Essentials of

Materials Science and Engineering

Second Edition

Donald R. Askeland Pradeep P. Fulay

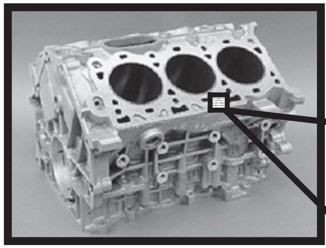
What is Materials Science and Engineering?

Performance or Properties to Cost Ratio

Synthesis and Processing

Composition

Structure



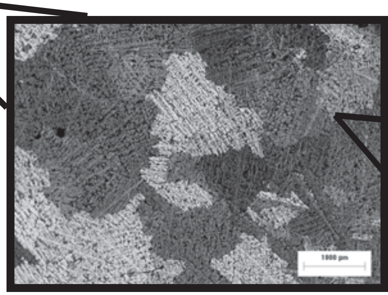
Macro-Scale Structure

Engine Block

≅ upto 1 meter

Performance Criteria

- **Power generated**
- **Efficiency**
- **Durability**
- **Cost**



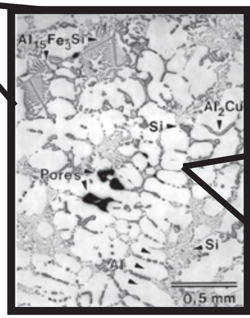
Microstructure

- Grains

≅ 1 – 10 millimeters

Properties affected

- High cycle fatigue
- Ductility



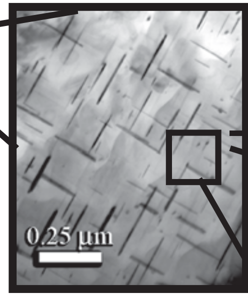
Microstructure

- Dendrites & Phases

≅ 50 – 500 micrometers

Properties affected

- Yield strength
- Ultimate tensile strength
- High cycle fatigue
- Low cycle fatigue
- Thermal Growth
- Ductility



Nano-structure

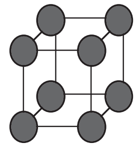
- Precipitates

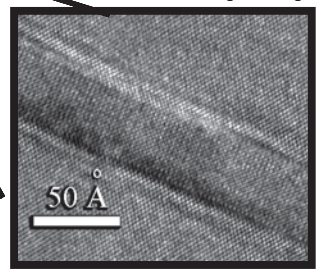
≅ 3-100 nanometers

Properties affected

- Yield strength
- Ultimate tensile strength
- Low cycle fatigue
- Ductility

Unit Cell





Atomic-scale structure

≅ 1-100 Angstroms

Properties affected

- Young's modulus
- Thermal Growth

A real-world example of important microstructural features at different length-scales, resulting from the sophisticated synthesis and processing used, and the properties they influence. The atomic, nano, micro, and macro-scale structures of cast aluminum alloys (for engine blocks) in relation to the properties affected and performance are shown. The materials science and engineering (MSE) tetrahedron that represents this approach is shown in the upper right corner.

(Illustrations Courtesy of John Allison and William Donlon, Ford Motor Company)

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Essentials of Materials Science and Engineering

Second Edition

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University of Missouri—Rolla, Emeritus

Pradeep P. Fulay
University of Pittsburgh

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Donald R. Askeland and Pradeep P. Fulay

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To Mary Sue and Tyler
—*Donald R. Askeland*

To Suyash, Aarohee, and Jyotsna
—*Pradeep P. Fulay*

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Preface

This book, *Essentials of Materials Science and Engineering Second Edition*, is a direct result of the success of the *Fifth Edition* of *The Science and Engineering of Materials*, published in 2006. We received positive feedback on both the contents and the integrated approach we used to develop materials science and engineering foundations by presenting the student with real-world applications and problems.

This positive feedback gave us the inspiration to develop *Essentials of Materials Science and Engineering*. The main objective of this book is to provide a *concise* overview of the principles of materials science and engineering for undergraduate students in varying engineering and science disciplines. This *Essentials* text contains the same integrated approach as the *Fifth Edition*, using real-world applications to present and then solve fundamental material science and engineering problems.

The contents of the *Essentials of Materials Science and Engineering* book have been carefully selected such that the reader can develop key ideas that are essential to a solid understanding of materials science and engineering. This book also contains several new examples of modern applications of advanced materials such as those used in information technology, energy technology, nanotechnology microelectromechanical systems (MEMS), and biomedical technology.

The concise approach used in this book will allow instructors to complete an introductory materials science and engineering course in one semester.

We feel that while reading and using this book, students will find materials science and engineering very interesting, and they will clearly see the relevance of what they are learning. We have presented many examples of modern applications of materials science and engineering that impact students' lives. Our feeling is that if students recognize that many of today's technological marvels depend on the availability of engineering materials they will be more motivated and remain interested in learning about how to apply the essentials of materials science and engineering.

Audience and Prerequisites

This book has been developed to cater to the needs of students from different engineering disciplines and backgrounds other than materials science and engineering (e.g., mechanical, industrial, manufacturing, chemical, civil, biomedical, and electrical engineering). At the same time, a conscious effort has been made so that the contents are very well suited for undergraduates majoring in materials science and engineering and closely related disciplines (e.g., metallurgy, ceramics, polymers, and engineering physics). In this sense, from a technical and educational perspective, the book has not been ''watered down'' in any way. The subjects presented in this text are a careful selection of topics based on our analysis of the needs and feedback from reviewers. Many of the topics related to electronic, magnetic, thermal, and optical properties have not been included in this book to keep the page length down. For instructors and students who wish to develop these omitted concepts, we suggest using the *Fifth Edition* of *The Science and Engineering of Materials*.

This text is intended for engineering students who have completed courses in general physics, chemistry, physics, and calculus. Completion of a general introduction to Engineering or Engineering Technology will be helpful, but not necessary. The text does not presume that the students have had any engineering courses related to statics, dynamics, or mechanics of materials.

Features

We have many unique features to this book.

Have You Ever Wondered? Questions Each chapter opens with a section entitled "*Have You Ever Wondered*?" These questions are designed to arouse the reader's interest, put things in perspective, and form the framework for what the reader will learn in that chapter.

Examples Many real-world Examples have been integrated to accompany the chapter discussions. These Examples specifically cover design considerations, such as operating temperature, presence of corrosive material, economic considerations, recyclability, and environmental constraints. The examples also apply to theoretical material and numeric calculations to further reinforce the presentation.

Glossary All of the Glossary terms that appear in the chapter are set in boldface type the first time they appear within the text. This provides an easy reference to the definitions provided in the end of each chapter Glossary.

Answers to Selected Problems The answers to the selected problems are provided at the end of the text to help the student work through the end-of-chapter problems.

Appendices and Endpapers Appendix A provides a listing of selected physical properties of metals and Appendix B presents the atomic and ionic radii of selected elements. The Endpapers include SI Conversion tables and Selected Physical Properties of elements.

Strategies for Teaching from the Book

Most of the material presented here can be covered in a typical one-semester course. By selecting the appropriate topics, however, the instructor can emphasize the desired materials (i.e., metals, alloys, ceramics, polymers, composites, etc.), provide an overview of materials, concentrate on behavior, or focus on physical properties. In addition, the text provides the student with a useful reference for subsequent courses in manufacturing, design, and materials selection. For students specializing in materials science and engineering, or closely related disciplines, sections related to synthesis and processing could be discussed in greater detail.

