities. The elements can be grouped into families and relationships established between and within the families by means of the Periodic Table, shown in Figure 2.1. In the horizontal direction there is a certain repetition, or periodicity, in the arrangement of elements. Metallic elements occupy the left and center portions of the chart, and nonmetals are located to the right. Between them, along a diagonal, is a transition zone containing elements called **metalloids** or **semimetals**. In principle, each of the elements can exist as a solid, liquid, or gas, depending on temperature and pressure. At room temperature and atmospheric pressure, they each have a natural phase; e.g., iron (Fe) is a solid, mercury (Hg) is a liquid, and nitrogen (N) is a gas.

The Periodic Table is organized into seven periods (rows) and eighteen groups (columns). The groups are labeled as follows:

- Groups 1-2 (Periods 1-2):** IA (1), IIA (2)
- Groups 13-18 (Periods 3-7):**
 - Period 3: IIIB (11-12), IVB (21-22), VB (23-24), VIB (25-28), VIIIB (29-30), IB (31-32), IIB (33-36)
 - Period 4: IIIA (19-20), IVA (21-22), VA (23-24), VIA (25-30)
 - Period 5: IIIA (37-38), IVA (39-40), VA (41-42), VIA (43-48)
 - Period 6: IIIA (55-56), IVA (57-58), VA (72-73), VIA (74-75)
 - Period 7: IIIA (87-88), IVA (89-90), VA (91-92), VIA (93-95), VIIA (96-99), VIIIA (100-103)
- Transition Zone:** A diagonal band of elements from groups IIIA to VIIA across periods 3 through 7.
- Nonmetals:** Elements in groups VIIA and VIIIA.

The table includes the following elements:

- Period 1:** Hydrogen (H, atomic number 1).
- Period 2:** Helium (He, atomic number 2), Lithium (Li, atomic number 3), and Beryllium (Be, atomic number 4).
- Period 3:** Sodium (Na, atomic number 11), Magnesium (Mg, atomic number 12), Scandium (Sc, atomic number 21), Titanium (Ti, atomic number 22), Vanadium (V, atomic number 23), Chromium (Cr, atomic number 24), Manganese (Mn, atomic number 25), Iron (Fe, atomic number 26), Cobalt (Co, atomic number 27), Nickel (Ni, atomic number 28), Copper (Cu, atomic number 29), Zinc (Zn, atomic number 30), Gallium (Ga, atomic number 31), Germanium (Ge, atomic number 32), Arsenic (As, atomic number 33), Phosphorus (P, atomic number 15), Sulfur (S, atomic number 16), Chlorine (Cl, atomic number 17), and Argon (Ar, atomic number 18).
- Period 4:** Potassium (K, atomic number 19), Calcium (Ca, atomic number 20), Thorium (Th, atomic number 58), Uranium (U, atomic number 92), Rhenium (Re, atomic number 75), Osmium (Os, atomic number 76), Iridium (Ir, atomic number 77), Rhodium (Rh, atomic number 44), Ruthenium (Ru, atomic number 45), Palladium (Pd, atomic number 46), Platinum (Pt, atomic number 78), Gold (Au, atomic number 79), Mercury (Hg, atomic number 80), Thallium (Tl, atomic number 81), Lead (Pb, atomic number 82), Bismuth (Bi, atomic number 83), Polonium (Po, atomic number 84), Astatine (At, atomic number 85), Francium (Fr, atomic number 87), and Radium (Ra, atomic number 88).
- Period 5:** Rubidium (Rb, atomic number 37), Strontium (Sr, atomic number 38), Yttrium (Y, atomic number 39), Zirconium (Zr, atomic number 40), Niobium (Nb, atomic number 41), Molybdenum (Mo, atomic number 42), Technetium (Tc, atomic number 43), Ruthenium (Ru, atomic number 44), Rhodium (Rh, atomic number 45), Palladium (Pd, atomic number 46), Platinum (Pt, atomic number 78), Gold (Au, atomic number 79), Mercury (Hg, atomic number 80), Thallium (Tl, atomic number 81), Lead (Pb, atomic number 82), Bismuth (Bi, atomic number 83), Polonium (Po, atomic number 84), Astatine (At, atomic number 85), Francium (Fr, atomic number 87), and Radium (Ra, atomic number 88).
- Period 6:** Cesium (Cs, atomic number 55), Barium (Ba, atomic number 56), Lanthanum (La, atomic number 57), Hafnium (Hf, atomic number 72), Tantalum (Ta, atomic number 73), tungsten (W, atomic number 74), Rhenium (Re, atomic number 75), Osmium (Os, atomic number 76), Iridium (Ir, atomic number 77), Rhodium (Rh, atomic number 44), Ruthenium (Ru, atomic number 45), Palladium (Pd, atomic number 46), Platinum (Pt, atomic number 78), Gold (Au, atomic number 79), Mercury (Hg, atomic number 80), Thallium (Tl, atomic number 81), Lead (Pb, atomic number 82), Bismuth (Bi, atomic number 83), Polonium (Po, atomic number 84), Astatine (At, atomic number 85), Francium (Fr, atomic number 87), and Radium (Ra, atomic number 88).
- Period 7:** Francium (Fr, atomic number 87), Radium (Ra, atomic number 88), Actinium (Ac, atomic number 89), Cerium (Ce, atomic number 58), Praseodymium (Pr, atomic number 59), Neodymium (Nd, atomic number 60), Promethium (Pm, atomic number 61), Samarium (Sm, atomic number 62), Europium (Eu, atomic number 63), Gadolinium (Gd, atomic number 64), Terbium (Tb, atomic number 65), Dysprosium (Dy, atomic number 66), Holmium (Ho, atomic number 67), Erbium (Er, atomic number 68), Thulium (Tm, atomic number 69), Ytterbium (Yb, atomic number 70), Lutetium (Lu, atomic number 71), Thorium (Th, atomic number 90), Protactinium (Pa, atomic number 91), Uranium (U, atomic number 92), Neptunium (Np, atomic number 93), Plutonium (Pu, atomic number 94), Americium (Am, atomic number 95), Curium (Cm, atomic number 96), Bk, Curium (Cf, atomic number 97), Es, Curium (Es, atomic number 98), Fm, Curium (Fm, atomic number 99), Md, Curium (Md, atomic number 100), No, Curium (No, atomic number 101), and Lw, Curium (Lw, atomic number 103).

FIGURE 2.1 Periodic Table of Elements. The atomic number and symbol are listed for the 103 elements.

In the table, the elements are arranged into vertical columns and horizontal rows in such a way that similarities exist among elements in the same columns. For example, in the extreme right column are the **noble gases** (helium, neon, argon, krypton, xenon, and radon), all of which exhibit great chemical stability and low reaction rates. The **halogens** (fluorine, chlorine, bromine, iodine, and astatine) in column VIIA share similar properties (hydrogen is not included among the halogens). The **noble metals** (copper, silver, and gold) in column IB have similar properties. Generally, there are correlations in properties among elements within a given column, whereas differences exist among elements in different columns.

Many of the similarities and differences among the elements can be explained by their respective atomic structures. The simplest model of atomic structure, called the planetary model, shows the electrons of the atom orbiting around the nucleus at certain fixed distances, called shells, as shown in Figure 2.2. The hydrogen atom (atomic number 1) has one electron in the orbit closest to the nucleus. Helium (atomic number 2) has two. Also shown in the figure are the atomic structures for fluorine (atomic number 9), neon (atomic number 10), and sodium (atomic number 11). One might infer from these models that there is a maximum number of electrons that can be contained in a given orbit. This turns out to be correct, and the maximum is defined by

$$\text{Maximum number of electrons in an orbit} = 2n^2$$

where n identifies the orbit, with $n = 1$ closest to the nucleus.

The number of electrons in the outermost shell, relative to the maximum number allowed, determines to a large extent the atom's chemical affinity for other atoms. These outer-shell electrons are called **valence electrons**. For example, because a hydrogen atom has only one electron in its single orbit, it readily combines with another hydrogen atom to form a hydrogen molecule H_2 . For the same reason, hydrogen also reacts readily with various other elements (e.g., to form H_2O). In the helium atom, the two electrons in its only orbit are the maximum allowed ($2n^2 = 2(1)^2 = 2$), and so helium is very stable. Neon is stable for the same reason: Its outermost orbit ($n = 2$) has eight electrons (the maximum allowed), so neon is an inert gas.

In contrast to neon, fluorine has one fewer electron in its outer shell ($n = 2$) than the maximum allowed and is readily attracted to other elements that might share an

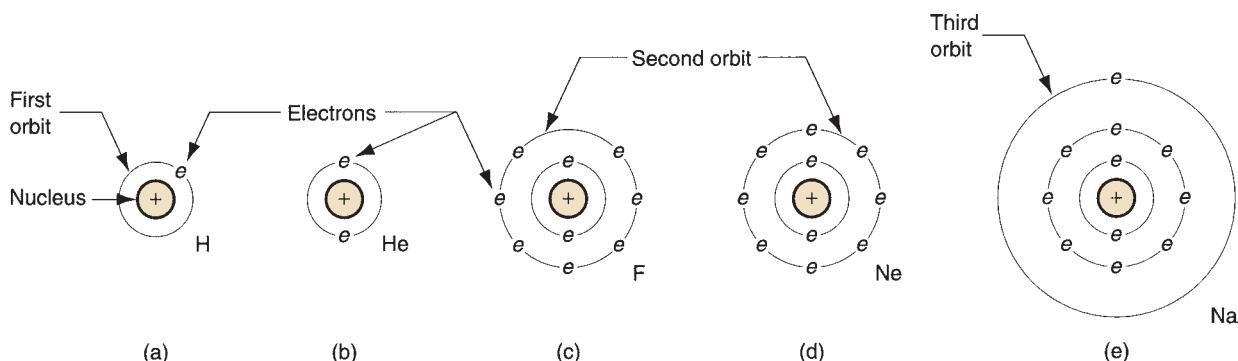


FIGURE 2.2 Simple model of atomic structure for several elements: (a) hydrogen, (b) helium, (c) fluorine, (d) neon, and (e) sodium.

