

# 1 CHAPTER

## Introduction to Materials Science and Engineering



NASA (Source: [www.nasa.gov](http://www.nasa.gov))

**O**ppportunity and Spirit, two “robot geologists” designed and constructed by NASA, have finally provided irrefutable evidence that some regions of Mars were once covered with water. The rovers are masterpieces of engineering achievement whose design and construction required expert scientists, designers, and engineers in a variety of fields. One such field is the field of materials science. Consider the materials engineering and selection issues in constructing the rovers, delivering them to Mars using launch vehicles, landing the rovers safely on the Mars surface, controlling the movement and activities of the rovers, performing scientific experiments, collecting and storing data, and, finally, communicating the gathered data back to earth. All major classes of materials including metals, polymers, ceramics, composites, and electronic are used in the structure of the rovers. The Mars missions push the boundaries of knowledge and creativity in the field of materials science and engineering. Through the study of materials science and engineering, we can understand and appreciate the challenges and complexities involved in such missions. ■

## LEARNING OBJECTIVES

By the end of this chapter, students will be able to . . .

1. Describe the subject of materials science and engineering as a scientific discipline.
2. Cite the primary classification of solid materials.
3. Give distinctive features of each group of materials.
4. Cite one material from each group. Give some applications of different types of materials.
5. Evaluate how much you know, and how much you do not know about materials.

## 1.1 MATERIALS AND ENGINEERING

Humankind, materials, and engineering have evolved over the passage of time and are continuing to do so. All of us live in a world of dynamic change, and materials are no exception. The advancement of civilization has historically depended on the improvement of materials to work with. Prehistoric humans were restricted to naturally accessible materials such as stone, wood, bones, and fur. Over time, they moved from the materials Stone Age into the newer Copper (Bronze) and Iron Ages. Note that this advance did not take place uniformly everywhere—we shall see that this is true in nature even down to the microscopic scale. Even today we are restricted to the materials we can obtain from earth's crust and atmosphere (Table 1.1). According to Webster's dictionary, materials may be defined as substances of which something is composed or made. Although this definition is broad, from an engineering application point of view, it covers almost all relevant situations.

The production and processing of materials into finished goods constitutes a large part of our present economy. Engineers design most manufactured products and the processing systems required for their production. Since products require materials, engineers should be knowledgeable about the internal structure and properties of materials so that they can choose the most suitable ones for each application and develop the best processing methods.

Research and development engineers create new materials or modify the properties of existing ones. Design engineers use existing, modified, or new materials to design and create new products and systems. Sometimes design engineers have a problem in their design that requires a new material to be created by research scientists and engineers. For example, engineers designing a *high-speed civil transport* (HSCT) (Fig. 1.1) will have to develop new high-temperature materials that will withstand temperatures as high as 1800°C (3250°F) so that airspeeds as high as Mach 12 to 25 can be attained.<sup>1</sup> Research is currently underway to develop new

<sup>1</sup>Mach 1 equals the speed of sound in air.

**Table 1.1** The most common elements in planet earth's crust and atmosphere by weight percentage and volume

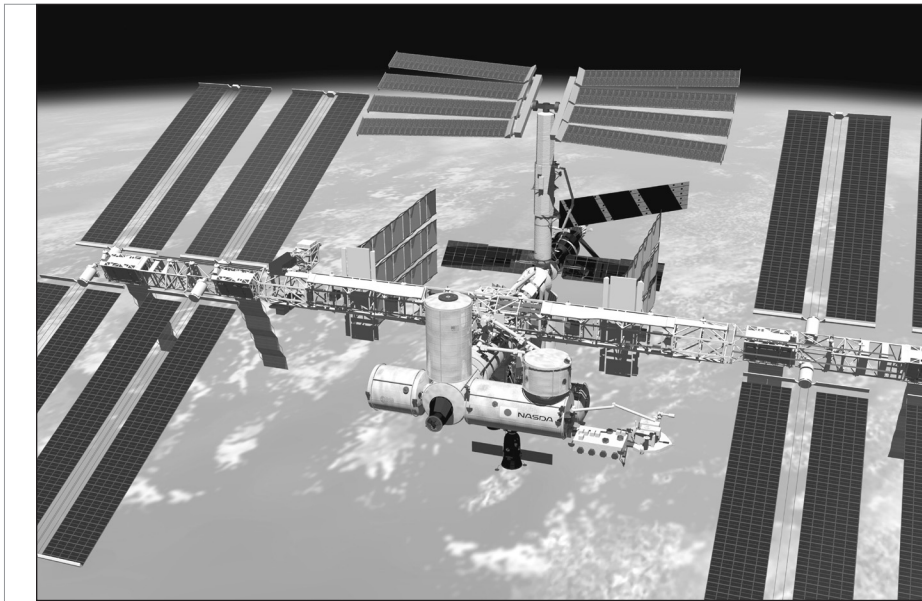
Element	Weight percentage of the earth's crust
Oxygen (O)	46.60
Silicon (Si)	27.72
Aluminum (Al)	8.13
Iron (Fe)	5.00
Calcium (Ca)	3.63
Sodium (Na)	2.83
Potassium (K)	2.70
Magnesium (Mg)	2.09
Total	98.70

Gas	Percent of dry air by volume
Nitrogen (N <sub>2</sub> )	78.08
Oxygen (O <sub>2</sub> )	20.95
Argon (Ar)	0.93
Carbon dioxide (CO <sub>2</sub> )	0.03



**Figure 1.1** High-speed civil transport image shows the Hyper-X at Mach 7 with the engines operating. Rings indicate surface flow speeds.  
 (© The Boeing Company.)



**Figure 1.2**  
The International Space Station  
(© AFP/CORBIS)

ceramic-matrix composites, refractory intermetallic compounds, and single-crystal superalloys for this and other similar applications.

One area that demands the most from materials scientists and engineers is space exploration. The design and construction of the *International Space Station* (ISS) and *Mars Exploration Rover* (MER) missions are examples of space research and exploration activities that require the absolute best from our materials scientists and engineers. The construction of ISS, a large research laboratory moving at a speed of 27,000 km/h through space, required selection of materials that would function in an environment far different than ours on earth (Fig. 1.2). The materials must be lightweight to minimize payload weight during liftoff. The outer shell must protect against the impact of tiny meteoroids and man-made debris. The internal air pressure of roughly 15 psi is constantly stressing the modules. Additionally, the modules must withstand the massive stresses at launch. Materials selection for MERs is also a challenge, especially considering that they must survive an environment in which night temperatures could be as low as  $-96^{\circ}\text{C}$ . These and other constraints push the limits of material selection in the design of complex system.