Supplements

Supplements for the instructor include:

- The Instructor's Solutions Manual that provides complete, worked-out solutions to selected text problems and additional text items.
- Power Point slides of all figures from the textbook available from the book website at http://academic.cengage.com/engineering.

Acknowledgments

It takes a team of many people and a lot of hard work to create a quality textbook. We are indebted to all of the people who provided the assistance, encouragement, and constructive criticism leading to the preparation of this book.

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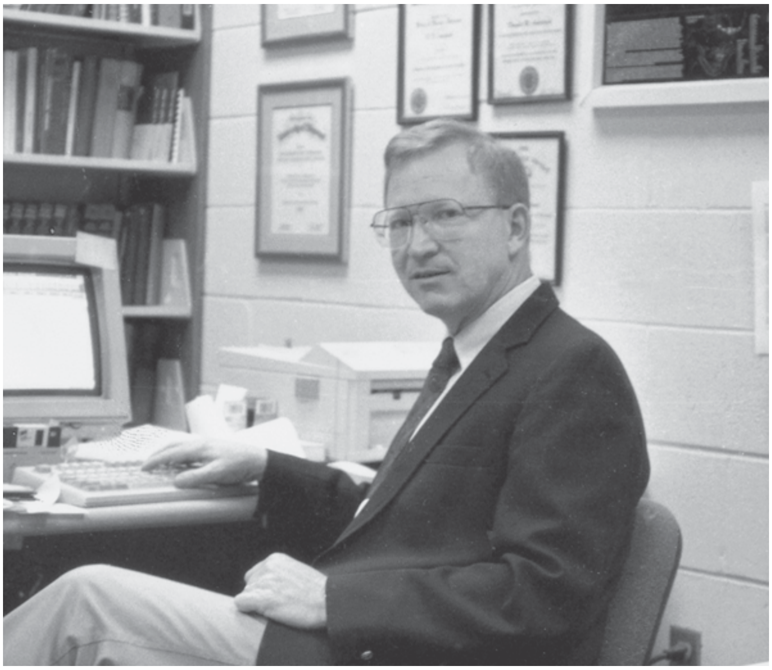

Donald R. Askeland is a Distinguished Teaching Professor Emeritus of Metallurgical Engineering at the University of Missouri–Rolla. He received his degrees from the Thayer School of Engineering at Dartmouth College and the University of Michigan prior to joining the faculty at the University of Missouri–Rolla in 1970. Dr. Askeland taught a number of courses in materials and manufacturing engineering to students in a variety of engineering and science curricula. He received a number of awards for excellence in teaching and advising at UMR. He served as a Key Professor for the Foundry Educational Foundation and received several awards for his service to that organization. His teaching and research were directed primarily to metals casting and joining, in particular lost foam casting, and resulted in over 50 publications and a number of awards for service and best papers from the American Foundry Society.

Dr. Pradeep Fulay has been a Professor of Materials Science and engineering in the Department of Mechanical Engineering and Materials Science for almost 19 years. Currently, Dr. Fulay serves as the Program Director (PD) for the Electronic, Photonic Devices Technology Program (EPDT) at the National Science Foundation (NSF). He joined the University of Pittsburgh in 1989, was promoted to Associate Professor in 1994, and then to full professor in 1999. Dr. Fulay received a Ph.D. in Materials Science and Engineering from the University of Arizona (1989) and a B. Tech (1983) and M. Tech (1984) in Metallurgical Engineering from the Indian Institute of Technology Bombay (Mumbai) India.

He has authored close to 60 publications and has two U.S. patents issued. He has received the Alcoa Foundation and Ford Foundation research awards.

He has been an outstanding teacher and educator and was listed on the Faculty Honor Roll at the University of Pittsburgh (2001) for outstanding services and assistance. From 1992–1999, he was the William Kepler Whiteford Faculty Fellow at the University of Pittsburgh. From August to December 2002, Dr. Fulay was a visiting scientist at the Ford Scientific Research Laboratory in Dearborn, MI.

Dr. Fulay's primary research areas are chemical synthesis and processing of ceramics, electronic ceramics and magnetic materials, development of smart materials and systems. He was the President of Ceramic Educational Council (2003–2004) and a Member of the Program Committee for the Electronics Division of the American ceramic society since 1996.

He has also served as an Associate Editor for the *Journal of the American Ceramic Society* (1994–2000). He has been the lead organizer for symposia on ceramics for sol-gel processing, wireless communications, and smart structures and sensors. In 2002, Dr. Fulay was elected as a Fellow of the American Ceramic Society. Dr. Fulay's research has been supported by National Science Foundation (NSF) and other organizations.

1

Introduction to Materials Science and Engineering

Have You Ever Wondered?

- *Why do jewellers add copper to gold?*
- *How sheet steel can be processed to produce a high-strength, lightweight, energy absorbing, malleable material used in the manufacture of car chassis?*
- *Can we make flexible and lightweight electronic circuits using plastics?*
- *What is a "smart material?"*
- *What is a superconductor?*

In this chapter, we will introduce you to the field of materials science and engineering (MSE) using different real-world examples. We will then provide an introduction to the classification of materials. Materials science underlies most technological advances. Understanding the basics of materials and their applications will not only make you a better engineer, but will help you during the design process. In order to be a good designer, you must learn what materials will be appropriate to use in different applications. The most important aspect of materials is that they are *enabling*; materials make things happen. For example, in the history of civilization, materials such as stone, iron, and bronze played a key role in mankind's development. In today's fast-paced world, the discovery of silicon single crystals and an understanding of their properties have enabled the information age.

In this chapter and throughout the book, we will provide compelling examples of real-world applications of engineered materials. The diversity of applications and the unique uses of materials illustrate why an engineer needs to thoroughly understand and know how to apply the principles of materials science and engineering. In each chapter, we begin with a section entitled *Have You Ever Wondered?* These questions are designed to pique your curiosity, put things in perspective, and form a framework for what you will learn in that chapter.

1-1 What is Materials Science and Engineering?

Materials science and engineering (MSE) is an interdisciplinary field concerned with inventing new materials and improving previously known materials by developing a deeper understanding of the microstructure-composition-synthesis-processing relationships. The term **composition** means the chemical make-up of a material. The term **structure** means a description of the arrangement of atoms, as seen at different levels of detail. Materials scientists and engineers not only deal with the development of materials, but also with the **synthesis** and **processing** of materials and manufacturing processes related to the production of components. The term "synthesis" refers to how materials are made from naturally occurring or man-made chemicals. The term "processing" means how materials are shaped into useful components. One of the most important functions of materials scientists and engineers is to establish the relationships between the properties of a material and its performance. In **materials science**, the emphasis is on the underlying relationships between the synthesis and processing, structure, and properties of materials. In **materials engineering**, the focus is on how to translate or transform materials into a useful device or structure.