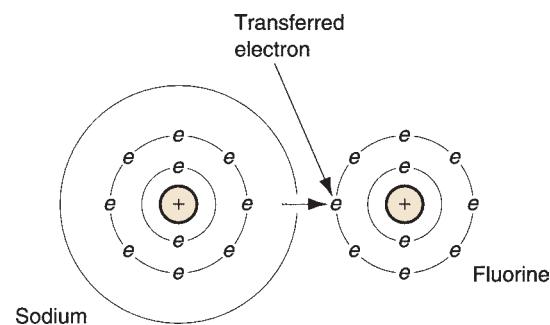


FIGURE 2.3 The sodium fluoride molecule formed by the transfer of the “extra” electron of the sodium atom to complete the outer orbit of the fluorine atom.

electron to make a more stable set. The sodium atom seems divinely made for the situation, with one electron in its outermost orbit. It reacts strongly with fluorine to form the compound sodium fluoride, as pictured in Figure 2.3.

At the low atomic numbers considered here, the prediction of the number of electrons in the outer orbit is straightforward. As the atomic number increases to higher levels, the allocation of electrons to the different orbits becomes somewhat more complicated. There are rules and guidelines, based on quantum mechanics, that can be used to predict the positions of the electrons among the various orbits and explain their characteristics. A discussion of these rules is somewhat beyond the scope of this coverage of manufacturing materials.

2.2 Bonding between Atoms and Molecules

Atoms are held together in molecules by various types of bonds that depend on the valence electrons. By comparison, molecules are attracted to each other by weaker bonds, which generally result from the electron configuration in the individual molecules. Thus, we have two types of bonding: (1) primary bonds, generally associated with the formation of molecules; and (2) secondary bonds, generally associated with attraction between molecules. Primary bonds are much stronger than secondary bonds.

Primary Bonds Primary bonds are characterized by strong atom-to-atom attractions that involve the exchange of valence electrons. Primary bonds include the following forms: (a) ionic, (b) covalent, and (c) metallic, as illustrated in Figure 2.4. Ionic and covalent bonds are called *intramolecular* bonds because they involve attractive forces between atoms within the molecule.

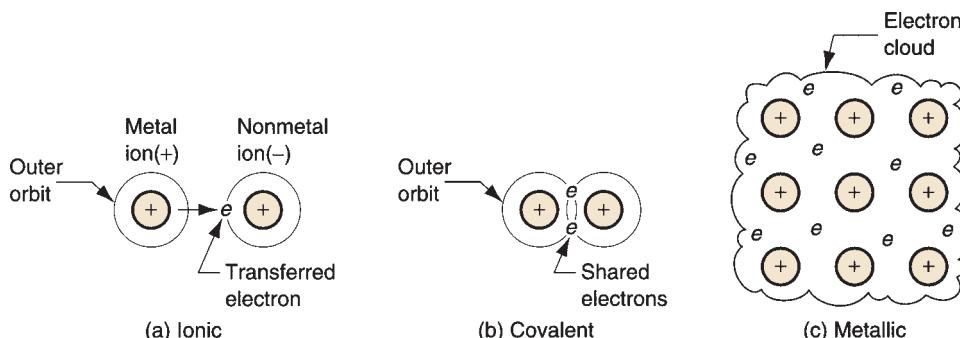


FIGURE 2.4 Three forms of primary bonding: (a) ionic, (b) covalent, and (c) metallic.

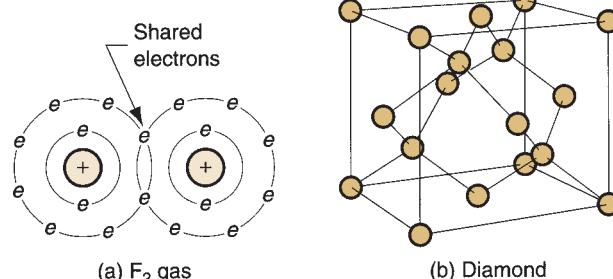
In the **ionic bond**, the atoms of one element give up their outer electron(s), which are in turn attracted to the atoms of some other element to increase their electron count in the outermost shell to eight. In general, eight electrons in the outer shell is the most stable atomic configuration (except for the very light atoms), and nature provides a very strong bond between atoms that achieves this configuration. The previous example of the reaction of sodium and fluorine to form sodium fluoride (Figure 2.3) illustrates this form of atomic bond. Sodium chloride (table salt) is a more common example. Because of the transfer of electrons between the atoms, sodium and fluorine (or sodium and chlorine) **ions** are formed, from which this bonding derives its name. Properties of solid materials with ionic bonding include low electrical conductivity and poor ductility.

The **covalent bond** is one in which electrons are shared (as opposed to transferred) between atoms in their outermost shells to achieve a stable set of eight. Fluorine and diamond are two examples of covalent bonds. In fluorine, one electron from each of two atoms is shared to form F_2 gas, as shown in Figure 2.5(a). In the case of diamond, which is carbon (atomic number 6), each atom has four neighbors with which it shares electrons. This produces a very rigid three-dimensional structure, not adequately represented in Figure 2.5(b), and accounts for the extreme high hardness of this material. Other forms of carbon (e.g., graphite) do not exhibit this rigid atomic structure. Solids with covalent bonding generally possess high hardness and low electrical conductivity.

The metallic bond is, of course, the atomic bonding mechanism in pure metals and metal alloys. Atoms of the metallic elements generally possess too few electrons in their outermost orbits to complete the outer shells for all of the atoms in, say, a given block of metal. Accordingly, instead of sharing on an atom-to-atom basis, **metallic bonding** involves the sharing of outer-shell electrons by all atoms to form a general electron cloud that permeates the entire block. This cloud provides the attractive forces to hold the atoms together and form a strong, rigid structure in most cases. Because of the general sharing of electrons, and their freedom to move within the metal, metallic bonding provides for good electrical conductivity. Other typical properties of materials characterized by metallic bonding include good conduction of heat and good ductility. (Although some of these terms are yet to be defined, the reader's general understanding of material properties is assumed.)

Secondary Bonds Whereas primary bonds involve atom-to-atom attractive forces, secondary bonds involve attraction forces between molecules, or **intermolecular forces**. There is no transfer or sharing of electrons in secondary bonding, and these bonds are

FIGURE 2.5 Two examples of covalent bonding:
(a) fluorine gas F_2 , and
(b) diamond.



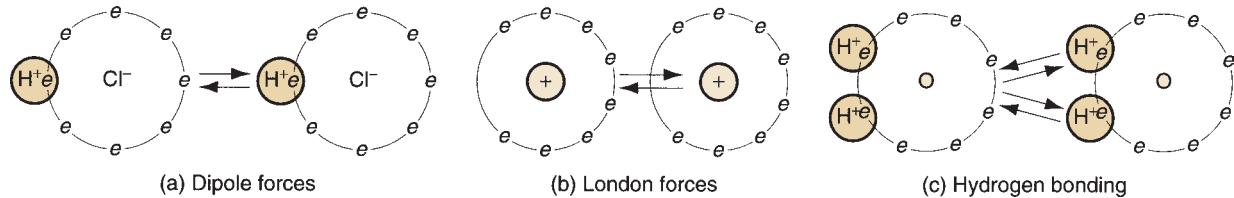


FIGURE 2.6 Three types of secondary bonding: (a) dipole forces, (b) London forces, and (c) hydrogen bonding.

therefore weaker than primary bonds. There are three forms of secondary bonding: (a) dipole forces, (b) London forces, and (c) hydrogen bonding, illustrated in Figure 2.6. Types (a) and (b) are often referred to as *van der Waals* forces, after the scientist who first studied and quantified them.

Dipole forces arise in a molecule comprised of two atoms that have equal and opposite electrical charges. Each molecule therefore forms a dipole, as shown in Figure 2.6(a) for hydrogen chloride. Although the material is electrically neutral in its aggregate form, on a molecular scale the individual dipoles attract each other, given the proper orientation of positive and negative ends of the molecules. These dipole forces provide a net intermolecular bonding within the material.

London forces involve attractive forces between nonpolar molecules; that is, the atoms in the molecule do not form dipoles in the sense of the preceding paragraph. However, owing to the rapid motion of the electrons in orbit around the molecule, temporary dipoles form when more electrons happen to be on one side of the molecule than the other, as suggested by Figure 2.6(b). These instantaneous dipoles provide a force of attraction between molecules in the material.

Finally, **hydrogen bonding** occurs in molecules containing hydrogen atoms that are covalently bonded to another atom (e.g., oxygen in H_2O). Because the electrons needed to complete the shell of the hydrogen atom are aligned on one side of its nucleus, the opposite side has a net positive charge that attracts the electrons of atoms in neighboring molecules. Hydrogen bonding is illustrated in Figure 2.6(c) for water, and is generally a stronger intermolecular bonding mechanism than the other two forms of secondary bonding. It is important in the formation of many polymers.

2.3 Crystalline Structures

Atoms and molecules are used as building blocks for the more macroscopic structure of matter that is considered here and in the following section. When materials solidify from the molten state, they tend to close ranks and pack tightly, in many cases arranging themselves into a very orderly structure, and in other cases, not quite so orderly. Two fundamentally different material structures can be distinguished: (1) crystalline and (2) noncrystalline. Crystalline structures are examined in this section, and noncrystalline in the next.