We must remember that materials usage and engineering designs are constantly changing. This change continues to accelerate. No one can predict the long-term future advances in material design and usage. In 1943 the prediction was made that successful people in the United States would own their own autogyros (auto-airplanes).

How wrong that prediction was! At the same time, the transistor, the integrated circuit, and television (color and high definition included) were neglected. Thirty years ago, many people would not have believed that some day computers would become a common household item similar to a telephone or a refrigerator. And today, we still find it hard to believe that some day space travel will be commercialized and we may even colonize Mars. Nevertheless, science and engineering push and transform our most unachievable dreams to reality.

The search for new materials goes on continuously. For example, mechanical engineers search for higher-temperature materials so that jet engines can operate more efficiently. Electrical engineers search for new materials so that electronic devices can operate faster and at higher temperatures. Aerospace engineers search for materials with higher strength-to-weight ratios for aerospace vehicles. Chemical and materials engineers look for more highly corrosion-resistant materials. Various industries look for *smart materials and devices* and *microelectromechanical systems* (MEMs) to be used as sensors and actuators in their respective applications. More recently, the field of *nanomaterials* has attracted a great deal of attention from scientists and engineers all over the world. Novel structural, chemical, and mechanical properties of nanomaterials have opened new and exciting possibilities in the application of these materials to a variety of engineering and medical problems. These are only a few examples of the search by engineers and scientists for new and improved materials and processes for a multitude of applications. In many cases what was impossible yesterday is a reality today!

Engineers in all disciplines should have some basic and applied knowledge of engineering materials so that they will be able to do their work more effectively when using them. The purpose of this book is to serve as an introduction to the internal structure, properties, processing, and applications of engineering materials. Because of the enormous amount of information available about engineering materials and due to the limitations of this book, the presentation has had to be selective.

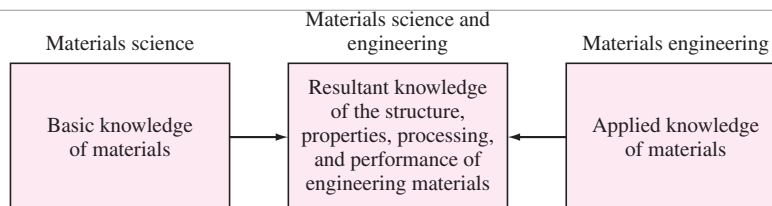
## 1.2 MATERIALS SCIENCE AND ENGINEERING

**Materials science** is primarily concerned with the search for basic knowledge about the internal structure, properties, and processing of materials. **Materials engineering** is mainly concerned with the use of fundamental and applied knowledge of materials so that the materials can be converted into products needed or desired by society. The term *materials science and engineering* combines both materials science and materials engineering and is the subject of this book. Materials science is at the basic knowledge end of the materials knowledge spectrum and materials engineering is at the applied knowledge end, and there is no demarcation line between the two (Fig. 1.3)

Figure 1.4 shows a three-ringed diagram that indicates the relationship among the basic sciences (and mathematics), materials science and engineering, and the other engineering disciplines. The basic sciences are located within the inner ring or

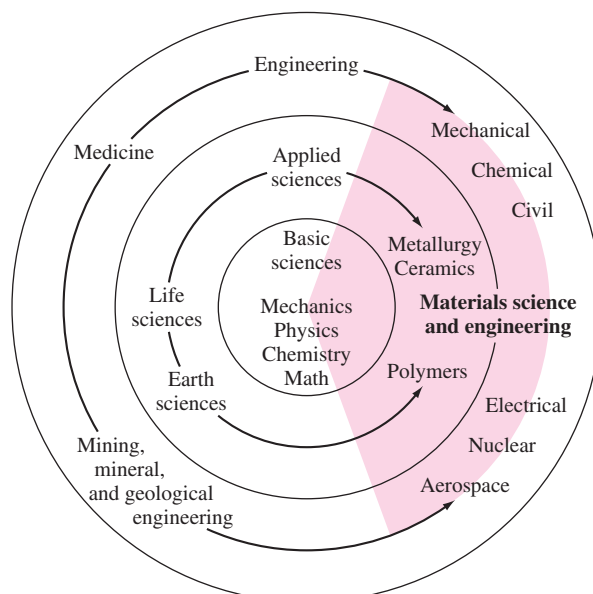
1.2 Materials Science and Engineering

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**Figure 1.3**

Materials knowledge spectrum. Using the combined knowledge of materials from materials science and materials engineering enables engineers to convert materials into the products needed by society.



**Figure 1.4**

This diagram illustrates how materials science and engineering form a bridge of knowledge from the basic sciences to the engineering disciplines.  
(Courtesy of the National Academy of Science.)

core of the diagram, while the various engineering disciplines (mechanical, electrical, civil, chemical, etc.) are located in the outermost third ring. The applied sciences, metallurgy, ceramics, and polymer science are located in the middle ring. Materials science and engineering is shown to form a bridge of materials knowledge from the basic sciences (and mathematics) to the engineering disciplines.



### 1.3 TYPES OF MATERIALS

For convenience most engineering materials are divided into *three* main or fundamental classes: **metallic materials**, **polymeric materials**, and **ceramic materials**. In this chapter we shall distinguish among them on the basis of some of their important mechanical, electrical, and physical properties. In subsequent chapters we shall study the internal structural differences among these types of materials. In addition to the three main classes of materials, we shall consider two processing or applicational classes, **composite materials** and **electronic materials**, because of their great engineering importance.

#### 1.3.1 Metallic Materials

These materials are inorganic substances that are composed of one or more metallic elements and may also contain some nonmetallic elements. Examples of metallic elements are iron, copper, aluminum, nickel, and titanium. Nonmetallic elements such as carbon, nitrogen, and oxygen may also be contained in metallic materials. Metals have a crystalline structure in which the atoms are arranged in an orderly manner. Metals in general are good thermal and electrical conductors. Many metals are relatively strong and ductile at room temperature, and many maintain good strength even at high temperatures.

Metals and alloys<sup>2</sup> are commonly divided into two classes: **ferrous metals and alloys** that contain a large percentage of iron such as the steels and cast irons and **nonferrous metals and alloys** that do not contain iron or contain only a relatively small amount of iron. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel. The distinction between ferrous and nonferrous alloys is made because of the significantly higher usage and production of steels and cast irons when compared to other alloys.