One of the most fascinating aspects of materials science involves the investigation into the structure of a material. The structure of materials has a profound influence on many properties of materials, even if the overall composition does not change! For example, if you take a pure copper wire and bend it repeatedly, the wire not only becomes harder but also becomes increasingly brittle! Eventually, the pure copper wire becomes so hard and brittle that it will break rather easily. The electrical resistivity of wire will also increase as we bend it repeatedly. In this simple example, note that we did not change the material's composition (i.e., its chemical make up). The changes in the material's properties are often due to a change in its internal structure. If you examine the wire after bending using an optical microscope, it will look the same as before (other than the bends, of course). However, its structure has been changed at a very small or microscopic scale. The structure at this microscopic scale is known as **microstructure**. If we can understand what has changed at a micrometer level, we can begin to discover ways to control the material's properties.

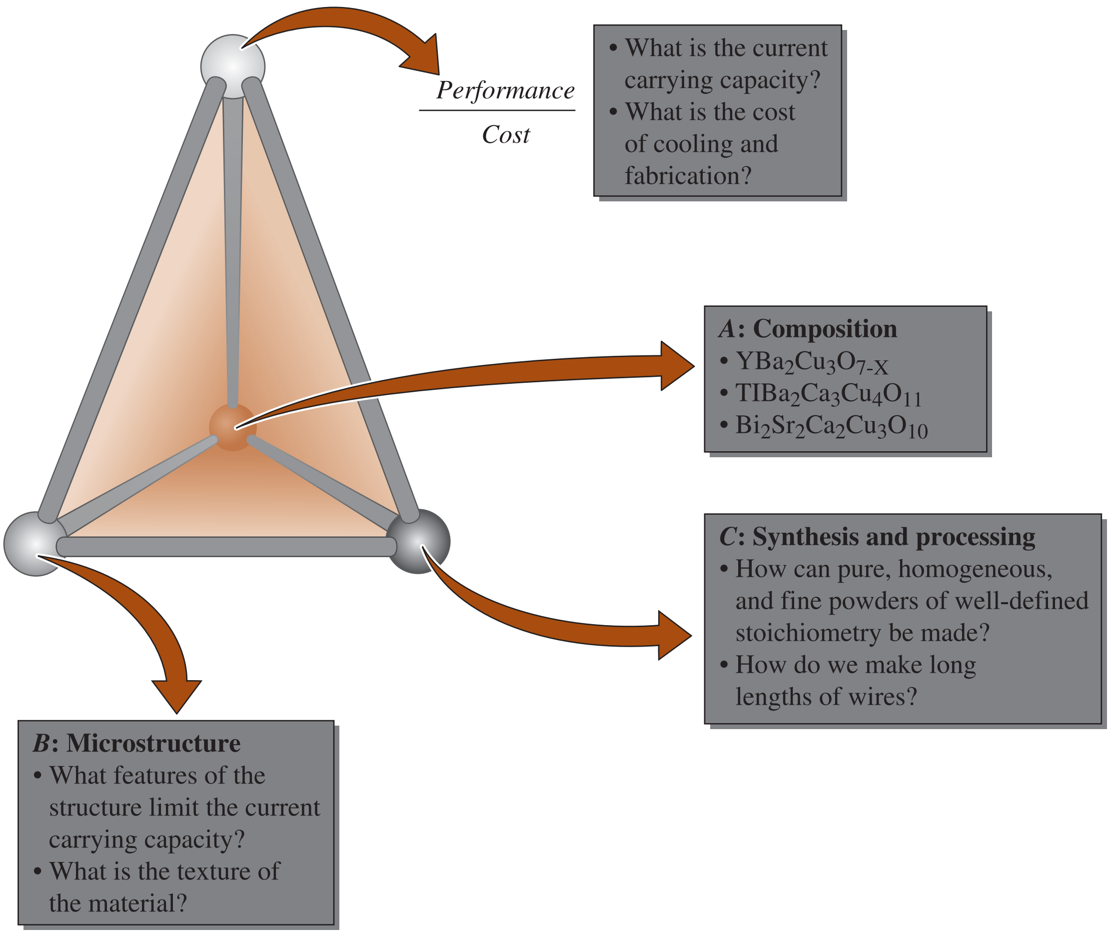

Figure 1-1 Application of the tetrahedron of materials science and engineering to ceramic superconductors. Note that the microstructure-synthesis and processing-composition are all interconnected and affect the performance-to-cost ratio.

Let's put the materials science and engineering tetrahedron in perspective by examining a sample product–ceramic superconductors invented in 1986 (Figure 1-1). You may be aware that ceramic materials usually do not conduct electricity. Scientists found, serendipitously, that certain ceramic compounds based on yttrium barium copper oxides (known as *YBCO*) can actually carry electrical current without any resistance under certain conditions. Based on what was known then about metallic superconductors and the electrical properties of ceramics, superconducting behavior in ceramics was not considered as a strong possibility. Thus, the first step in this case was the *discovery* of superconducting behavior in ceramic materials. These materials were discovered through some experimental research. A limitation of these materials is that they can superconduct only at low temperatures (<150 K).

The next step was to determine how to make these materials better. By "better" we mean: How can we retain superconducting behavior in these materials at higher temperatures, or how can we transport a large amount of current over a long distance? This involves materials processing and careful structure-property studies. Materials scientists wanted to know how the composition and microstructure affect the superconducting behavior. They also want to know if there are other compounds that exhibited superconductivity. Through experimentation, the scientists developed controlled *synthesis* of ultrafine powders or thin films that are used to create useful devices.

An example of approaching this from a *materials engineering* perspective will be to find a way to make long wires for power transmission. In applications, we ultimately want to know if we can make reliable and reproducible long lengths of superconducting wires that are superior to the current copper and aluminum wires. Can we produce such wires in a cost-effective way?

The next challenge was to make long lengths of ceramic superconductor wires. Ceramic superconductors are brittle, so making long lengths of wires was difficult. Thus, *materials processing* techniques had to be developed to create these wires. One successful way of creating these superconducting wires was to fill hollow silver tubes with powders of superconductor ceramic and then draw wires.

Although the discovery of ceramic superconductors did cause a lot of excitement, the path toward translating that discovery into useful products has been met by many challenges related to the synthesis and processing of these materials.

Sometimes, discoveries of new materials, phenomena, or devices are heralded as *revolutionary*. Today, as we look back, the 1948 discovery of the silicon-based transistor used in computer chips is considered revolutionary. On the other hand, materials that have evolved over a period of time can be just as important. These materials are considered as *evolutionary*. Many alloys based on iron, copper, and the like are examples of evolutionary materials. Of course, it is important to recognize that what are considered as evolutionary materials now, did create revolutionary advances many years back. It is not uncommon for materials or phenomena to be discovered first and then for many years to go by before commercial products or processes appear in the marketplace. The transition from the development of novel materials or processes to useful commercial or industrial applications can be slow and difficult.

Let's examine another example using the materials science and engineering tetrahedron. Let's look at "sheet steels" used in the manufacture of car chassis. Steels, as you may know, have been used in manufacturing for more than a hundred years. Earlier steels probably existed in a crude form during the Iron Age, thousands of years ago. In the manufacture of automobile chassis, a material is needed that possesses extremely high strength but is easily formed into aerodynamic contours. Another consideration is fuel-efficiency, so the sheet steel must also be thin and lightweight. The sheet steels should also be able to absorb significant amounts of energy in the event of a crash, thereby increasing vehicle safety. These are somewhat contradictory requirements.

Thus, in this case, materials scientists are concerned with the sheet steel's

- composition;
- strength;
- density;
- energy absorption properties; and
- ductility (formability).