Many materials form into crystals on solidification from the molten or liquid state. It is characteristic of virtually all metals, as well as many ceramics and polymers. A **crystalline structure** is one in which the atoms are located at regular and recurring positions in three dimensions. The pattern may be replicated millions of times within

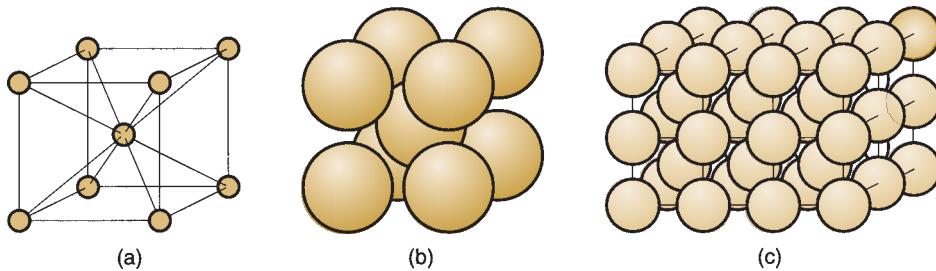


FIGURE 2.7 Body-centered cubic (BCC) crystal structure: (a) unit cell with atoms indicated as point locations in a three-dimensional axis system; (b) unit cell model showing closely packed atoms (sometimes called the hard-ball model); and (c) repeated pattern of the BCC structure.

a given crystal. The structure can be viewed in the form of a **unit cell**, which is the basic geometric grouping of atoms that is repeated. To illustrate, consider the unit cell for the body-centered cubic (BCC) crystal structure shown in Figure 2.7, one of the common structures found in metals. The simplest model of the BCC unit cell is illustrated in Figure 2.7(a). Although this model clearly depicts the locations of the atoms within the cell, it does not indicate the close packing of the atoms that occurs in the real crystal, as in Figure 2.7(b). Figure 2.7(c) shows the repeating nature of the unit cell within the crystal.

2.3.1 TYPES OF CRYSTAL STRUCTURES

In metals, three lattice structures are common: (1) body-centered cubic (BCC), (2) face-centered cubic (FCC), and (3) hexagonal close-packed (HCP), illustrated in Figure 2.8. Crystal structures for the common metals are presented in Table 2.1. It should be noted that some metals undergo a change of structure at different temperatures. Iron, for example, is BCC at room temperature; it changes to FCC above 912°C (1674°F) and back to BCC at temperatures above 1400°C (2550°F). When a metal (or other material) changes structure like this, it is referred to as being **allotropic**.

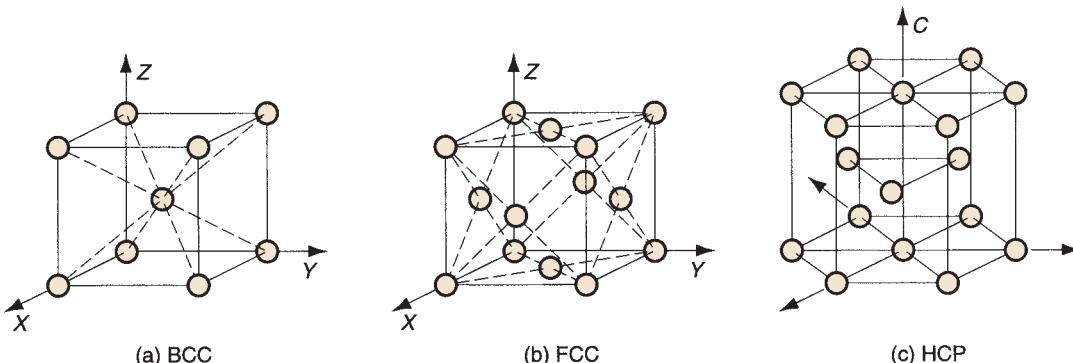


FIGURE 2.8 Three types of crystal structures in metals: (a) body-centered cubic, (b) face-centered cubic, and (c) hexagonal close-packed.

TABLE • 2.1 Crystal structures for the common metals (at room temperature).

Body-Centered Cubic (BCC)	Face-Centered Cubic (FCC)	Hexagonal Close-Packed (HCP)
Chromium (Cr)	Aluminum (Al)	Magnesium (Mg)
Iron (Fe)	Copper (Cu)	Titanium (Ti)
Molybdenum (Mo)	Gold (Au)	Zinc (Zn)
Tantalum (Ta)	Lead (Pb)	
Tungsten (W)	Silver (Ag)	
	Nickel (Ni)	

2.3.2 IMPERFECTIONS IN CRYSTALS

Thus far, crystal structures have been discussed as if they were perfect—the unit cell repeated in the material over and over in all directions. A perfect crystal is sometimes desirable to satisfy aesthetic or engineering purposes. For instance, a perfect diamond (contains no flaws) is more valuable than one containing imperfections. In the production of integrated circuit chips, large single crystals of silicon possess desirable processing characteristics for forming the microscopic details of the circuit pattern.

However, there are various reasons why a crystal's lattice structure may not be perfect. The imperfections often arise naturally because of the inability of the solidifying material to continue the replication of the unit cell indefinitely without interruption. Grain boundaries in metals are an example. In other cases, the imperfections are introduced purposely during the manufacturing process, for example, the addition of an alloying ingredient in a metal to increase its strength.

The various imperfections in crystalline solids are also called defects. Either term, **imperfection** or **defect**, refers to deviations in the regular pattern of the crystalline lattice structure. They can be catalogued as (1) point defects, (2) line defects, and (3) surface defects.

Point defects are imperfections in the crystal structure involving either a single atom or a few atoms. The defects can take various forms including, as shown in Figure 2.9: (a) **vacancy**, the simplest defect, involving a missing atom within the lattice structure; (b) **ion-pair vacancy**, also called a **Schottky defect**, which involves

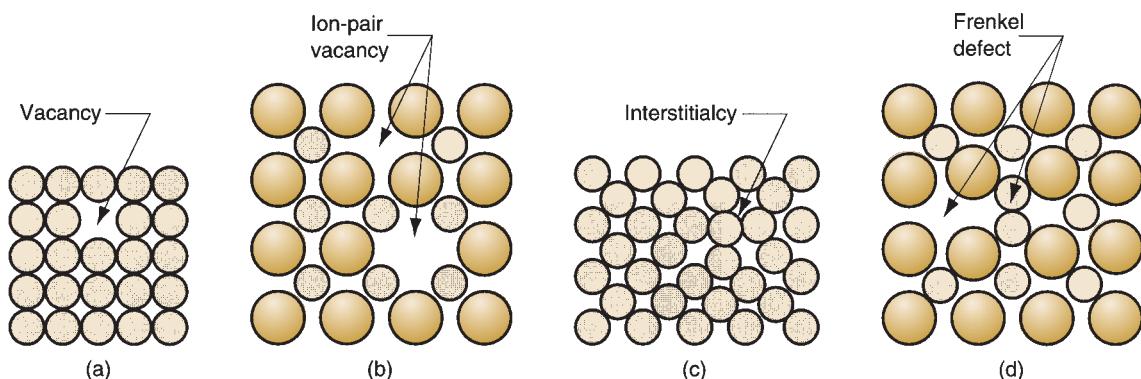


FIGURE 2.9 Point defects: (a) vacancy, (b) ion-pair vacancy, (c) interstitialcy, and (d) displaced ion.

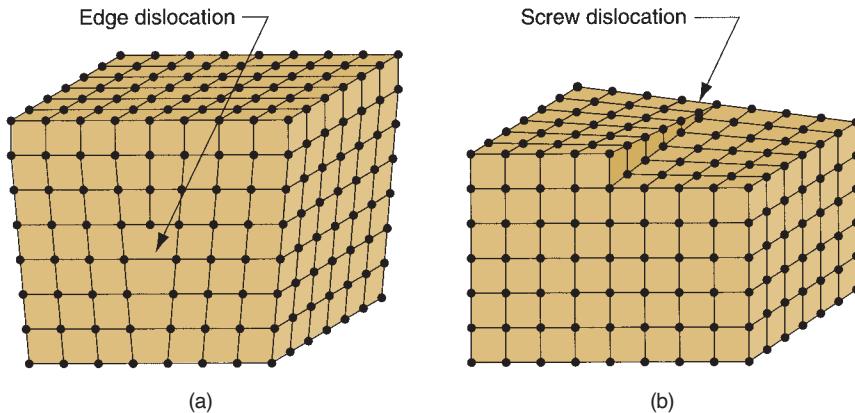


FIGURE 2.10 Line defects: (a) edge dislocation and (b) screw dislocation.

a missing pair of ions of opposite charge in a compound that has an overall charge balance; (c) **interstitialcy**, a lattice distortion produced by the presence of an extra atom in the structure; and (d) **displaced ion**, known as a **Frenkel defect**, which occurs when an ion becomes removed from a regular position in the lattice structure and inserted into an interstitial position not normally occupied by such an ion.

A **line defect** is a connected group of point defects that forms a line in the lattice structure. The most important line defect is the **dislocation**, which can take two forms: (a) edge dislocation and (b) screw dislocation. An **edge dislocation** is the edge of an extra plane of atoms that exists in the lattice, as illustrated in Figure 2.10(a). A **screw dislocation**, Figure 2.10(b), is a spiral within the lattice structure wrapped around an imperfection line, like a screw is wrapped around its axis. Both types of dislocations can arise in the crystal structure during solidification (e.g., casting), or they can be initiated during a deformation process (e.g., metal forming) performed on the solid material. Dislocations are useful in explaining certain aspects of mechanical behavior in metals.