Metals in their alloyed and pure forms are used in numerous industries including aerospace, biomedical, semiconductor, electronic, energy, civil structural, and transport. The U.S. production of basic metals such aluminum, copper, zinc, and magnesium is expected to follow the U.S. economy fairly closely. However, the production of iron and steel has been less than expected because of global competition and the always-important economical reasons. Materials scientists and engineers are constantly attempting to improve the properties of existing alloys and to design and produce new alloys with improved strength, high temperature strength, creep (see Sec. 7.4), and fatigue (see Sec. 7.2) properties. The existing alloys may be improved by better chemistry, composition control, and processing techniques. For example, by 1961, new and improved nickel-base, iron-nickel-cobalt-base *superalloys* were available for use in high-pressure turbine airfoils in aircraft gas turbines. The term superalloy was used because of their improved performance at elevated temperatures of approximately 540°C (1000°F) and high stress levels. Figures 1.5 and 1.6 show a PW-400 gas turbine engine that is made primarily of metal alloys and superalloys. The metals used inside the engine must be

<sup>2</sup>A metal alloy is a combination of two or more metals or a metal (metals) and a nonmetal (nonmetals).

1.3 Types of Materials

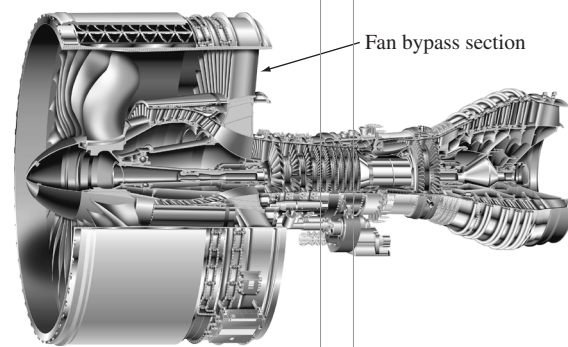
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**Figure 1.5**

The aircraft turbine engine (PW 4000) shown is made principally of metal alloys. The latest high-temperature, heat resistant, high-strength nickel-base alloys are used in this engine. This engine has many advanced, service-proven technologies to enhance operational performance and durability. These include second-generation single-crystal turbine blade materials, powder metal disks, and an improved full authority digital electronic control.

*(Courtesy of Pratt & Whitney Co.)*



**Figure 1.6**

Cutaway of the PW 4000 112-in. (284.48 cm) gas turbine engine, showing fan bypass section.

*(Courtesy of Pratt & Whitney Co.)*

able to withstand high temperature and pressures generated during its operation. By 1980, casting techniques were improved to produce directionally solidified columnar grain (see Sec. 4.2) and single crystal casting nickel-base alloys (see Sec. 5.x4). By the 1990s, single crystal directionally solidified cast alloys were standard in many aircraft gas turbine applications. The better performance of superalloys at elevated operating temperatures, significantly improved the efficiency of the aircraft engines.

Many metal alloys such as titanium alloys, stainless steel, and cobalt-base alloys are also used in biomedical applications including orthopedic implants, heart valves, fixations devices, and screws. These materials offer high strength, stiffness, and biocompatibility. Biocompatibility is important because the environment inside the human body is extremely corrosive, and therefore materials used for such applications must be effectively impervious to this environment.

In addition to better chemistry and composition control, researchers and engineers also concentrate on improving new processing techniques of these materials. Processes such as hot isostatic pressing and isothermal forging have led to improved

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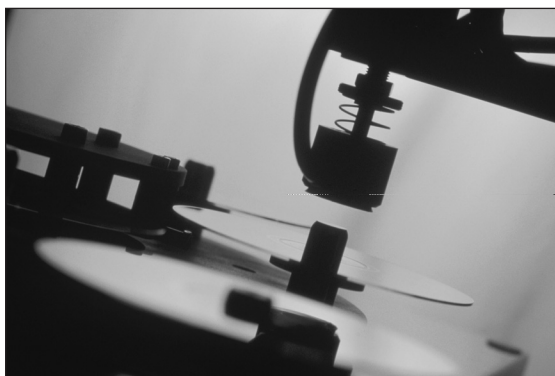
fatigue life of many alloys. Also, powder metallurgy techniques will continue to be important since improved properties can be obtained for some alloys with lower finished product cost.

### 1.3.2 Polymeric Materials

Most polymeric materials consist of long molecular chains or networks that are usually based on organics (carbon-containing precursors). Structurally, most polymeric materials are noncrystalline, but some consist of mixtures of crystalline and noncrystalline regions. The strength and ductility of polymeric materials vary greatly. Because of the nature of their internal structure, most polymeric materials are poor conductors of electricity. Some of these materials are good insulators and are used for electrical insulative applications. One of the more recent applications of polymeric materials has been in manufacture of *digital video disks* (DVDs) (Fig. 1.7). In general, polymeric materials have low densities and relatively low softening or decomposition temperatures.

Historically, plastic materials have been the fastest growing basic material in the United States, with a growth rate of 9 percent per year on a weight basis Fig. (1.14). However, the growth rate of plastics through 1995 dropped to below 5 percent, a significant decrease. This drop was expected because plastics have already substituted for metals, glass, and paper in most of the main volume markets, such as packaging and construction, for which plastics are suitable.

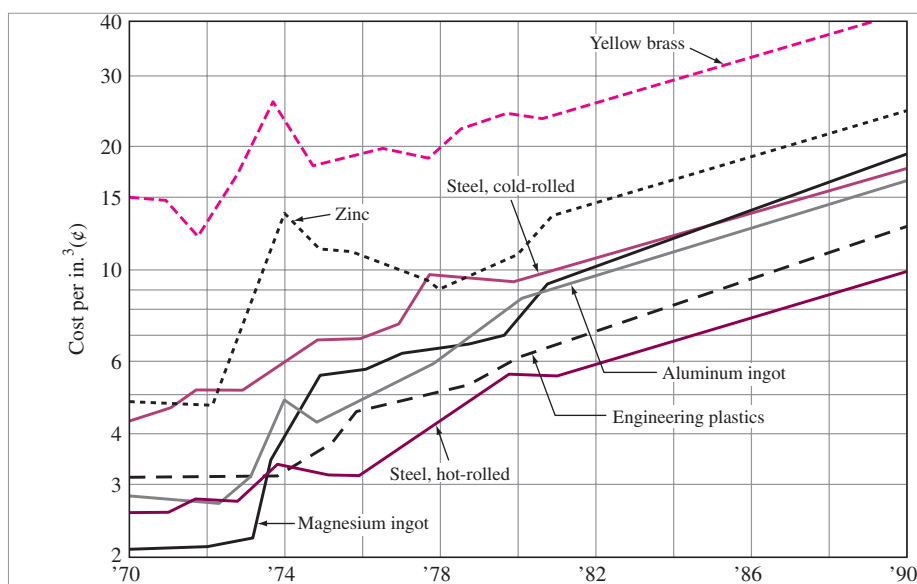
Engineering plastics such as nylon are expected to remain competitive with metals, according to some predictions. Figure 1.8 shows expected costs for engineering plastic resins versus some common metals. The polymer-supplying industries are increasingly focusing development of polymer-polymer mixtures, also known as *alloys* or *blends*, to fit specific applications for which no other single polymer is suitable. Because blends are produced based on existing polymers with well-known



**Figure 1.7**

Plastic resin producers are developing ultrapure, high-flow grades of polycarbonate plastic for DVDs.