Materials scientists would examine steel at a microscopic level to determine if its properties can be altered to meet all of these requirements. They also would have to process this material into a car chassis in a cost-effective way. Will the shaping process itself affect the mechanical properties of the steel? What kind of coatings can be developed to make the steel corrosion-resistant? We also need to know if these steels could be welded easily. From this discussion, you can see that many issues need to be considered during the design and materials selection for any product.

1-2 Classification of Materials

There are different ways of classifying materials. One way is to describe five groups (Table 1-1):

1. **metals** and **alloys**;
2. ceramics, **glasses**, and **glass-ceramics**;
3. polymers (plastics);
4. semiconductors; and
5. composite materials.

Materials in each of these groups possess different structures and properties. The differences in strength, which are compared in Figure 1-2, illustrate the wide range of properties engineers can select from. Since metallic materials are extensively used for

TABLE 1-1 ■ ***Representative examples, applications, and properties for each category of materials***

	Examples of Applications	Properties
Metals and Alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration-damping
Alloy steels	Wrenches, automobile chassis	Significantly strengthened by heat treatment
Ceramics and Glasses		
SiO_2-Na_2O-CaO	Window glass or soda-lime glass	Optically transparent, thermally insulating
Al_2O_3, MgO, SiO_2	Refractories (i.e., heat-resistant lining of furnaces) for containing molten metal	Thermally insulating, withstand high temperatures, relatively inert to molten metal
Barium titanate	Capacitors for microelectronics	High ability to store charge
Silica	Optical fibers for information technology	Refractive index, low optical losses
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Epoxy	Encapsulation of integrated circuits	Electrically insulating and moisture-resistant
Phenolics	Adhesives for joining plies in plywood	Strong, moisture resistant
Semiconductors		
Silicon (Si)	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, lasers, laser diodes, etc.
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel, with the corrosion resistance of titanium

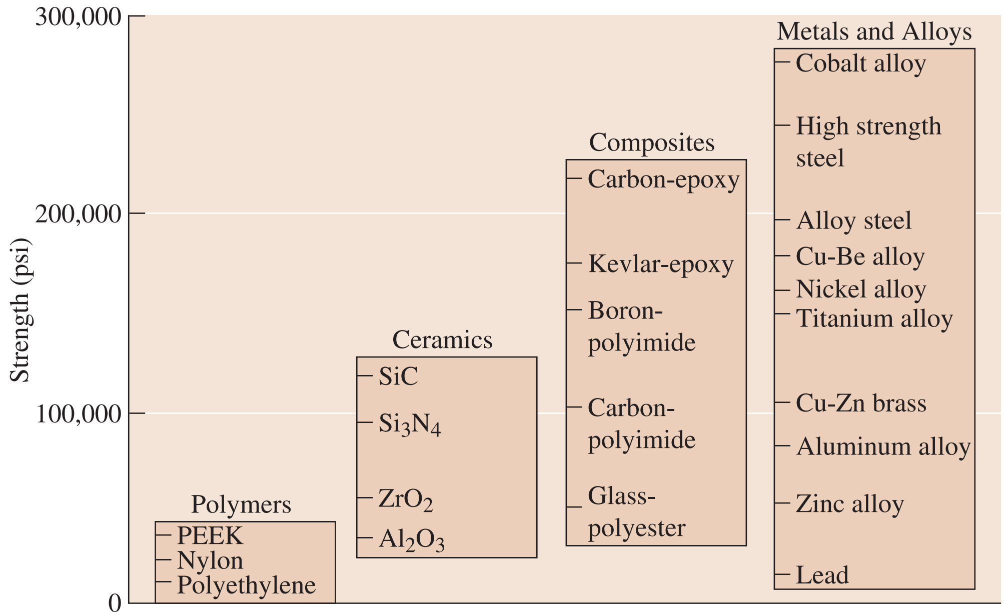

Figure 1-2 Representative strengths of various categories of materials. The strength of ceramics is under a compressive stress.

load-bearing applications, their mechanical properties are of great practical interest. We briefly introduce these here. The term "stress" refers to load or force per unit area. "Strain" refers to elongation or change in dimension divided by original dimension. Application of "stress" causes "strain." If the strain goes away after the load or applied stress is removed, the strain is said to be "elastic." If the strain remains after the stress is removed, the strain is said to be "plastic." When the deformation is elastic, stress and strain are linearly related, the slope of the stress-strain diagram is known as the elastic or Young's modulus. A level of stress needed to initiate plastic deformation is known as "yield strength." The maximum percent deformation we can get is a measure of the ductility of a metallic material. These concepts are discussed further in Chapter 6.

Metals and Alloys These include steels, aluminum, magnesium, zinc, cast iron, titanium, copper, and nickel. In general, metals have good electrical and thermal conductivity. Metals and alloys have relatively high strength, high stiffness, ductility or formability, and shock resistance. They are particularly useful for structural or load-bearing applications. Although pure metals are occasionally used, combinations of metals called alloys provide improvement in a particular desirable property or permit better combinations of properties. The cross section of a jet engine shown in Figure 1-3 illustrates the use of metallic materials for a number of critical applications.

Ceramics Ceramics can be defined as inorganic crystalline materials. Ceramics are probably the most "natural" materials. Beach sand and rocks are examples of naturally occurring ceramics. Advanced ceramics are materials made by refining naturally occurring ceramics and other special processes. Advanced ceramics are used in substrates that house computer chips, sensors and actuators, capacitors, spark plugs, inductors, and electrical insulation. Some ceramics are used as thermal-barrier coatings to protect metallic substrates in turbine engines. Ceramics are also used in such consumer products as paints, plastics, tires, and for industrial applications such as the tiles for the space

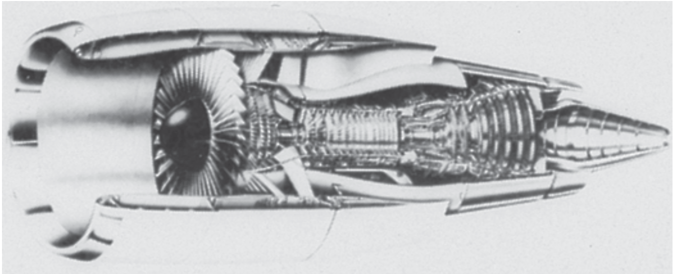

Figure 1-3 A section through a jet engine. The forward compression section operates at low to medium temperatures, and titanium parts are often used. The rear combustion section operates at high temperatures and nickel-based superalloys are required. The outside shell experiences low temperatures, and aluminum and composites are satisfactory. (*Courtesy of GE Aircraft Engines.*)

shuttle, a catalyst support, and oxygen sensors used in cars. Traditional ceramics are used to make bricks, tableware, sanitaryware, refractories (heat-resistant material), and abrasives. In general, due to the presence of porosity (small holes), ceramics tend to be brittle. Ceramics must also be heated to very high temperatures before they can melt. Ceramics are strong and hard, but also very brittle. We normally prepare fine powders of ceramics and convert these into different shapes. New processing techniques make ceramics sufficiently resistant to fracture that they can be used in load-bearing applications, such as impellers in turbine engines (Figure 1-4). Ceramics have exceptional