Surface defects are imperfections that extend in two directions to form a boundary. The most obvious example is the external surface of a crystalline object that defines its shape. The surface is an interruption in the lattice structure. Surface boundaries can also lie inside the material. Grain boundaries are the best example of these internal surface interruptions. Metallic grains are discussed in a moment, but first let consider how deformation occurs in a crystal lattice, and how the process is aided by the presence of dislocations.

2.3.3 DEFORMATION IN METALLIC CRYSTALS

When a crystal is subjected to a gradually increasing mechanical stress, its initial response is to deform **elastically**. This can be likened to a tilting of the lattice structure without any changes of position among the atoms in the lattice, in the manner depicted in Figure 2.11(a) and (b). If the force is removed, the lattice structure (and therefore the crystal) returns to its original shape. If the stress reaches a high value relative to the electrostatic forces holding the atoms in their lattice positions, a permanent shape change occurs, called **plastic deformation**. What has happened is that the atoms in the lattice have permanently moved from their previous locations, and a new equilibrium lattice has been formed, as suggested by Figure 2.11(c).

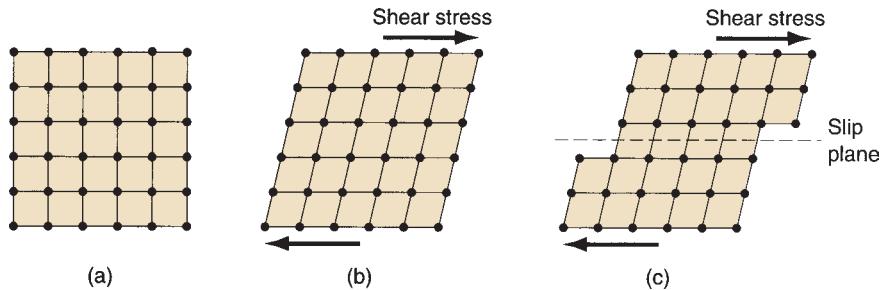


FIGURE 2.11 Deformation of a crystal structure: (a) original lattice; (b) elastic deformation, with no permanent change in positions of atoms; and (c) plastic deformation, in which atoms in the lattice are forced to move to new “homes.”

The lattice deformation shown in (c) of the figure is one possible mechanism, called *slip*, by which plastic deformation can occur in a crystalline structure. The other is called *twinning*, discussed later.

Slip involves the relative movement of atoms on opposite sides of a plane in the lattice, called the *slip plane*. The slip plane must be somehow aligned with the lattice structure (as indicated in the sketch), and so there are certain preferred directions along which slip is more likely to occur. The number of these *slip directions* depends on the lattice type. The three common metal crystal structures are somewhat more complicated, especially in three dimensions, than the square lattice depicted in Figure 2.11. It turns out that HCP has the fewest slip directions, BCC the most, and FCC falls in between. HCP metals show poor ductility and are generally difficult to deform at room temperature. Metals with BCC structure would figure to have the highest ductility, if the number of slip directions were the only criterion. However, nature is not so simple. These metals are generally stronger than the others, which complicates the issue, and the BCC metals usually require higher stresses to cause slip. In fact, some of the BCC metals exhibit poor ductility. Low carbon steel is a notable exception; although relatively strong, it is widely used with great commercial success in sheet-metal-forming operations, where it exhibits good ductility. The FCC metals are generally the most ductile of the three crystal structures, combining a good number of slip directions with (usually) relatively low to moderate strength. All three of these metal structures become more ductile at elevated temperatures, and this fact is often exploited in shaping them.

Dislocations play an important role in facilitating slip in metals. When a lattice structure containing an edge dislocation is subjected to a shear stress, the material deforms much more readily than in a perfect structure. This is explained by the fact that the dislocation is put into motion within the crystal lattice in the presence of the stress, as shown in the series of sketches in Figure 2.12. Why is it easier to move a dislocation through the lattice than it is to deform the lattice itself? The answer is that the atoms at the edge dislocation require a smaller displacement within the distorted lattice structure to reach a new equilibrium position. Thus, a lower energy level is needed to realign the atoms into the new positions than if the lattice were missing the dislocation. A lower stress level is therefore required to effect the deformation. Because the new position manifests a similar distorted lattice, movement of atoms at the dislocation continues at the lower stress level.

The slip phenomenon and the influence of dislocations have been explained here on a very microscopic basis. On a larger scale, slip occurs many times over

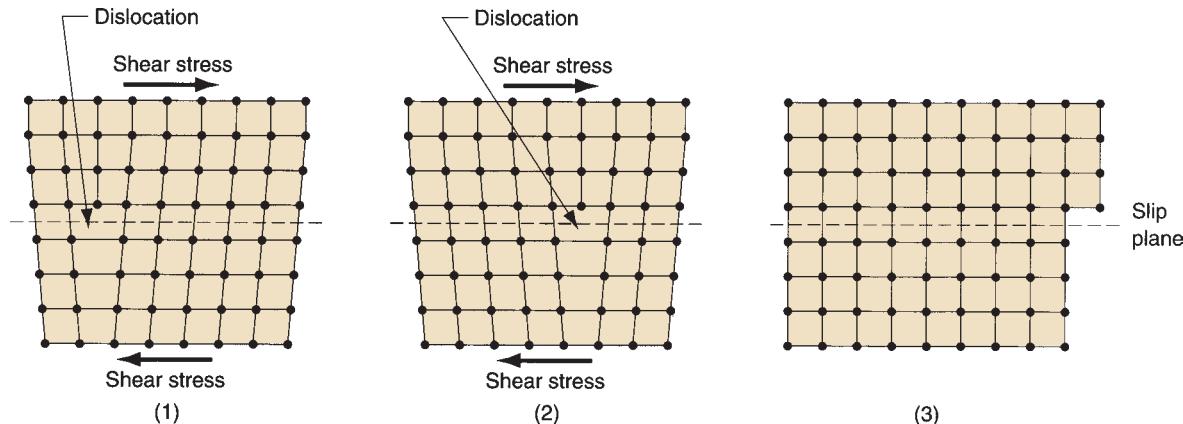


FIGURE 2.12 Effect of dislocations in the lattice structure under stress. In the series of diagrams, the movement of the dislocation allows deformation to occur under a lower stress than in a perfect lattice.

throughout the metal when subjected to a deforming load, thus causing it to exhibit the familiar macroscopic behavior of stretching, compressing, or bending. Dislocations represent a good-news–bad-news situation. Because of dislocations, the metal is more ductile and yields more readily to plastic deformation (forming) during manufacturing. However, from a product design viewpoint, the metal is not nearly as strong as it would be in the absence of dislocations.

Twining is a second way in which metal crystals plastically deform. **Twining** can be defined as a mechanism of plastic deformation in which atoms on one side of a plane (called the twinning plane) are shifted to form a mirror image of the other side of the plane. It is illustrated in Figure 2.13. The mechanism is important in HCP metals (e.g., magnesium, zinc) because they do not slip readily. Besides structure, another factor in twinning is the rate of deformation. The slip mechanism requires more time than twinning, which can occur almost instantaneously. Thus, when the deformation rate is very high, metals twin that would otherwise slip. Low carbon steel is an example that illustrates this rate sensitivity; when subjected to high strain rates it twins, whereas at moderate rates it deforms by slip.

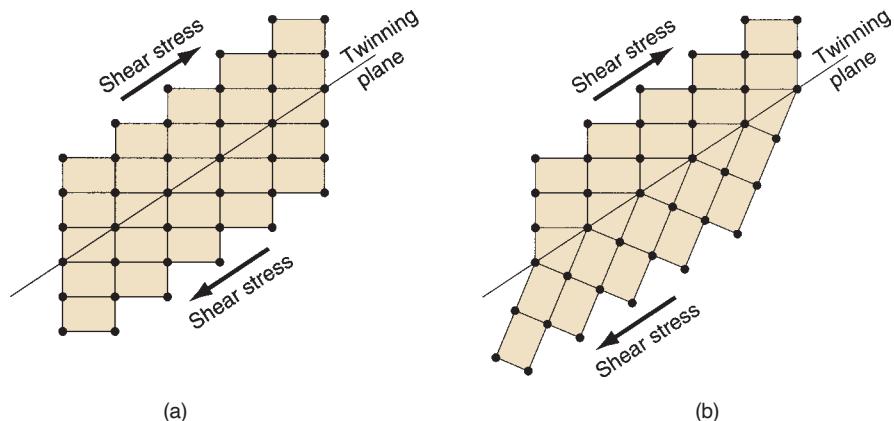


FIGURE 2.13 Twining involves the formation of an atomic mirror image (i.e., a “twin”) on the opposite side of the twinning plane: (a) before and (b) after twinning.

2.3.4 GRAINS AND GRAIN BOUNDARIES IN METALS

A given block of metal may contain millions of individual crystals, called **grains**. Each grain has its own unique lattice orientation; but collectively, the grains are randomly oriented within the block. Such a structure is referred to as **polycrystalline**. It is easy to understand how such a structure is the natural state of the material. When the block is cooled from the molten state and begins to solidify, nucleation of individual crystals occurs at random positions and orientations throughout the liquid. As these crystals grow they finally interfere with each other, forming at their interface a surface defect—a **grain boundary**. The grain boundary consists of a transition zone, perhaps only a few atoms thick, in which the atoms are not aligned with either grain.

The size of the grains in the metal block is determined by the number of nucleation sites in the molten material and the cooling rate of the mass, among other factors. In a casting process, the nucleation sites are often created by the relatively cold walls of the mold, which motivates a somewhat preferred grain orientation at these walls.