(© George B. Diebold/CORBIS.)



**Figure 1.8**

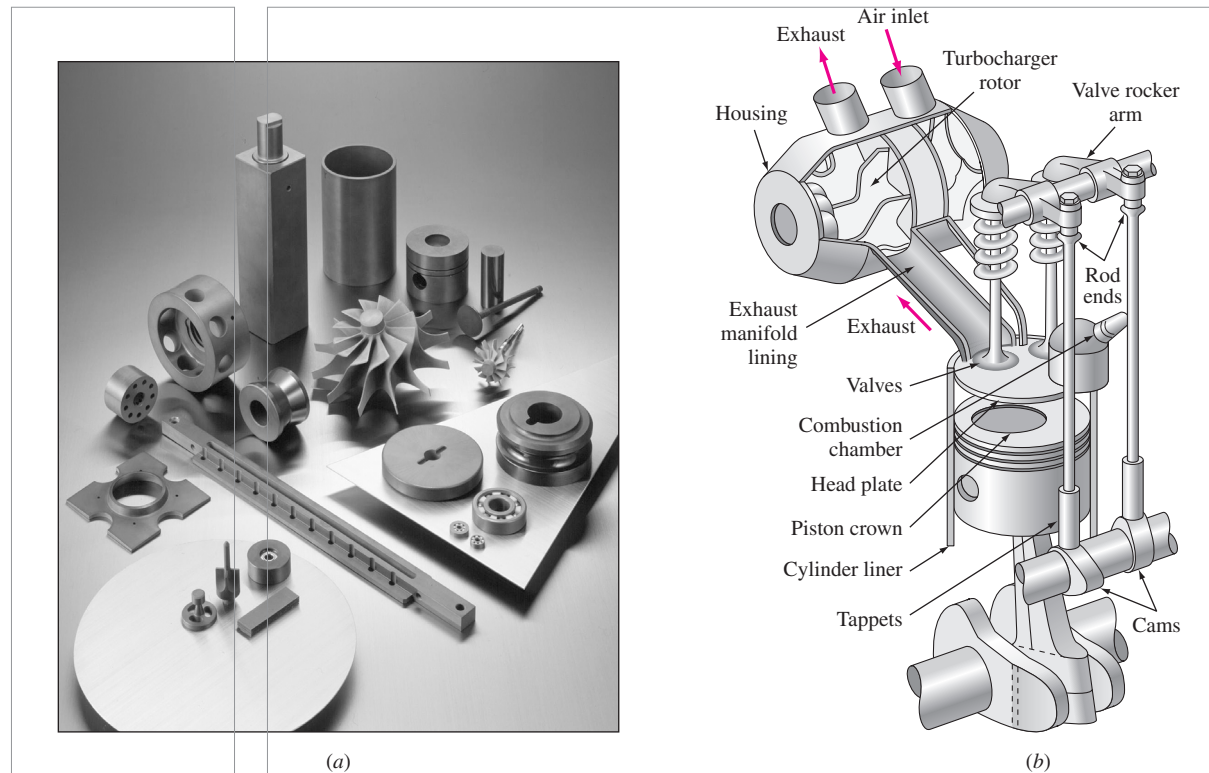
Historical and expected competitive costs of engineering plastic resins versus some common metals from 1970 to 1990. Engineering plastics are expected to remain competitive with cold-rolled steel and other metals.

(After *Modern Plastics*, August 1982, p. 12, and new data, 1998.)

properties, their development is less costly and more reliable than synthesizing a new single polymer for a specific application. For example, elastomers (a highly deformable type of polymer) are often blended with other plastics to improve the impact strength of the material. Such blends have important usage in automotive bumpers, power tool housing, sporting goods, and the synthetic components used in many indoor track facilities, which are generally made of a combination of rubber and polyurethane. Acrylic coatings blended with various fibers and fillers and with brilliant colors are used as coating material for tennis courts and playgrounds. Yet, other polymer-coating materials are being used for protection against corrosion, aggressive chemical environments, thermal shock, impact, wear, and abrasion. Finally, the insulative property along with high heat and wear resistance of many ceramics make them useful for furnace linings for heat treatment and melting of metals such as steel. The search for new plastics and alloys continues because of their lower cost and suitable properties for many applications.

### 1.3.3 Ceramic Materials

Ceramic materials are inorganic materials that consist of metallic and nonmetallic elements chemically bonded together. Ceramic materials can be crystalline, non-crystalline, or mixtures of both. Most ceramic materials have high-hardness and high-temperature strength but tend to be brittle. Advantages of ceramic materials for



**Figure 1.9**

(a) Examples of a newly developed generation of engineered ceramic materials for advanced engine applications. The black items include engine valves, valve seat inserts, and piston pins made of silicon nitride. The white item is a port-manifold liner made of an alumina ceramic material.

(Courtesy of Kyocera Industrial Ceramics Corp.)

(b) Potential ceramic component applications in a turbocharged diesel engine.

(After *Metals and Materials*, December 1988.)

engineering applications include light weight, high strength and hardness, good heat and wear resistance, reduced friction, and insulative properties (Figs. 1.9 and 1.10).

The historic rate of growth of traditional ceramic materials such as clay, glass, and stone in the United States has been 3.6 percent (1966 to 1980). The expected growth rate of these materials from 1982 to 1995 followed the U.S. economy. In the past few decades an entirely new family of ceramics of oxides, nitrides, and carbides, with improved properties, have been produced. The new generation of ceramic materials called *engineering ceramics*, *structural ceramics*, or *advanced ceramics* has higher strength, better wear and corrosion resistance (even at higher temperatures), and enhanced thermal shock resistance. Among the established advanced ceramic materials are alumina (oxide), silicon nitride (nitride) and silicon carbide (carbide).