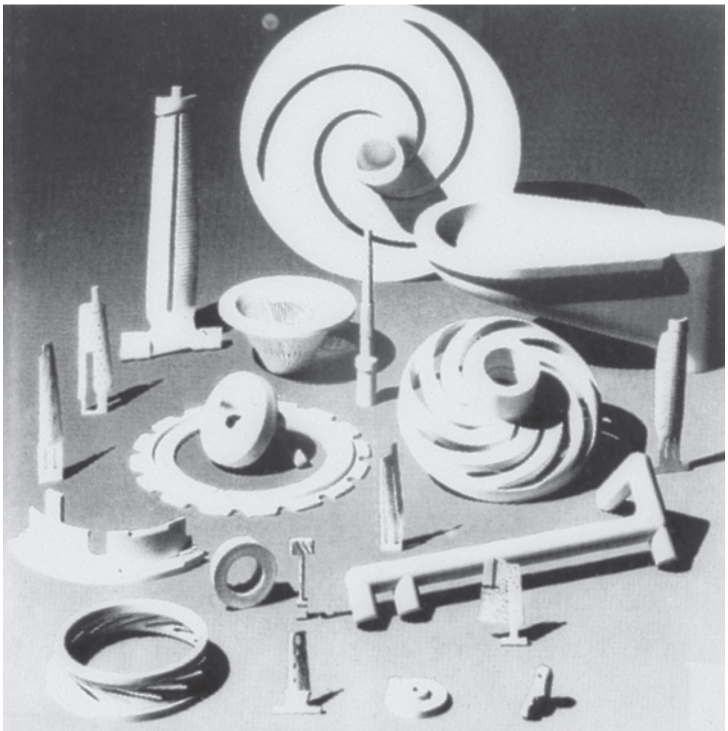

Figure 1-4 A variety of complex ceramic components, including impellers and blades, which allow turbine engines to operate more efficiently at higher temperatures. (*Courtesy of Certech, Inc.*)

strength under compression (Figure 1-2). Can you believe that the weight of an entire fire truck can be supported using four ceramic coffee cups?

Glasses and Glass-Ceramics Glass is an amorphous material, often, but not always, derived from molten silica. The term "amorphous" refers to materials that do not have a regular, periodic arrangement of atoms. Amorphous materials will be discussed in detail in Chapter 3. The fiber optics industry is founded on optical fibers made by using high-purity silica glass. Glasses are also used in houses, cars, computer and television screens, and hundreds of other applications. Glasses can be thermally treated (tempered) to make them stronger. Forming glasses and nucleating (creating) small crystals within them by a special thermal process creates materials that are known as glass-ceramics. Zerodur™ is an example of a glass-ceramic material that is used to make the mirror substrates for large telescopes (e.g., the Chandra and Hubble telescopes). Glasses and glass-ceramics are usually processed by melting and casting.

Polymers Polymers are typically organic materials produced using a process known as **polymerization**. Polymeric materials include rubber (elastomers) and many types of adhesives. Many polymers have very good electrical resistivity. They can also provide good thermal insulation. Although they have lower strength, polymers have a very good **strength-to-weight ratio**. They are typically not suitable for use at high temperatures. Many polymers have very good resistance to corrosive chemicals. Polymers have thousands of applications ranging from bulletproof vests, compact disks (CDs), ropes, and liquid crystal displays (LCDs) to clothes and coffee cups. **Thermoplastic** polymers, in which the long molecular chains are not rigidly connected, have good ductility and formability; **thermosetting** polymers are stronger but more brittle because the molecular chains are tightly linked (Figure 1-5). Polymers are used in many applications, including electronic devices. Thermoplastics are made by shaping their molten form. Thermosets are typically cast into molds. The term **plastics** is used to describe polymeric materials containing additives that enhance their properties.

Semiconductors Silicon, germanium, and gallium arsenide-based semiconductors are part of a broader class of materials known as electronic materials. The electrical conductivity of semiconducting materials is between that of ceramic insulators and metallic conductors. **Semiconductors** have enabled the information age. In semiconductors, the

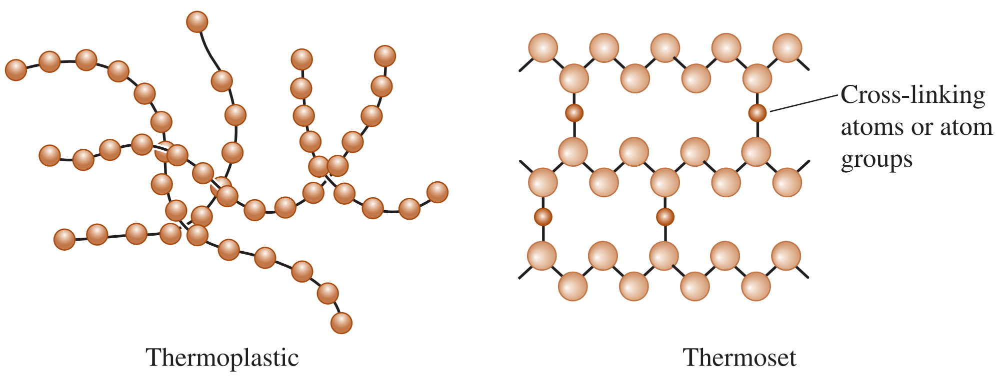

Figure 1-5 Polymerization occurs when small molecules, represented by the circles, combine to produce larger molecules, or polymers. The polymer molecules can have a structure that consists of many chains that are entangled but not connected (thermoplastics) or can form three-dimensional networks in which chains are cross-linked (thermosets).

level of conductivity is controlled to enable their use in electronic devices such as transistors, diodes, etc., that are used to build integrated circuits. In many applications, we need large single crystals of semiconductors. These are grown from molten materials. Often, thin films of semiconducting materials are also made using specialized processes.

Composite Materials The main idea in developing **composites** is to blend the properties of different materials. The composites are formed from two or more materials, producing properties not found in any single material. Concrete, plywood, and fiberglass are examples of composite materials. Fiberglass is made by dispersing glass fibers in a polymer matrix. The glass fibers make the polymer matrix stiffer, without significantly increasing its density. With composites we can produce lightweight, strong, ductile, high temperature-resistant materials or we can produce hard, yet shock-resistant, cutting tools that would otherwise shatter. Advanced aircraft and aerospace vehicles rely heavily on composites such as carbon-fiber-reinforced polymers. Sports equipment such as bicycles, golf clubs, tennis rackets, and the like also make use of different kinds of composite materials that are light and stiff.

1-3 Functional Classification of Materials

We can classify materials based on whether the most important function they perform is mechanical (structural), biological, electrical, magnetic, or optical. This classification of materials is shown in Figure 1-6. Some examples of each category are shown. These categories can be broken down further into subcategories.

Aerospace Light materials such as wood and an aluminum alloy (that accidentally strengthened the alloy used for making the engine even more by picking up copper from the mold used for casting) were used in the Wright brothers' historic flight. Aluminum alloys, plastics, silica for space shuttle tiles, carbon-carbon composites, and many other materials belong to this category.

Biomedical Our bones and teeth are made, in part, from a naturally formed ceramic known as hydroxyapatite. A number of artificial organs, bone replacement parts, cardiovascular stents, orthodontic braces, and other components are made using different plastics, titanium alloys, and nonmagnetic stainless steels. Ultrasonic imaging systems make use of ceramics known as *PZT* (lead zirconium titanate). Magnets used for magnetic resonance imaging make use of metallic niobium tin-based superconductors.