Grain size is inversely related to cooling rate: Faster cooling promotes smaller grain size, whereas slower cooling has the opposite effect. Grain size is important in metals because it affects mechanical properties. Smaller grain size is generally preferable from a design viewpoint because it means higher strength and hardness. It is also desirable in certain manufacturing operations (e.g., metal forming), because it means higher ductility during deformation and a better surface on the finished product.

Another factor influencing mechanical properties is the presence of grain boundaries in the metal. They represent imperfections in the crystalline structure that interrupt the continued movement of dislocations. This helps to explain why smaller grain size—therefore more grains and more grain boundaries—increases the strength of the metal. By interfering with dislocation movement, grain boundaries also contribute to the characteristic property of a metal to become stronger as it is deformed. The property is called **strain hardening**, and it is examined more closely in Chapter 3 on mechanical properties.

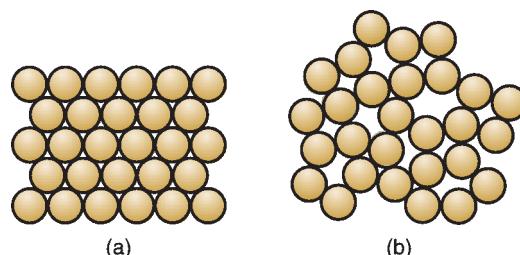
2.4 Noncrystalline (Amorphous) Structures

Many important materials are noncrystalline—liquids and gases, for example. Water and air have noncrystalline structures. A metal loses its crystalline structure when it is melted. Mercury is a liquid metal at room temperature, with its melting point of -38°C (-37°F). Important classes of engineering materials have a noncrystalline form in their solid state; the term **amorphous** is often used to describe these materials. Glass, many plastics, and rubber fall into this category. Many important plastics are mixtures of crystalline and noncrystalline forms. Even metals can be amorphous rather than crystalline, given that the cooling rate during transformation from liquid to solid is fast enough to inhibit the atoms from arranging themselves into their preferred regular patterns. This can happen, for instance, if the molten metal is poured between cold, closely spaced, rotating rolls.

Two closely related features distinguish noncrystalline from crystalline materials: (1) absence of a long-range order in the molecular structure, and (2) differences in melting and thermal expansion characteristics.

The difference in molecular structure can be visualized with reference to Figure 2.14. The closely packed and repeating pattern of the crystal structure is shown on the left; and the less dense and random arrangement of atoms in the noncrystalline

FIGURE 2.14 Illustration of difference in structure between: (a) crystalline and (b) noncrystalline materials. The crystal structure is regular, repeating, and denser, while the noncrystalline structure is more loosely packed and random.



material on the right. The difference is demonstrated by a metal when it melts. The more loosely packed atoms in the molten metal show an increase in volume (reduction in density) compared with the material's solid crystalline state. This effect is characteristic of most materials when melted (ice is a notable exception; liquid water is denser than solid ice). It is a general characteristic of liquids and solid amorphous materials that they are absent of long-range order as on the right in our figure.

The melting phenomenon will now be examined in more detail, and in doing so, the second important difference between crystalline and noncrystalline structures is illustrated. As indicated above, a metal experiences an increase in volume when it melts from the solid to the liquid state. For a pure metal, this volumetric change occurs rather abruptly, at a constant temperature (i.e., the melting temperature T_m), as indicated in Figure 2.15. The change represents a discontinuity from the slopes on either side in the plot. The gradual slopes characterize the metal's **thermal expansion**—the change in volume as a function of temperature, which is usually different in the solid and liquid states. Associated with the sudden volume increase as the metal transforms from solid to liquid at the melting point is the addition of a certain quantity of heat, called the **heat of fusion**, which causes the atoms to lose the dense, regular arrangement of the crystalline structure. The process is reversible; it operates in both directions. If the molten metal is cooled through its melting temperature, the same abrupt change in volume occurs (except that it is a decrease), and the same quantity of heat is given off by the metal.

An amorphous material exhibits quite different behavior than that of a pure metal when it changes from solid to liquid, as shown in Figure 2.15. The process is again reversible, but observe the behavior of the amorphous material during

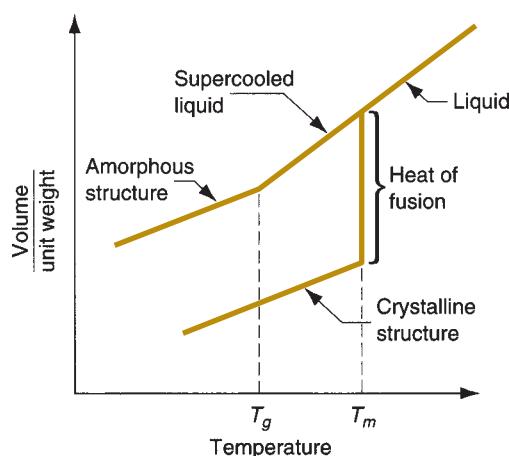


FIGURE 2.15 Characteristic change in volume for a pure metal (a crystalline structure), compared to the same volumetric changes in glass (a noncrystalline structure).

cooling from the liquid state, rather than during melting from the solid, as before. Glass (silica, SiO_2) is used to illustrate. At high temperatures, glass is a true liquid, and the molecules are free to move about as in the usual definition of a liquid. As the glass cools, it gradually transforms into the solid state, going through a transition phase, called a **supercooled liquid**, before finally becoming rigid. It does not show the sudden volumetric change that is characteristic of crystalline materials; instead it passes through its melting temperature T_m without a change in its thermal expansion slope. In this supercooled liquid region, the material becomes increasingly viscous as the temperature continues to decrease. As it cools further, a point is finally reached at which the supercooled liquid converts to a solid. This is called the **glass-transition temperature** T_g . At this point, there is a change in the thermal expansion slope. (It might be more precise to refer to it as the thermal contraction slope; however, the slope is the same for expansion and contraction). The rate of thermal expansion is lower for the solid material than for the supercooled liquid.

The difference in behavior between crystalline and noncrystalline materials can be traced to the response of their respective atomic structures to changes in temperature. When a pure metal solidifies from the molten state, the atoms arrange themselves into a regular and recurring structure. This crystal structure is much more compact than the random and loosely packed liquid from which it formed. Thus, the process of solidification produces the abrupt volumetric contraction observed in Figure 2.15 for the crystalline material. By contrast, amorphous materials do not achieve this repeating and closely packed structure at low temperatures. The atomic structure is the same random arrangement as in the liquid state; thus, there is no abrupt volumetric change as these materials transition from liquid to solid.

2.5 Engineering Materials

This section summarizes how atomic structure, bonding, and crystal structure (or absence thereof) are related to the type of engineering material: metals, ceramics, and polymers.

Metals Metals have crystalline structures in the solid state, almost without exception. The unit cells of these crystal structures are almost always BCC, FCC, or HCP. The atoms of the metals are held together by metallic bonding, which means that their valence electrons can move about with relative freedom (compared with the other types of atomic and molecular bonding). These structures and bonding generally make the metals strong and hard. Many of the metals are quite ductile (capable of being deformed, which is useful in manufacturing), especially the FCC metals. Other general properties of metals related to structure and bonding include high electrical and thermal conductivity, opaqueness (impervious to light rays), and reflectivity (capacity to reflect light rays).

Ceramics Ceramic molecules are characterized by ionic or covalent bonding, or both. The metallic atoms release or share their outermost electrons to the nonmetallic atoms, and a strong attractive force exists within the molecules. The general properties that result from these bonding mechanisms include high hardness and stiffness (even at elevated temperatures) and brittleness (no ductility). The bonding also means that ceramics are electrically insulating (nonconducting), refractory (thermally resistant), and chemically inert.

Ceramics possess either a crystalline or noncrystalline structure. Most ceramics have a crystal structure, whereas glasses based on silica (SiO_2) are amorphous. In certain cases, either structure can exist in the same ceramic material. For example, silica occurs in nature as crystalline quartz. When this mineral is melted and then cooled, it solidifies to form fused silica, which has a noncrystalline structure.

Polymers A polymer molecule consists of many repeating *mers* to form very large molecules held together by covalent bonding. Elements in polymers are usually carbon plus one or more other elements such as hydrogen, nitrogen, oxygen, and chlorine. Secondary bonding (van der Waals) holds the molecules together within the aggregate material (intermolecular bonding). Polymers have either a glassy structure or mixture of glassy and crystalline. There are differences among the three polymer types. In **thermoplastic polymers**, the molecules consist of long chains of mers in a linear structure. These materials can be heated and cooled without substantially altering their linear structure. In **thermosetting polymers**, the molecules transform into a rigid, three-dimensional structure on cooling from a heated plastic condition. If thermosetting polymers are reheated, they degrade chemically rather than soften. **Elastomers** have large molecules with coiled structures. The uncoiling and recoiling of the molecules when subjected to stress cycles motivate the aggregate material to exhibit its characteristic elastic behavior.

The molecular structure and bonding of polymers provide them with the following typical properties: low density, high electrical resistivity (some polymers are used as insulating materials), and low thermal conductivity. Strength and stiffness of polymers vary widely. Some are strong and rigid (although not matching the strength and stiffness of metals or ceramics), whereas others exhibit highly elastic behavior.

4

Physical Properties of Materials

Chapter Contents

4.1 Volumetric and Melting Properties

- 4.1.1 Density
- 4.1.2 Thermal Expansion
- 4.1.3 Melting Characteristics

4.2 Thermal Properties

- 4.2.1 Specific Heat and Thermal Conductivity
- 4.2.2 Thermal Properties in Manufacturing

4.3 Mass Diffusion

4.4 Electrical Properties

- 4.4.1 Resistivity and Conductivity
- 4.4.2 Classes of Materials by Electrical Properties

4.5 Electrochemical Processes

Physical properties, as the term is used here, defines the behavior of materials in response to physical forces other than mechanical. They include volumetric, thermal, electrical, and electrochemical properties. Components in a product must do more than simply withstand mechanical stresses. They must conduct electricity (or prevent its conduction), allow heat to be transferred (or allow it to escape), transmit light (or block its transmission), and satisfy myriad other functions.