**Figure 1.10**  
High-performance ceramic ball bearings and races are made from titanium and carbon nitride feedstocks through power metal technology.  
(© Tom Pantages photo/Courtesy Bearing Works.)

An important aerospace application for advanced ceramics is the use of ceramic tiles for the space shuttle. The ceramic tiles are made of silicon carbide because of its ability to act as a heat shield and to quickly return normal temperatures upon removal of the heat source. These ceramic materials thermally protect the aluminum internal structure of the space shuttle during ascent and reentry into the earth's atmosphere (see Figs. 11.50 and 11.51). Another application for advanced ceramics that points to the versatility, importance, and future growth of this class of materials is its use as a cutting tool material. For instance, silicon nitride with a high thermal shock resistance and fracture toughness is an excellent cutting tool material.

The applications for ceramic materials are truly unlimited as they can be applied to aerospace, metal manufacturing, biomedical, automobile, and numerous other industries. The two main drawbacks for this class of materials are that they are (1) difficult to process into finished products and are therefore expensive and (2) brittle and have low fracture toughness compared to metals. If techniques for developing high toughness ceramics are developed further, these materials could show a tremendous upsurge for engineering applications.

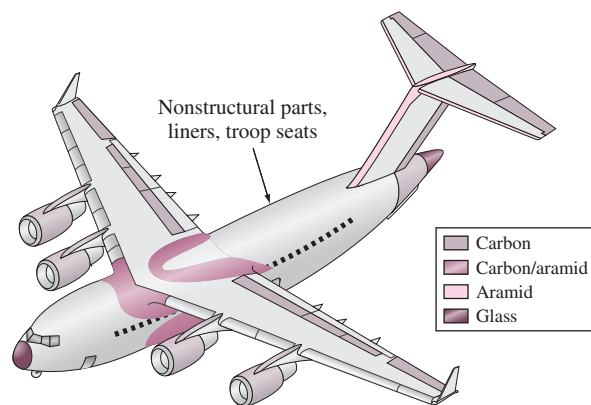
#### 1.3.4 Composite Materials

A composite material may be defined as two or more materials (phases or constituents) integrated to form a new one. The constituents keep their properties and the overall composite will have properties different than each of them. Most composite materials consist of a selected filler or reinforcing material and a compatible resin binder to obtain the specific characteristics and properties desired. Usually, the components do not dissolve in each other, and they can be physically identified by an interface between

them. Composites can be of many types. Some of the predominant types are fibrous (composed of fibers in a matrix) and particulate (composed of particles in a matrix). Many different combinations of reinforcements and matrices are used to produce composite materials. For example, the matrix material may be a metal such as aluminum, a ceramic such as alumina, or a polymer such as epoxy. Depending of the type of matrix used, the composite may be classified as a *metal matrix composite* (MMC), *ceramic matrix composite* (CMC), or a *polymer matrix composite* (PMC). The fiber or particulate materials may also be selected from any of the three main classes of materials with examples such as carbon, glass, aramid, silicon carbide, and others. The combinations of materials utilized in the design of composites depend mainly on the type of application and the environment in which the material will be used.

Composite materials have replaced numerous metallic components especially in aerospace, avionics, automobile, civil structural, and sports equipment industries. An average annual gain of about 5 percent is predicted for the future usage of these materials. One reason is due to their high strength and stiffness-to-weight ratio. Some advanced composites have stiffness and strength similar to some metals but with significantly lower density, and therefore lower overall component weight. These characteristics make advanced composites extremely attractive in situations where component weight is critical. Generally speaking, similar to ceramic materials, the main disadvantage of most composite materials is their brittleness and low fracture toughness. Some of these shortcomings may be improved, in certain situations, by the proper selection of the matrix material.

Two outstanding types of *modern composite materials* used for engineering applications are fiberglass-reinforcing material in a polyester or epoxy matrix and carbon fibers in an epoxy matrix. **Figure 1.1** shows schematically where carbon-fiber-epoxy



**Figure 1.11**

Overview of the wide variety of composite parts used in the Air Force's C-17 transport. This airplane has a wingspan of 165 ft and uses 15,000 lb of advanced composites.

(After *Advanced Composites*, May/June 1988, p. 53.)



composite material was used for the wings and engines of the C-17 transport plane. Since these airplanes have been constructed, new cost-saving procedures and modifications have been introduced (See *Aviation Week & Space Technology* for June 9, 1997, p. 30).

### 1.3.5 Electronic Materials

Electronic materials are not a major type of material by **production** volume but are an extremely important type of material for advanced engineering technology. The most important electronic material is pure silicon that is modified in various ways to change its electrical characteristics. A multitude of complex electronic circuits can be miniaturized on a silicon chip that is about 3/4 in. square (1.90 cm square) (Fig. 1.12). Microelectronic devices have made possible such new products as communication satellites, advanced computers, handheld calculators, digital watches, and robots (Fig. 1.13).

The use of silicon and other semiconductor materials in solid-state and microelectronics has shown a tremendous growth since 1970, and this growth pattern is expected to continue. The impact of computers and other industrial types of equipment using integrated circuits made from silicon chips has been spectacular. The full effect of computerized robots in modern manufacturing is yet to be determined. Electronic materials will undoubtedly play a vital role in the "factories of the future" in which almost all manufacturing may be done by robots assisted by computer-controlled machine tools.

Over the years integrated circuits have been made with a greater and greater density of transistors located on a single silicon chip with a corresponding decrease in transistor width. For example, in 1998 the point-to-point resolution for the smallest measurement on a silicon chip was 0.18  $\mu\text{m}$  and the diameter of the silicon wafer used was 12 in. (300 mm). Another improvement may be the replacement of aluminum by copper for interconnects because of the higher conductivity of copper.

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**Figure 1.12**  
Modern microprocessors have a multitude of outlets, as indicated on this picture of Intel's Pentium II microprocessor.  
(© Don Mason/CORBIS.)