Electronic Materials As mentioned before, semiconductors, such as those made from silicon, are used to make integrated circuits for computer chips. Barium titanate ($BaTiO_3$), tantalum oxide (Ta_2O_5), and many other dielectric materials are used to make ceramic capacitors and other devices. Superconductors are used in making powerful magnets. Copper, aluminum, and other metals are used as conductors in power transmission and in microelectronics.

Energy Technology and Environmental Technology The nuclear industry uses materials such as uranium dioxide and plutonium as fuel. Numerous other materials, such as glasses and stainless steels, are used in handling nuclear materials and managing radioactive waste. New technologies related to batteries and fuel cells make use of many ceramic materials such as zirconia (ZrO_2) and polymers. The battery technology has

Figure 1-6 Functional classification of materials. Notice that metals, plastics, and ceramics occur in different categories. A limited number of examples in each category are provided.

gained significant importance owing to the need for many electronic devices that require longer lasting and portable power. Fuel cells are also being used in some cars. The oil and petroleum industry widely uses zeolites, alumina, and other materials as catalyst substrates. They use Pt, Pt/Rh and many other metals as catalysts. Many membrane technologies for purification of liquids and gases make use of ceramics and plastics. Solar power is generated using materials such as crystalline Si and amorphous silicon (a:Si:H).

Magnetic Materials Computer hard disks and audio and video cassettes make use of many ceramic, metallic, and polymeric materials. For example, particles of a special form of iron oxide, known as gamma iron oxide (γ-Fe_2O_3) are deposited on a polymer substrate to make audio cassettes. High-purity iron particles are used for making videotapes. Computer hard disks are made using alloys based on cobalt-platinum-tantalum-chromium (Co-Pt-Ta-Cr) alloys. Many magnetic ferrites are used to make inductors and components for wireless communications. Steels based on iron and silicon are used to make transformer cores.

Photonic or Optical Materials Silica is used widely for making optical fibers. Almost ten million kilometers of optical fiber have been installed around the world. Optical materials are used for making semiconductor detectors and lasers used in fiber optic communications systems and other applications. Similarly, alumina (Al_2O_3) and yttrium aluminum garnets (*YAG*) are used for making lasers. Amorphous silicon is used to make solar cells and photovoltaic modules. Polymers are used to make liquid crystal displays (*LCDs*).

Smart Materials A **smart material** can sense and respond to an external stimulus such as a change in temperature, the application of a stress, or a change in humidity or chemical environment. Usually a smart-material-based system consists of sensors and actuators that read changes and initiate an action. An example of a passively smart material is lead zirconium titanate (*PZT*) and shape-memory alloys. When properly processed, *PZT* can be subjected to a stress and a voltage is generated. This effect is used to make such devices as spark generators for gas grills and sensors that can detect underwater objects such as fish and submarines. Other examples of smart materials include magnetorheological or MR fluids. These are magnetic paints that respond to magnetic fields and are being used in suspension systems of automobiles. Other examples of smart materials and systems are photochromic glasses and automatic dimming mirrors based on electrochromic materials.

Structural Materials These materials are designed for carrying some type of stress. Steels, concrete, and composites are used to make buildings and bridges. Steels, glasses, plastics, and composites are also used widely to make automotives. Often in these applications, combinations of strength, stiffness, and toughness are needed under different conditions of temperature and loading.

1-4 Classification of Materials Based on Structure

As mentioned before, the term ‘‘structure’’ means the arrangement of a material’s atoms; the structure at a microscopic scale is known as ‘‘microstructure.’’ We can view these arrangements at different scales, ranging from a few angstrom units to a millimeter. We will learn in Chapter 3 that some materials may be **crystalline** (where the material’s atoms are arranged in a periodic fashion) or they may be amorphous (where the material’s atoms do not have a long-range order). Some crystalline materials may be in the form of one crystal and are known as **single crystals**. Others consist of many crystals or **grains** and are known as **polycrystalline**. The characteristics of crystals or grains (size, shape, etc.) and that of the regions between them, known as the **grain boundaries**, also affect the properties of materials. We will further discuss these concepts in later chapters. A micrograph of a stainless steel sample (showing grains and grain boundaries) is shown in Figure 1-7. For this sample, each grain reflects the light differently and this produces a contrast between the grains.

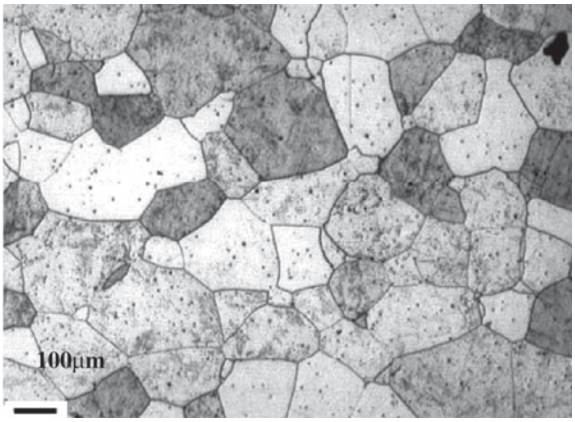

Figure 1-7
Micrograph of stainless steel showing grains and grain boundaries. (*Courtesy Dr. Hua and Dr. DeArdo—University of Pittsburgh.*)

1-5 Environmental and Other Effects

The structure-property relationships in materials fabricated into components are often influenced by the surroundings to which the material is subjected during use. This can include exposure to high or low temperatures, cyclical stresses, sudden impact, corrosion or oxidation. These effects must be accounted for in design to ensure that components do not fail unexpectedly.

Temperature Changes in temperature dramatically alter the properties of materials (Figure 1-8). Metals and alloys that have been strengthened by certain heat treatments or forming techniques will lose their strength when heated. A tragic reminder of this is the collapse of the steel beams used in the World Trade Center towers on September 11, 2001.

High temperatures change the structure of ceramics and cause polymers to melt or char. Very low temperatures, at the other extreme, may cause a metal or polymer to fail in a brittle manner, even though the applied loads are low. This low temperature em-

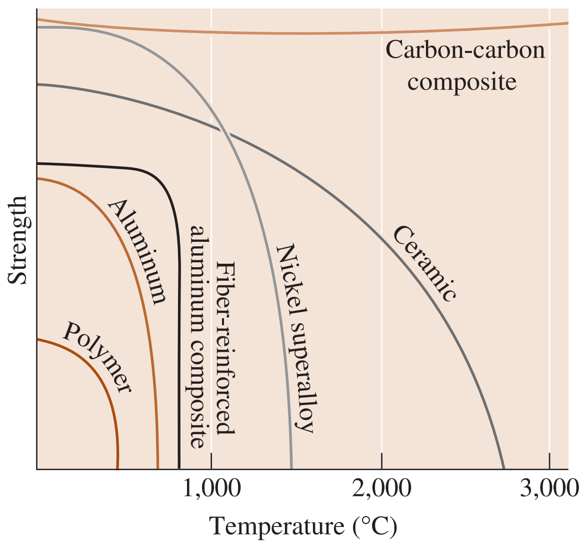

Figure 1-8
Increasing temperature normally reduces the strength of a material. Polymers are suitable only at low temperatures. Some composites, such as carbon-carbon composites, special alloys, and ceramics, have excellent properties at high temperatures.