Physical properties are important in manufacturing because they often influence the performance of the process. For example, thermal properties of the work material in machining determine the cutting temperature, which affects how long the tool can be used before it fails. In microelectronics, electrical properties of silicon and the way in which these properties can be altered by various chemical and physical processes comprise the basis of semiconductor manufacturing.

This chapter covers the physical properties that are most important in manufacturing—properties that are encountered in subsequent chapters of the book. They are divided into major categories such as volumetric, thermal, electrical, and so on. Also, as in the previous chapter on mechanical properties, the importance of these properties in manufacturing is discussed.

4.1 Volumetric and Melting Properties

These properties are related to the volume of solids and how they are affected by temperature. The properties include density, thermal expansion, and melting point. They are explained in the following, and typical values for selected engineering materials are presented in Table 4.1.

TABLE • 4.1 Volumetric properties in U.S. customary units for selected engineering materials.

Material	Density, r		Coefficient of Thermal Expansion, α		Melting Point, T_m	
	g/cm^3	lb/in^3	$8\text{C}^{21} 3 \ 10^{26}$	$8\text{F}^{21} 3 \ 10^{26}$	8C	8F
Metals						
Aluminum	2.70	0.098	24	13.3	660	1220
Copper	8.97	0.324	17	9.4	1083	1981
Iron	7.87	0.284	12.1	6.7	1539	2802
Lead	11.35	0.410	29	16.1	327	621
Magnesium	1.74	0.063	26	14.4	650	1202
Nickel	8.92	0.322	13.3	7.4	1455	2651
Steel	7.87	0.284	12	6.7	a	a
Tin	7.31	0.264	23	12.7	232	449
Titanium	4.51	0.163	8.6	4.7	1668	3034
Tungsten	19.30	0.697	4.0	2.2	3410	6170
Zinc	7.15	0.258	40	22.2	420	787
Ceramics and Silicon						
Glass	2.5	0.090	1.8–9.0	1.0–5.0	b	b
Alumina	3.8	0.137	9.0	5.0	NA	NA
Silica	2.66	0.096	NA	NA	b	b
Silicon	2.33	0.085	2.6	1.4	1414	2577
Polymers						
Phenol resins	1.3	0.047	60	33	c	c
Nylon	1.16	0.042	100	55	b	b
Teflon	2.2	0.079	100	55	b	b
Natural rubber	1.2	0.043	80	45	b	b
Polyethylene (low density)	0.92	0.033	180	100	b	b
Polystyrene	1.05	0.038	60	33	b	b

Compiled from, [2], [3], [4], and other sources.

^aMelting characteristics of steel depend on composition.

^bSoftens at elevated temperatures and does not have a well-defined melting point.

^cChemically degrades at high temperatures. NA = not available; value of property for this material could not be obtained.

4.1.1 DENSITY

In engineering, the density of a material is its weight per unit volume. Its symbol is r , and typical units are g/cm^3 (lb/in^3). The density of an element is determined by its atomic number and other factors such as atomic radius and atomic packing. The term **specific gravity** expresses the density of a material relative to the density of water and is therefore a ratio with no units.

Density is an important consideration in the selection of a material for a given application, but it is generally not the only property of interest. Strength is also important, and the two properties are often related in a **strength-to-weight ratio**, which is the tensile strength of the material divided by its density. The ratio is useful in comparing materials for structural applications in aircraft, automobiles, and other products in which weight and energy are of concern.

4.1.2 THERMAL EXPANSION

The density of a material is a function of temperature. The general relationship is that density decreases with increasing temperature. Put another way, the volume per

unit weight increases with temperature. Thermal expansion is the name given to this effect that temperature has on density. It is usually expressed as the ***coefficient of thermal expansion***, which measures the change in length per degree of temperature, as mm/mm/ $^{\circ}$ C (in/in/ $^{\circ}$ F). It is a length ratio rather than a volume ratio because this is easier to measure and apply. It is consistent with the usual design situation in which dimensional changes are of greater interest than volumetric changes. The change in length corresponding to a given temperature change is given by:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1) \quad (4.1)$$

where α = coefficient of thermal expansion, $^{\circ}$ C $^{-1}$ ($^{\circ}$ F $^{-1}$); and L_1 and L_2 are lengths, mm (in), corresponding, respectively, to temperatures T_1 and T_2 , $^{\circ}$ C ($^{\circ}$ F).

Values of coefficient of thermal expansion given in Table 4.1 suggest that it has a linear relationship with temperature. This is only an approximation. Not only is length affected by temperature, but the thermal expansion coefficient itself is also affected. For some materials it increases with temperature; for other materials it decreases. These changes are usually not significant enough to be of much concern, and values like those in the table are quite useful in design calculations for the range of temperatures contemplated in service. Changes in the coefficient are more substantial when the metal undergoes a phase transformation, such as from solid to liquid, or from one crystal structure to another.

In manufacturing operations, thermal expansion is put to good use in shrink fit and expansion fit assemblies (Section 31.3), in which a part is heated to increase its size or cooled to decrease its size to permit insertion into some other part. When the part returns to ambient temperature, a tightly fitted assembly is obtained. Thermal expansion can be a problem in heat treatment (Chapter 26) and welding (Section 29.6) because of thermal stresses that develop in the material during these processes.

4.1.3 MELTING CHARACTERISTICS

For a pure element, the ***melting point*** T_m is the temperature at which the material transforms from solid to liquid state. The reverse transformation, from liquid to solid, occurs at the same temperature and is called the ***freezing point***. For crystalline elements, such as metals, the melting and freezing temperatures are the same. A certain amount of heat energy, called the ***heat of fusion***, is required at this temperature to accomplish the transformation from solid to liquid.

Melting of a metal element at a specific temperature assumes equilibrium conditions. Exceptions occur in nature; for example, when a molten metal is cooled, it may remain in the liquid state below its freezing point if nucleation of crystals does not initiate immediately. When this happens, the liquid is said to be ***supercooled***.

There are other variations in the melting process—differences in the way melting occurs in different materials. For example, unlike pure metals, most metal alloys do not have a single melting point. Instead, melting begins at a certain temperature, called the ***solidus***, and continues as the temperature increases until finally converting completely to the liquid state at a temperature called the ***liquidus***. Between the two temperatures, the alloy is a mixture of solid and molten metals, the amounts of each being inversely proportional to their relative distances from the liquidus and solidus. Although most alloys behave in this way, exceptions are eutectic alloys that

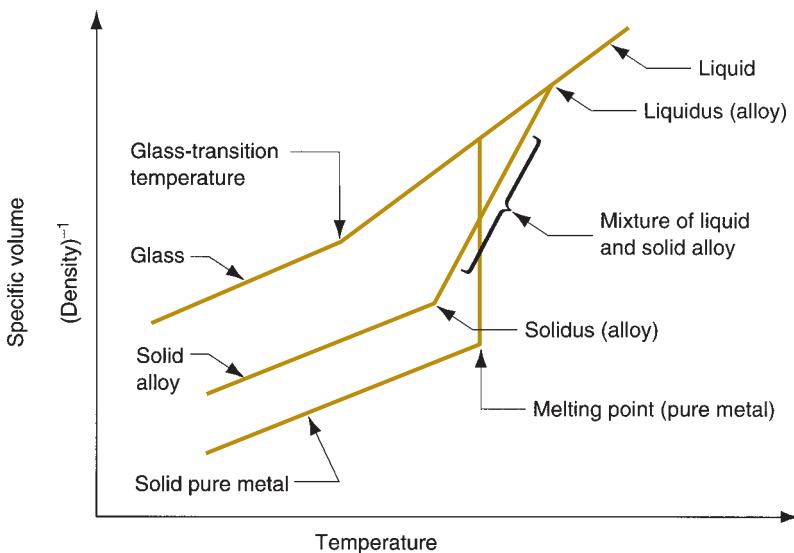


FIGURE 4.1 Changes in volume per unit weight ($1/\text{density}$) as a function of temperature for a hypothetical pure metal, alloy, and glass; all exhibiting similar thermal expansion and melting characteristics.

melt (and freeze) at a single temperature. These issues are examined in the discussion of phase diagrams in Chapter 6.

Another difference in melting occurs with noncrystalline materials (glasses). In these materials, there is a gradual transition from solid to liquid states. The solid material gradually softens as temperature increases, finally becoming liquid at the melting point. During softening, the material has a consistency of increasing plasticity (increasingly like a fluid) as it gets closer to the melting point.

These differences in melting characteristics among pure metals, alloys, and glass are portrayed in Figure 4.1. The plots show changes in density as a function of temperature for three hypothetical materials: a pure metal, an alloy, and glass. Plotted in the figure is the volumetric change, which is the reciprocal of density.

The importance of melting in manufacturing is obvious. In metal casting (Chapters 10 and 11), the metal is melted and then poured into a mold cavity. Metals with lower melting points are generally easier to cast, but if the melting temperature is too low, the metal loses its applicability as an engineering material. Melting characteristics of polymers are important in plastic molding and other polymer shaping processes (Chapter 13). Sintering of powdered metals and ceramics requires knowledge of melting points. Sintering does not melt the materials, but the temperatures used in the process must approach the melting point to achieve the required bonding of the powders (Chapters 15 and 16).