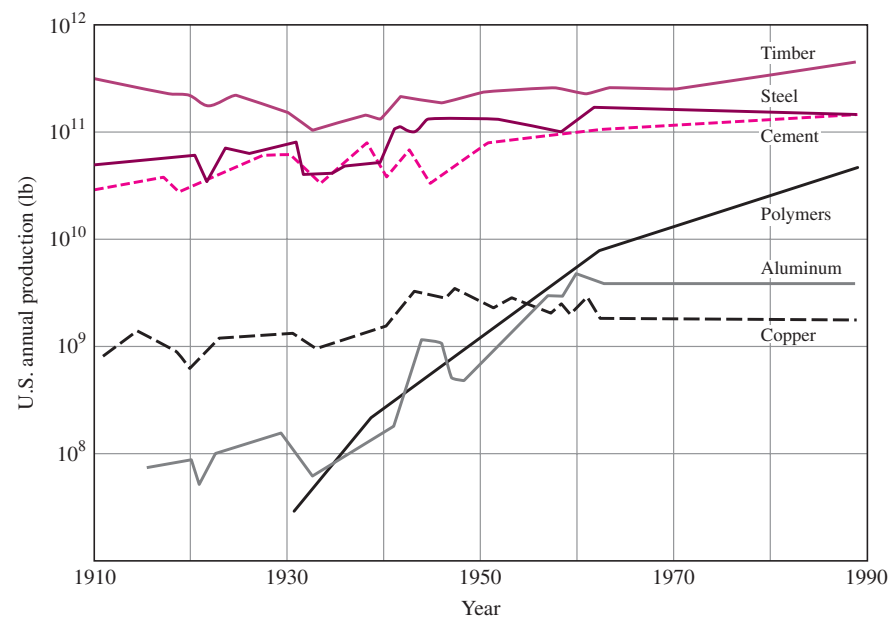
**Figure 1.13**  
Computerized robots weld a 1994 GM vehicle in Shreveport, LA.  
(© Charles O'Rear/CORBIS.)

### 1.4 COMPETITION AMONG MATERIALS

Materials compete with each other for existing and new markets. Over a period of time many factors arise that make it possible for one material to replace another for certain applications. Certainly cost is a factor. If a breakthrough is made in the processing of a certain type of material so that its cost is decreased substantially, this material may replace another for some applications. Another factor that causes material replacement changes is the development of a new material with special properties for some applications. As a result, over a period of time, the usage of different materials changes.

Figure 1.14 shows graphically how the production of six materials in the United States on a weight basis varied over the past years. Aluminum and polymers show an outstanding increase in production since 1930. On a volume basis the production increases for aluminum and polymers are even more accentuated since these are light materials.

The competition among materials is evident in the composition of the U.S. auto. In 1978 the average U.S. auto weighed 4000 lb (1800 kg) and consisted of about 60 percent cast iron and steel, 10 to 20 percent plastics, and 3 to 5 percent aluminum. The 1985 U.S. auto by comparison weighed an average of 3100 lb (1400 kg) and consisted of 50 to 60 percent cast iron and steel, 10 to 20 percent plastics, and



**Figure 1.14**

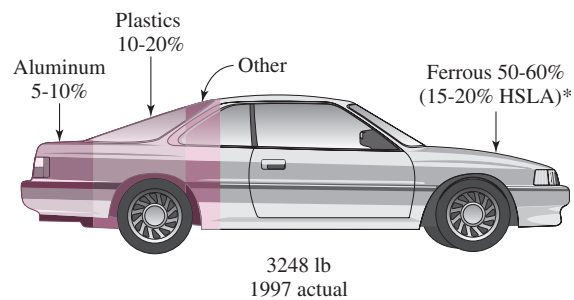
Competition of six major materials produced in the United States on a weight (pound) basis. The rapid rise in the production of aluminum and polymers (plastics) is evident.

1.4 Competition Among Materials

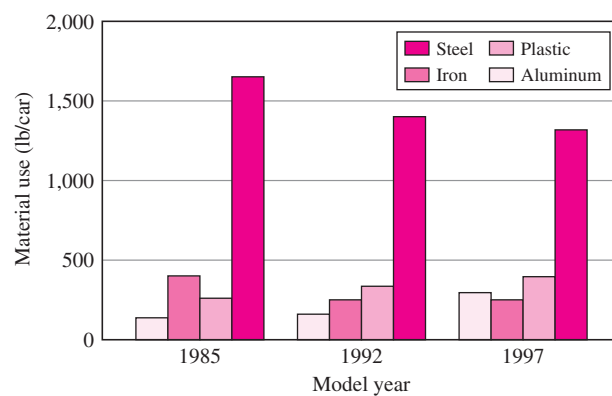
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5 to 10 percent aluminum. Thus in the period 1978–1985 the percentage of steel declined, that of polymers increased, and that of aluminum remained about the same. In 1997 the domestic U.S. auto weighed an average of 3248 lb (1476 kg), and plastics comprised about 7.4 percent of it (Fig. 1.15). The trend in the usage of materials appears to be more aluminum and steel in autos and less *cast iron*. The amount of plastics (by percentage) in autos appears to be about the same (Fig. 1.16).

For some applications only certain materials can meet the engineering requirements for a design, and these materials may be relatively expensive. For example, the modern jet engine (Fig. 1.5) requires high-temperature nickel-base superalloys to function. These materials are expensive, and no cheap substitute has been found to replace them. Thus, although cost is an important factor in engineering design, the materials used must also meet performance specifications. Replacement of one material by another will continue in the future since new materials are being discovered and new processes are being developed.



**Figure 1.15**  
 Breakdown of weight percentages of major materials used in the average 1985 U.S. automobile.  
 \*HSLA—High Strength Low Alloy Steel



**Figure 1.16**  
 Predictions and use of materials in U.S. automobile.  
 (After J.G. Simon, *Adv. Mat. & Proc.*, 133:63(1988) and new data.)

## 1.5 RECENT ADVANCES IN MATERIALS SCIENCE AND TECHNOLOGY AND FUTURE TRENDS

In recent decades, a number of exciting initiatives in materials science have been undertaken that could potentially revolutionize the future of the field. Smart materials and devices and nanomaterials are two classes of materials that will critically affect and devices all major industries.

### 1.5.1 Smart Materials

Some materials have been around for years but are finding more applications. They have the ability to sense external environmental stimuli (temperature, stress, light, humidity, and electric and magnetic fields) and respond to them by changing their properties (mechanical, electrical, or appearance), structure, or functions. These materials are generically called *smart materials*. Smart materials or systems that use smart materials consist of sensors and actuators. The sensory component detects a change in the environment, and the actuator component performs a specific function or a response. For instance, some smart materials change or produce color when exposed to changes in temperature, light intensity, or an electric current.