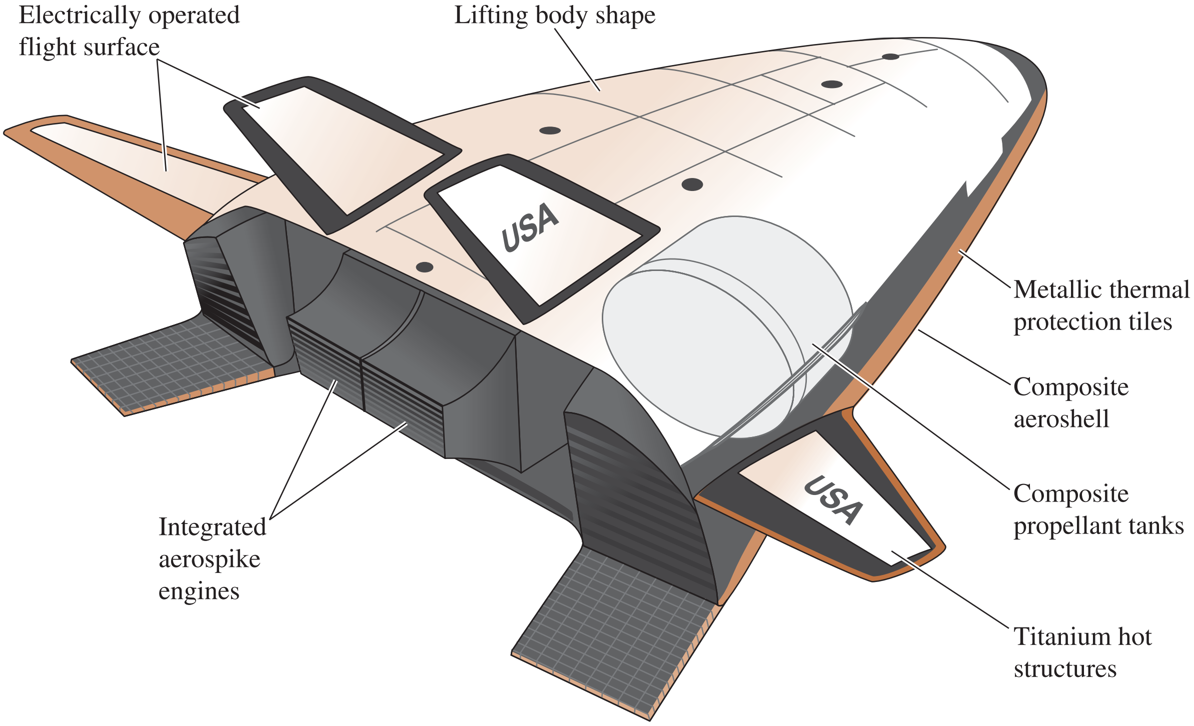

Figure 1-9 Schematic of a *X-33* plane prototype. Notice the use of different materials for different parts. This type of vehicle will test several components for the *Venturestar* (*From ''A Simpler Ride into Space,'' by T.K. Mattingly, October, 1997,* Scientific American, *p. 125. Copyright © 1997 Slim Films.*)

brittlement was a factor that caused the *Titanic* to fracture and sink. Similarly, the 1986 *Challenger* accident, in part, was due to embrittlement of rubber O-rings. The reasons why some polymers and metallic materials become brittle are different. We will discuss these concepts in later chapters.

The design of materials with improved resistance to temperature extremes is essential in many technologies related to aerospace. As faster speeds are attained, more heating of the vehicle skin occurs because of friction with the air. At the same time, engines operate more efficiently at higher temperatures. So, in order to achieve higher speed and better fuel economy, new materials have gradually increased allowable skin and engine temperatures. But materials engineers are continually faced with new challenges. The *X-33* and *Venturestar* are examples of advanced reusable vehicles intended to carry passengers into space using a single stage of rocket engines. Figure 1-9 shows a schematic of the *X-33* prototype. The development of even more exotic materials and processing techniques is necessary in order to tolerate the high temperatures that will be encountered.

Corrosion Most of the time, failure of materials occurs as a result of corrosion and some form of tensile overload. Most metals and polymers react with oxygen or other gases, particularly at elevated temperatures. Metals and ceramics may disintegrate and polymers and nonoxide ceramics may oxidize. Materials are also attacked by corrosive liquids, leading to premature failure. The engineer faces the challenge of selecting materials or coatings that prevent these reactions and permit operation in extreme environments. In space applications, we may have to consider the effects of the presence of radiation, the presence of atomic oxygen, and the impact from debris.

Fatigue In many applications, components must be designed such that the load on the material may not be enough to cause permanent deformation. However, when we do load and unload the material thousands of times, small cracks may begin to develop and materials fail as these cracks grow. This is known as **fatigue failure**. In designing load-bearing components, the possibility of fatigue must be accounted for.

Strain Rate You may be aware of the fact that Silly Putty®, a silicone- (not silicon-) based plastic, can be stretched significantly if we pull it slowly (small rate of strain). If you pull it fast (higher rate of strain) it snaps. A similar behavior can occur with many metallic materials. Thus, in many applications, the level and rate of strain have to be considered.

In many cases, the effects of temperature, fatigue, stress, and corrosion may be interrelated, and other outside effects could affect the material's performance.

1-6 Materials Design and Selection

When a material is designed for a given application, a number of factors must be considered. The material must possess the desired physical and mechanical properties. It must be capable of being processed or manufactured into the desired shape, and must provide an economical solution to the design problem. Satisfying these requirements in a manner that protects the environment—perhaps by encouraging recycling of the materials—is also essential. In meeting these design requirements, the engineer may have to make a number of tradeoffs in order to produce a serviceable, yet marketable, product.

As an example, material cost is normally calculated on a cost-per-pound basis. We must consider the **density** of the material, or its weight-per-unit volume, in our design and selection (Table 1-2). Aluminum may cost more per pound than steel, but it is only one-third the weight of steel. Although parts made from aluminum may have to be thicker, the aluminum part may be less expensive than the one made from steel because of the weight difference.

TABLE 1-2 ■ ***Strength-to-weight ratios of various materials***

Material	Strength (lb/in.^{2})	Density (lb/in.^{3})	Strength-to-weight ratio (in.)
Polyethylene	1,000	0.030	0.03×10^6
Pure aluminum	6,500	0.098	0.07×10^6
Al_2O_3	30,000	0.114	0.26×10^6
Epoxy	15,000	0.050	0.30×10^6
Heat-treated alloy steel	240,000	0.280	0.86×10^6
Heat-treated aluminum alloy	86,000	0.098	0.88×10^6
Carbon-carbon composite	60,000	0.065	0.92×10^6
Heat-treated titanium alloy	170,000	0.160	1.06×10^6
Kevlar-epoxy composite	65,000	0.050	1.30×10^6
Carbon-epoxy composite	80,000	0.050	1.60×10^6

In some instances, particularly in aerospace applications, the weight issue is critical, since additional vehicle weight increases fuel consumption and reduces range. By using materials that are lightweight but very strong, aerospace or automobile vehicles can be designed to improve fuel efficiency. Many advanced aerospace vehicles use composite materials instead of aluminum alloys. These composites, such as carbon-epoxy, are more expensive than the traditional aluminum alloys; however, the fuel savings yielded by the higher strength-to-weight ratio of the composite (Table 1-2) may offset the higher initial cost of the aircraft. The body of one of the latest Boeing aircrafts known as the Dreamliner is made almost entirely from carbon-carbon composite materials. There are literally thousands of applications in which similar considerations apply. Usually the selection of materials involves trade-offs between many properties.