4.2 Thermal Properties

Much of the previous section is concerned with the effects of temperature on volumetric properties of materials. Certainly, thermal expansion, melting, and heat of fusion are thermal properties because temperature determines the thermal energy level of the atoms, leading to the changes in the materials. The current section examines several additional thermal properties—ones that relate to the storage and flow of heat within a substance. The usual properties of interest are specific heat

TABLE • 4.2 Values of common thermal properties for selected materials. Values are at room temperature, and these values change for different temperatures.

Material	Specific Heat		Thermal Conductivity		Material	Specific Heat		Thermal Conductivity	
	Cal/g °C ^a or Btu/lbm °F	J/s mm °C	Btu/hr in °F	Cal/g °C ^a or Btu/lbm °F		J/s mm °C	Btu/hr in °F		
Metals									
Aluminum	0.21	0.22	9.75	Alumina	0.18	0.029	1.4		
Cast iron	0.11	0.06	2.7	Concrete	0.2	0.012	0.6		
Copper	0.092	0.40	18.7	Polymers					
Iron	0.11	0.072	2.98	Phenolics	0.4	0.00016	0.0077		
Lead	0.031	0.033	1.68	Polyethylene	0.5	0.00034	0.016		
Magnesium	0.25	0.16	7.58	Teflon	0.25	0.00020	0.0096		
Nickel	0.105	0.070	2.88	Natural rubber	0.48	0.00012	0.006		
Steel	0.11	0.046	2.20	Other					
Stainless steel ^b	0.11	0.014	0.67	Silicon	0.17	0.149	6.6		
Tin	0.054	0.062	3.0	Water (liquid)	1.00	0.0006	0.029		
Zinc	0.091	0.112	5.41	Ice	0.46	0.0023	0.11		

Compiled from [2], [3], [6], and other sources.

^aSpecific heat has the same numerical value in Btu/lbm-F or Cal/g-C. 1.0 Calorie = 4.186 Joule.

^bAustenitic (18-8) stainless steel.

and thermal conductivity, values of which are compiled for selected materials in Table 4.2.

4.2.1 SPECIFIC HEAT AND THERMAL CONDUCTIVITY

The specific heat C of a material is defined as the quantity of heat energy required to increase the temperature of a unit mass of the material by one degree. Some typical values are listed in Table 4.2. To determine the amount of energy needed to heat a certain weight of a metal in a furnace to a given elevated temperature, the following equation can be used:

$$H = C W (T_2 - T_1) \quad (4.2)$$

where H = amount of heat energy, J (Btu); C = specific heat of the material, J/kg °C (Btu/lb °F); W = its weight, kg (lb); and $(T_2 - T_1)$ = change in temperature, °C (°F).

The volumetric heat storage capacity of a material is often of interest. This is simply density multiplied by specific heat rC . Thus, **volumetric specific heat** is the heat energy required to raise the temperature of a unit volume of material by one degree, J/mm³ °C (Btu/in³ °F).

Conduction is a fundamental heat-transfer process. It involves transfer of thermal energy within a material from molecule to molecule by purely thermal motions; no transfer of mass occurs. The thermal conductivity of a substance is therefore its capability to transfer heat through itself by this physical mechanism. It is measured by the **coefficient of thermal conductivity** k , which has typical units of J/s mm °C (Btu/in hr °F). The coefficient of thermal conductivity is generally high in metals, low in ceramics and plastics.

The ratio of thermal conductivity to volumetric specific heat is frequently encountered in heat transfer analysis. It is called the *thermal diffusivity* K and is determined as

$$K = \frac{k}{rC} \quad (4.3)$$

Thermal diffusivity is used to calculate cutting temperatures in machining (Section 20.5.1).

4.2.2 THERMAL PROPERTIES IN MANUFACTURING

Thermal properties play an important role in manufacturing because heat generation is common in so many processes. In some operations heat is the energy that accomplishes the process; in others heat is generated as a consequence of the process.

Specific heat is of interest for several reasons. In processes that require heating of the material (e.g., casting, heat treating, and hot metal forming), specific heat determines the amount of heat energy needed to raise the temperature to a desired level, according to Equation (4.2).

In many processes carried out at ambient temperature, the mechanical energy to perform the operation is converted to heat, which raises the temperature of the work part. This is common in machining and cold forming of metals. The temperature rise is a function of the metal's specific heat. Coolants are often used in machining to reduce these temperatures, and here the fluid's heat capacity is critical. Water is almost always employed as the base for these fluids because of its high heat-carrying capacity.

Thermal conductivity functions to dissipate heat in manufacturing processes, sometimes beneficially, sometimes not. In mechanical processes such as metal forming and machining, much of the power required to operate the process is converted to heat. The ability of the work material and tooling to conduct heat away from its source is highly desirable in these processes.

On the other hand, high thermal conductivity of the work metal is undesirable in fusion welding processes such as arc welding. In these operations, the heat input must be concentrated at the joint location so that the metal can be melted. For example, copper is generally difficult to weld because its high thermal conductivity allows heat to be conducted from the energy source into the work too rapidly, inhibiting heat buildup for melting at the joint.

4.3 Mass Diffusion

In addition to heat transfer in a material, there is also mass transfer. *Mass diffusion* involves movement of atoms or molecules within a material or across a boundary between two materials in contact. It is perhaps more appealing to one's intuition that such a phenomenon occurs in liquids and gases, but it also occurs in solids. It occurs in pure metals, in alloys, and between materials that share a common interface. Because of thermal agitation of the atoms in a material (solid, liquid, or gas), atoms are continuously moving about. In liquids and gases, where the level of thermal agitation is high, it is a free-roaming movement. In solids (metals in particular), the atomic motion is facilitated by vacancies and other imperfections in the crystal structure.

Diffusion can be illustrated by the series of sketches in Figure 4.2 for the case of two metals suddenly brought into intimate contact with each other. At the start, both

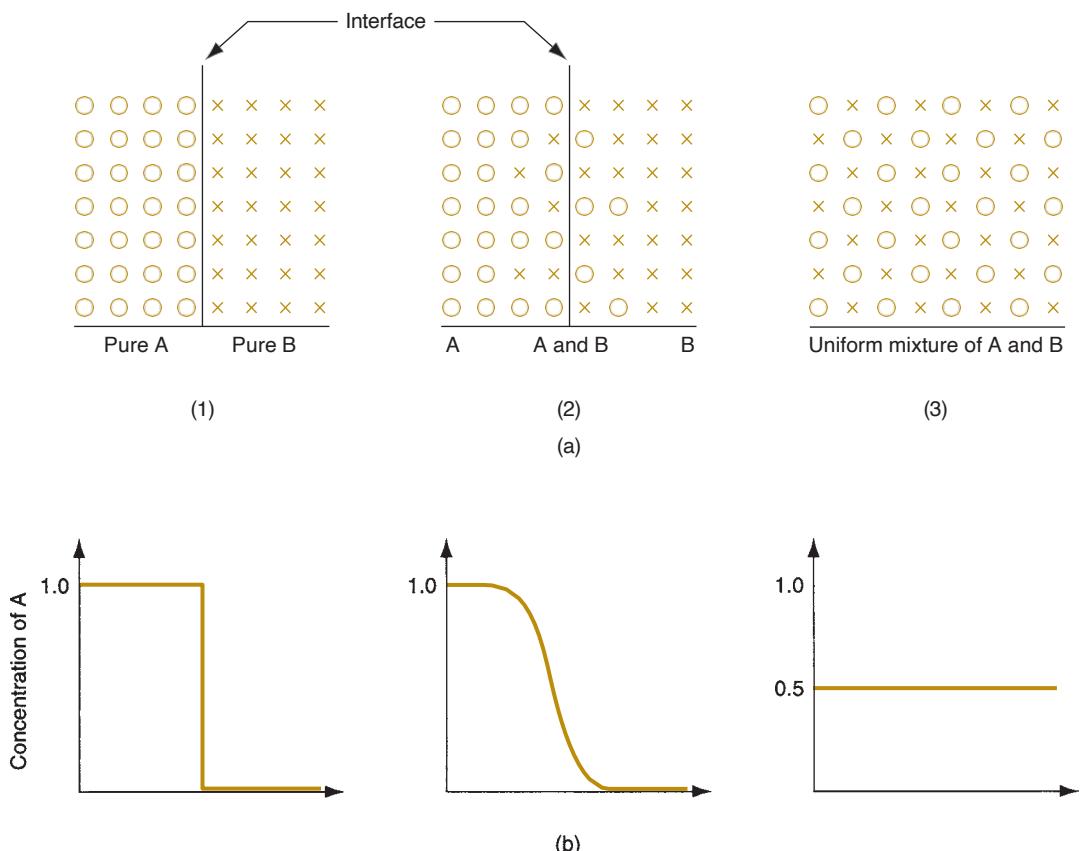


FIGURE 4.2 Mass diffusion: (a) model of atoms in two solid blocks in contact: (1) at the start when two pieces are brought together, they each have their individual compositions; (2) after some time, an exchange of atoms has occurred; and (3) eventually, a condition of uniform concentration occurs. The concentration gradient dc/dx for metal A is plotted in (b) of the figure.

metals have their own atomic structure; but with time there is an exchange of atoms, not only across the boundary, but within the separate pieces. Given enough time, the assembly of two pieces will finally reach a uniform composition throughout.

Temperature is an important factor in diffusion. At higher temperatures, thermal agitation is greater and the atoms can move about more freely. Another factor is the concentration gradient dc/dx , which indicates the concentration of the two types of atoms in a direction of interest defined by x . The concentration gradient is plotted in Figure 4.2(b) to correspond to the instantaneous distribution of atoms in the assembly. The relationship often used to describe mass diffusion is **Fick's first law**:

$$dm = -D \left(\frac{dc}{dt} \right) A dt \quad (4.4)$$

where dm = small amount of material transferred, D = diffusion coefficient of the metal, which increases rapidly with temperature, dc/dx = concentration gradient, A = area of the boundary, and dt represents a small time increment. An alternative expression of Equation (4.4) gives the mass diffusion rate:

$$\frac{dm}{dt} = -D \left(\frac{dc}{dx} \right) A \quad (4.5)$$

Although these equations are difficult to use in calculations because of the problem of assessing D , they are helpful in understanding diffusion and the variables on which D depends.