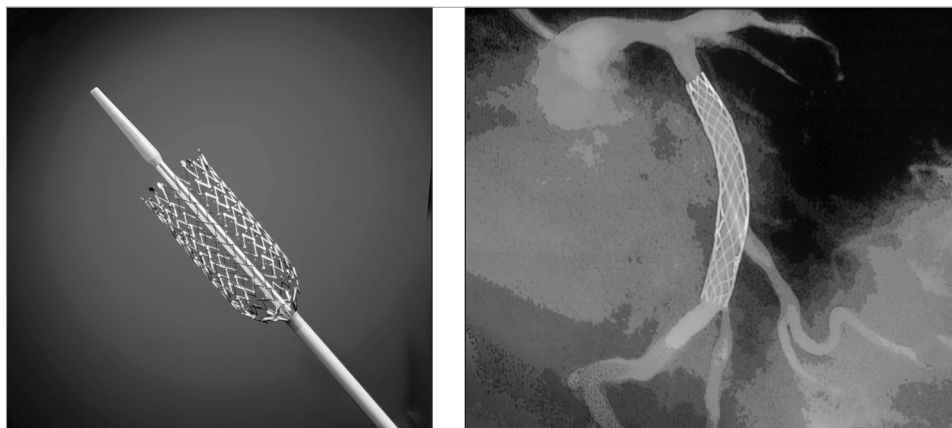
Some of the more technologically important smart materials that can function as actuators are *shape-memory alloys* and *piezoelectric* ceramics. Shape-memory alloys are metal alloys that, once strained, revert back to their original shape upon an increase in temperature above a critical transformation temperature. The change in shape back to the original is due to a change in the crystal structure above the transformation temperature. One biomedical application of a shape-memory alloys is as a stent for supporting weakened artery walls or for expanding narrowed arteries (Fig. 1.17). The deformed stent is first delivered in the appropriate position in the artery using a probe. The stent expands to its original shape and size after increasing its temperature to body temperature. For comparison, the conventional method of expanding or supporting an artery is through the use of a stainless steel tube that is expanded using a balloon. Examples of shape-memory alloys are nickel-titanium and copper-zinc-aluminum alloys.

Actuators may also be made of piezoelectric materials. The materials produce an electric field when exposed to a mechanical force. Conversely, a change in an external electric field will produce a mechanical response in the same material. Such materials may be used to sense and reduce undesirable vibrations of a component through their actuator response. Once a vibration is detected, a current is applied to produce a mechanical response that counters the effect of the vibration.

Now let us consider the design and development of systems at micrometer size scale that use smart materials and devices to sense, communicate, and actuate: such is the world of *microelectromechanical systems* (MEMs). Originally, MEMs were devices that integrated technology, electronic materials, and smart materials on a semiconductor chip to produce what were commonly known as a *micromachines*. The original MEMs device had the microscopic mechanical elements fabricated on silicon chips using integrated circuits technology; MEMs were used as sensors or

**1.5** Recent Advances in Materials Science and Technology and Future Trends

**19**



**Figure 1.17**

Shape-memory alloys used as a stent to expand narrowed arteries or support weakened ones.

(Source: <http://www.designinsite.dk/htmsider/inspmat.htm>.)

Courtesy of Nitinol Devices & Components

© Sovereign/Phototake NYC

actuators. But today the term “MEMs” is extended to any miniaturized device. The applications of MEMs are also numerous, including but not limited to micropumps, locking systems, motors, mirrors, and sensors. For instance, MEMs are used in automobile airbags to sense both the deceleration and the size of the person sitting in the car and to deploy the airbag at a proper speed.

### 1.5.2 Nanomaterials

Nanomaterials are generally defined as those materials that have a characteristic length scale (that is, particle diameter, grain size, layer thickness, etc.) smaller than 100 nm ( $1 \text{ nm} = 10^{-9} \text{ m}$ ). Nanomaterials can be metallic, polymeric, ceramic, electronic, or composite. In this respect, ceramic powder aggregates of less than 100 nm in size, bulk metals with grain size less than 100 nm, thin polymeric films with thickness less than 100 nm, and electronic wires with diameter less than 100 nm are all considered nanomaterials or nanostructured materials. At the nanoscale, the properties of the material are neither that of the molecular or atomic level nor that of the bulk material. Although a tremendous amount of research and development activities has been devoted to this topic in the past decade, early research on nanomaterials dates back to the 1960s when chemical flame furnaces were used to produce particles smaller than one micron ( $1 \text{ micron} = 10^{-6} \text{ m} = 10^3 \text{ nm}$ ) in size. The early applications of nanomaterials were as chemical catalysts and pigments. Metallurgists have always been aware that by refining the grain structure of a metal to ultrafine (submicron) levels, its strength and hardness increases significantly in comparison to the coarse-grained (micron-size) bulk metal. For example, nanostructured pure copper has a yield strength six times that of coarse-grained copper.



The reasons for the recent extraordinary attention to these materials may be due to the development of (1) new tools that make the observation and characterization of these materials possible and (2) new methods of processing and synthesizing nanostructured materials that enable researchers to produce these materials more easily and at a higher yield rate.

The future applications of nanomaterials are only limited to the imagination, and one of the major obstacle in fulfilling this potential is the ability to efficiently and inexpensively produce these materials. Consider the manufacturing of orthopaedic and dental implants from nanomaterials with better biocompatibility characteristics, better strength, and better wear characteristics than metals. One such material is nanocrystalline zirconia (zirconium oxide), a hard and wear resistant ceramic that is chemically stable and biocompatible. This material can be processed in a porous form, and when it is used as implant material, it allows for bone to grow into its pores, resulting in a more stable fixation. The metal alloys that are currently used for this application do not allow for such interaction and often loosen over time, requiring further surgery. Nanomaterials may also be used in producing paint or coating materials that are significantly more resistant to scratching and environmental damage. Also, electronic devices such as transistors diodes and even lasers may be developed on a nanowire. Such materials science advancements will have both technological and economical impact on all areas of engineering and industries.

Welcome to the fascinating and exceedingly interesting world of materials science and engineering!