Mass diffusion is used in several processes. A number of surface-hardening treatments are based on diffusion (Section 26.4), including carburizing and nitriding. Among the welding processes, diffusion welding (Section 29.5.2) is used to join two components by pressing them together and allowing diffusion to occur across the boundary to create a permanent bond. Diffusion is also used in electronics manufacturing to alter the surface chemistry of a semiconductor chip in microscopic localized regions to create circuit details (Section 33.4.3).

4.4 Electrical Properties

Engineering materials exhibit a great variation in their capacity to conduct electricity. This section defines the physical properties by which this capacity is measured.

4.4.1 RESISTIVITY AND CONDUCTIVITY

The flow of electrical current involves movement of *charge carriers*—infinitesimally small particles possessing an electrical charge. In solids, these charge carriers are electrons. In a liquid solution, charge carriers are positive and negative ions. The movement of charge carriers is driven by the presence of an electric voltage and resisted by the inherent characteristics of the material, such as atomic structure and bonding between atoms and molecules. This is the familiar relationship defined by Ohm's law:

$$I = \frac{E}{R} \quad (4.6)$$

where I = current, A; E = voltage, V; and R = electrical resistance, !1. The resistance in a uniform section of material (e.g., a wire) depends on its length L , cross-sectional area A , and the resistivity of the material r ; thus,

$$R = r \frac{L}{A} \quad \text{or} \quad r = R \frac{A}{L} \quad (4.7)$$

where resistivity has units of !1-m²/m or !1-m (!1-in). **Resistivity** is the basic property that defines a material's capability to resist current flow. Table 4.3 lists values of resistivity for selected materials. Resistivity is not a constant; instead it varies, as do so many other properties, with temperature. For metals, it increases with temperature.

It is often more convenient to consider a material as conducting electrical current rather than resisting its flow. The **conductivity** of a material is simply the reciprocal of resistivity:

$$\text{Electrical conductivity} = \frac{1}{r} \quad (4.8)$$

where conductivity has units of (!1-m)⁻¹ ((!1-in)⁻¹).

4.4.2 CLASSES OF MATERIALS BY ELECTRICAL PROPERTIES

Metals are the best **conductors** of electricity, because of their metallic bonding. They have the lowest resistivity (Table 4.3). Most ceramics and polymers, whose electrons are tightly bound by covalent and/or ionic bonding, are poor conductors. Many of these materials are used as **insulators** because they possess high resistivities.

TABLE • 4.3 Resistivity of selected materials.

Material	Resistivity		Material	Resistivity	
	V-m	V-in		V-m	V-in
Conductors					
Aluminum	2.8×10^{-8}	1.1×10^{-6}	Steel, low C	17.0×10^{-8}	6.7×10^{-6}
Aluminum alloys	4.0×10^{-8a}	1.6×10^{-6a}	Steel, stainless	70.0×10^{-8a}	27.6×10^{-6}
Cast iron	65.0×10^{-8a}	25.6×10^{-6a}	Tin	11.5×10^{-8}	4.5×10^{-6}
Copper	1.7×10^{-8}	0.67×10^{-6}	Zinc	6.0×10^{-8}	2.4×10^{-6}
Gold	2.4×10^{-8}	0.95×10^{-6}	Carbon	5000×10^{-8b}	2000×10^{-6b}
Iron	9.5×10^{-8}	3.7×10^{-6}	Semiconductors		$10^1\text{--}10^5$ $10^2\text{--}10^7$
Lead	20.6×10^{-8}	8.1×10^{-6}	Silicon	1.0×10^3	0.4×10^5
Magnesium	4.5×10^{-8}	1.8×10^{-6}	Insulators		$10^{12}\text{--}10^{15}$ $10^{13}\text{--}10^{17}$
Nickel	6.8×10^{-8}	2.7×10^{-6}	Natural rubber	1.0×10^{12b}	0.4×10^{14b}
Silver	1.6×10^{-8}	0.63×10^{-6}	Polyethylene	100×10^{12b}	40×10^{14b}

Compiled from various standard sources.

^aValue varies with alloy composition.

^bValue is approximate.

An insulator is sometimes referred to as a dielectric, because the term **dielectric** means nonconductor of direct current. It is a material that can be placed between two electrodes without conducting current between them. However, if the voltage is high enough, the current will suddenly pass through the material, for example, in the form of an arc. The **dielectric strength** of an insulating material, then, is the electrical potential required to break down the insulator per unit thickness. Appropriate units are volts/m (volts/in).

In addition to conductors and insulators (or dielectrics), there are also superconductors and semiconductors. A **superconductor** is a material that exhibits zero resistivity. It is a phenomenon that has been observed in certain materials at low temperatures approaching absolute zero. We might expect the existence of this phenomenon, due to the significant effect that temperature has on resistivity. That these superconducting materials exist is of great scientific interest. If materials could be developed that exhibit this property at more normal temperatures, there would be significant practical implications in power transmission, electronic switching speeds, and magnetic field applications.

Semiconductors have already proven their practical worth. Their applications range from mainframe computers to household appliances and automotive engine controllers. As one would guess, a **semiconductor** is a material whose resistivity lies between insulators and conductors. The typical range is shown in Table 4.3. The most commonly used semiconductor material today is silicon (Section 7.5.2), largely because of its abundance in nature, relative low cost, and ease of processing. What makes semiconductors unique is the capacity to significantly alter conductivities in their surface chemistries in microscopic areas to fabricate integrated circuits (Chapter 33).

Electrical properties play an important role in various manufacturing processes. Some of the nontraditional processes use electrical energy to remove material. Electric discharge machining (Section 25.3.1) uses the heat generated by electrical energy in the form of sparks to remove material from metals. Most of the important

welding processes use electrical energy to melt the joint metal. Finally, the capacity to alter electrical properties of semiconductor materials is the basis for microelectronics manufacturing.

4.5 Electrochemical Processes

Electrochemistry is a field of science concerned with the relationship between electricity and chemical changes, and with the conversion of electrical and chemical energy.

In a water solution, the molecules of an acid, base, or salt are dissociated into positively and negatively charged ions. These ions are the charge carriers in the solution—they allow electric current to be conducted, playing the same role that electrons play in metallic conduction. The ionized solution is called an **electrolyte**; and electrolytic conduction requires that current enter and leave the solution at **electrodes**. The positive electrode is called the **anode**, and the negative electrode is the **cathode**. The whole arrangement is called an **electrolytic cell**. At each electrode, some chemical reaction occurs, such as the deposition or dissolution of material, or the decomposition of gas from the solution. **Electrolysis** is the name given to these chemical changes occurring in the solution.

Consider a specific case of electrolysis: decomposition of water, illustrated in Figure 4.3. To accelerate the process, dilute sulfuric acid (H_2SO_4) is used as the electrolyte, and platinum and carbon (both chemically inert) are used as electrodes. The electrolyte dissociates in the ions H^+ and $\text{SO}_4^{=}$. The H^+ ions are attracted to the negatively charged cathode; upon reaching it they acquire an electron and combine into molecules of hydrogen gas:



The $\text{SO}_4^{=}$ ions are attracted to the anode, transferring electrons to it to form additional sulfuric acid and liberate oxygen:



The product H_2SO_4 is dissociated into ions of H^+ and $\text{SO}_4^{=}$ again and so the process continues.

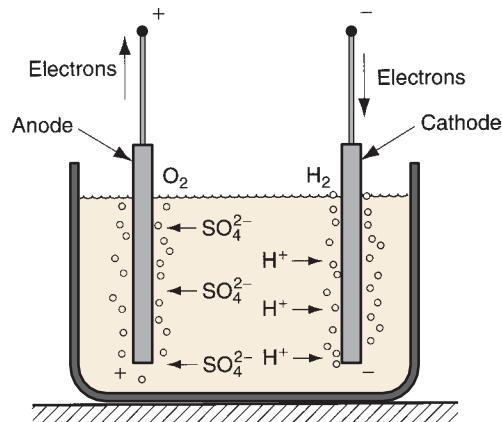


FIGURE 4.3 Example of electrolysis: decomposition of water.

In addition to the production of hydrogen and oxygen gases, as illustrated by the example, electrolysis is also used in several other industrial processes. Two examples are (1) **electroplating** (Section 27.3.1), an operation that adds a thin coating of one metal (e.g., chromium) to the surface of a second metal (e.g., steel) for decorative or other purposes; and (2) **electrochemical machining** (Section 25.2), a process in which material is removed from the surface of a metal part. Both these operations rely on electrolysis to either add or remove material from the surface of a metal part. In electroplating, the work part is set up in the electrolytic circuit as the cathode, so that the positive ions of the coating metal are attracted to the negatively charged part. In electrochemical machining, the work part is the anode, and a tool with the desired shape is the cathode. The action of electrolysis in this setup is to remove metal from the part surface in regions determined by the shape of the tool as it slowly feeds into the work.

The two physical laws that determine the amount of material deposited or removed from a metallic surface were first stated by the British scientist Michael Faraday:

1. The mass of a substance liberated in an electrolytic cell is proportional to the quantity of electricity passing through the cell.
2. When the same quantity of electricity is passed through different electrolytic cells, the masses of the substances liberated are proportional to their chemical equivalents.