## 1.6 DESIGN AND SELECTION

Material engineers should be knowledgeable of various classes of materials, their properties, structure, manufacturing processes involved, environmental issues, economic issues, and more. As the complexity of the component under consideration increases, the complexity of the analysis and the factors involved in the materials selection process also increase. Consider the materials selection issues for the frame and forks of a bicycle. The selected material must be strong enough to support the load without yielding (permanent deformation) or fracture. The chosen material must be stiff to resist excessive elastic deformation and fatigue failure (due to repeated loading). The corrosion resistance of the material may be a consideration over the life of the bicycle. Also, the weight of frame is important if the bicycle is used for racing: It must be lightweight. What materials will satisfy all of the above requirements? A proper materials selection process must consider the issues of strength, stiffness, weight, and shape of the component (shape factor) and utilize materials selection charts in order to determine the most suitable material for the application. The detailed selection process is outside the scope of this textbook, but we use this example as an exercise in identifying various material candidates for this application. It turns out that a number of materials may satisfy the strength, stiffness, and weight considerations including some aluminum alloys, titanium alloys, magnesium alloys, steel, *carbon fiber reinforced plastic (CFRP)*, and even wood. Wood has excellent

properties for our application but it cannot be easily shaped to form a frame and the forks. Further analysis shows CFRP is the best choice; it offers a strong, stiff, and lightweight frame that is both fatigue and corrosion resistant. However, the fabrication process is costly. Therefore, if cost is an issue, this material may not be the most suitable choice. The remaining materials, all metal alloys, are all suitable and comparatively easy to manufacture into the desired shape. If cost is a major issue, steel emerges as the most suitable choice. On the other hand, if lower bicycle weight is important, the aluminum alloy emerges as the most suitable material. Titanium and magnesium alloys are more expensive than both aluminum and steel alloys and are lighter than steel; they, however, do not offer significant advantages over aluminum.

### 1.7 SUMMARY

Materials science and materials engineering (collectively, materials science and engineering) form a bridge of materials knowledge between the basic sciences (and mathematics) and the engineering disciplines. Materials science is concerned primarily with the search for basic knowledge about materials, whereas materials engineering is concerned mainly with using applied knowledge about materials.

The three main types of materials are metallic, polymeric, and ceramic materials. Two other types of materials that are very important for modern engineering technology are composite and electronic materials. All these types of materials will be dealt with in this book. Smart materials and nanomaterials are presented as new classes of materials with novel and important applications in many industries.

Materials compete with each other for existing and new markets, and so the replacement of one material by another for some applications occurs. The availability of raw materials, cost of manufacturing, and the development of new materials and processes for products are major factors that cause changes in materials usage.

### 1.8 DEFINITIONS

#### Sec. 1.1

**Materials:** substances of which something is composed or made. The term *engineering materials* is sometimes used to refer specifically to materials used to produce technical products. However, there is no clear demarcation line between the two terms, and they are used interchangeably.

#### Sec. 1.2

**Materials science:** a scientific discipline that is primarily concerned with the search for basic knowledge about the internal structure, properties, and processing of materials.

**Materials engineering:** an engineering discipline that is primarily concerned with the use of fundamental and applied knowledge of materials so that they can be converted into products needed or desired by society.

**Metallic materials** (metals and metal alloys): inorganic materials that are characterized by high thermal and electrical conductivities. Examples are iron, steel, aluminum, and copper.

*Sec. 1.3*

**Ferrous metals and alloys:** metals and alloys that contain a large percentage of iron such as steels and cast irons.

**Nonferrous metals and alloys:** metals and alloys that do not contain iron, or if they do contain iron, it is only in a relatively small percentage. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel.

**Ceramic materials:** materials consisting of compounds of metals and nonmetals. Ceramic materials are usually hard and brittle. Examples are clay products, glass, and pure aluminum oxide that has been compacted and densified.

**Polymeric materials:** materials consisting of long molecular chains or networks of low-weight elements such as carbon, hydrogen, oxygen, and nitrogen. Most polymeric materials have low electrical conductivities. Examples are polyethylene and *polyvinyl chloride* (PVC).

**Composite materials:** materials that are mixtures of two or more materials. Examples are fiberglass-reinforcing material in a polyester or epoxy matrix.

**Electronic materials:** materials used in electronics, especially microelectronics. Examples are silicon and gallium arsenide.

## 1.9 PROBLEMS

- 1.1 What are materials? List eight commonly encountered engineering materials.
- 1.2 Define materials science and materials engineering.
- 1.3 What are the main classes of engineering materials?
- 1.4 What are some of the important properties of each of these engineering materials?
- 1.5 Define a composite material. Give an example of a composite material.
- 1.6 List some materials usage changes that you have observed over a period of time in some manufactured products. What reasons can you give for the changes that have occurred?
- 1.7 What factors might cause materials usage predictions to be incorrect?

## 1.10 MATERIALS SELECTION AND DESIGN PROBLEMS

1. Consider the common household component in a lightbulb: (a) identify various critical components of this item, (b) determine the material selected for each critical component, and (c) design a process that would be used to assemble the lightbulb.
2. *Total hip arthroplasty* (THA) is the process of total replacement of a damaged hip with an artificial prosthesis. (a) Identify the replacement components used in THA. (b) Identify the material(s) used in the manufacture of each component and why they are used. (c) What are some of the factors that the materials engineer should consider in selecting these materials?
3. Transistors are considered to have caused a revolution in electronics and consequently in many other industries. (a) Identify the critical components of a junction transistor. (b) Identify the material used in the manufacture of each component.
4. (a) Name the important factors in selecting materials for the frame of a mountain bike. (b) Steel, aluminum, and titanium alloys have all been used as the primary

1.10 Materials Selection and Design Problems

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- metals in the structure of a bicycle; determine the major weaknesses and strengths of each. (c) The more modern bikes are made of advanced composites. Explain why and name a specific composite used in the structure of a bike.
5. (a) Name the important criteria for selecting materials to use in a protective sports helmet. (b) Identify materials that would satisfy these criteria. (c) Why would a solid metal helmet not be a good choice?
  6. (a) Determine the needed properties of the material(s) used as the heat shield in the structure of a space shuttle. (b) Identify materials that would satisfy these requirements. (c) Why would titanium alloys not be a good choice for this application?
  7. (a) What kind of material is OFHC copper? (b) What are the desirable properties of OFHC copper? (c) What are the applications of OFHC copper in the power industry?
  8. (a) To which class of materials does PTFE belong? (b) What are its desirable properties? (c) What are its applications in cookware manufacturing industries?
  9. (a) To which class of materials does *cubic boron nitride* (cBN) belong? (b) What are its desirable properties? (c) What are its applications in the metal machining industries?
  10. (a) What are aramids? (b) What are their desirable properties? (c) What are their applications in sports equipment industries?
  11. (a) In what class of materials does GaAs (gallium arsenide) belong? (b) What are its desirable properties? (c) What are its applications in electronic industries?
  12. Nickel-base superalloys are used in the structure of aircraft turbine engines. What are the major properties of this metal that make it suitable for this application?