By this point of our discussion, we hope that you can appreciate that the properties of materials depend not only on composition, but also on how the materials are made (synthesis and processing) and, most importantly, their internal structure. This is why it is not a good idea for an engineer to simply refer to a handbook and select a material for a given application. The handbooks may be a good starting point. A good engineer will consider: the effects of how the material is made, what exactly is the composition of the candidate material for the application being considered, any processing that may have to be done for shaping the material or fabricating a component, the structure of the material after processing into a component or device, the environment in which the material will be used, and the cost-to-performance ratio. The knowledge of principles of materials science and engineering will empower you with the fundamental concepts. These will allow you to make technically sound decisions in designing with engineered materials.

EXAMPLE 1-1 *Materials for a Bicycle Frame*

Bicycle frames are made using steel, aluminum alloys, titanium alloys containing aluminum and vanadium, and carbon-fiber composites (Figure 1-10). (a) If a steel-frame bicycle weighs 30 pounds, what will be the weight of the frame assuming we use aluminum, titanium, and a carbon-fiber composite to make the frame in such a way that the volume of frame (the diameter of the tubes) is constant? (b) What other considerations can come into play in designing bicycle frames?

Figure 1-10 Bicycle frames need to be lightweight, stiff, and corrosion resistant (for Example 1-1). (*Courtesy of Chris harve/StockXpert.*)

Note: The densities of steel, aluminum alloy, titanium alloy, and carbon-fiber composite can be assumed to be 7.8, 2.7, 4.5, and 1.85 g/cm^3.

SOLUTION

(a) The weight of the bicycle frame made from steel is stated to be 30 pounds. The volume of this frame will be

$$V_{\text{frame}} = (30 \times 454 \text{ g/lb})/(7.8) = 1746 \text{ cm}^3$$

For aluminum frame the weight will be

$$W_{\text{al}} = (1746 \text{ cm}^3) \times (2.7 \text{ g/cm}^3) \times (1 \text{ lb}/454) \text{ grams} = 10.38 \text{ lbs}$$

Another and simpler way to arrive at this answer is to take the ratio of densities, since the volume is assumed constant.

The weight of the aluminum alloy frame

$$\begin{aligned} W_{\text{alloy}} &= (\text{density of aluminum alloy}/\text{density of steel}) \\ &\quad \times (\text{wt. of the steel frame}) \\ &= (2.7/7.8) \times 30 \text{ lb} = 10.38 \text{ lb} \end{aligned}$$

Thus, the aluminum frame weighs roughly one-third of the steel frame.

Similarly, the weight of titanium frame will be

$$\begin{aligned} W_{\text{Ti}} &= (\text{density of titanium alloy}/\text{density of steel}) \\ &\quad \times (\text{wt. of the steel frame}) \\ &= (4.5/7.8) \times 30 \text{ lb} = 17.3 \text{ lb} \end{aligned}$$

Finally, the weight of the frame made using carbon-fiber composite will be

$$\begin{aligned} W_{\text{cf}} &= (\text{density of carbon fiber composite}/\text{density of steel}) \\ &\quad \times (\text{wt. of the steel frame}) \\ &= (1.85/7.8) \times 30 \text{ lb} = 7.1 \text{ lb} \end{aligned}$$

As can be seen, substantial reduction in weight is possible using materials other than steel.

(b) One of the other factors that comes into play is the stiffness of the structure. This is related to the elastic modulus of the material (Chapter 2). For example, for the same tube dimensions, an aluminum tube will be not as stiff as steel. This will make the aluminum frame bicycle ride "soft." This effect can be compensated for by making the aluminum tubes larger in diameter and the walls of the tubes thicker. Some other factors to consider are the toughness of each of the materials. For example, even though a carbon-fiber frame is very light, it is relatively brittle. Additional considerations would be the ability to weld or join the frame to other parts of the bicycle, corrosion resistance, and of course, cost.

EXAMPLE 1-2 Ceramic-Carbon-Fiber Brakes for Cars

Car breaks are typically made using cast iron and weigh about 20 pounds. What other materials can be used to make brakes that would last long and weigh less?

SOLUTION

The brakes could be made using other lower density materials, such as aluminum or titanium. Cost and wear resistance are clearly important. Titanium alloys will be very expensive, and both titanium and aluminum will wear out more easily.

We could make the brakes out of ceramics, such as alumina (Al_2O_3) or silicon carbide (SiC), since both have densities lower than cast iron. However, ceramics are too brittle, and even though they have very good resistance, they will fracture easily.

We can use a material that is a composite of carbon fibers and ceramics, such as SiC. This composite material will provide the lightweight and wear-resistance necessary, so that the brakes do not have to be replaced often. Some companies are already producing such ceramic-carbon-fiber brakes.

SUMMARY

- The properties of engineered materials depend upon their composition, structure, synthesis, and processing. An important performance index for materials or devices is their cost-to-performance ratio.
- The structure at a microscopic level is known as the microstructure (length scale 10 nm to 1000 nm).
- Many properties of materials depend strongly on the structure, even if the composition of the material remains the same. This is why the structure-property or microstructure-property relationships in materials are extremely important.
- Materials are often classified as metals and alloys, ceramics, glasses, and glass ceramics, composites, polymers, and semiconductors.
- Metals and alloys have good strength, good ductility, and good formability. Pure metals have good electrical and thermal conductivity. Metals and alloys play an indispensable role in many applications such as automotives, buildings, bridges, aerospace, and the like.
- Ceramics are inorganic, crystalline materials. They are strong, serve as good electrical and thermal insulators, are often resistant to damage by high temperatures and corrosive environments, but are mechanically brittle. Modern ceramics form the underpinnings of many of the microelectronic and photonic technologies.
- Polymers have relatively low strength; however, the strength-to-weight ratio is very favorable. Polymers are not suitable for use at high temperatures. They have very good corrosion resistance, and—like ceramics—provide good electrical and thermal insulation. Polymers may be either ductile or brittle, depending on structure, temperature, and the strain rate.
- Materials can also be classified as crystalline or amorphous. Crystalline materials may be single crystal or polycrystalline.

- Selection of a material having the needed properties and the potential to be manufactured economically and safely into a useful product is a complicated process requiring the knowledge of the structure-property-processing-composition relationships.

GLOSSARY

Alloy A metallic material that is obtained by chemical combinations of different elements (e.g., steel is made from iron and carbon). Typically, alloys have better mechanical properties than pure metals.

Ceramics Crystalline inorganic materials characterized by good strength in compression, and high melting temperatures. Many ceramics are very good electrical insulators and have good thermal insulation behavior.

Composition The chemical make-up of a material.

Composites A group of materials formed from metals, ceramics, or polymers in such a manner that unusual combinations of properties are obtained (e.g., fiberglass).

Crystal structure The arrangement of the atoms in a crystalline material.

Crystalline material A material comprised of one or many crystals. In each crystal atoms or ions show a long-range periodic arrangement.

Density Mass per unit volume of a material, usually expressed in units of g/cm^3 or $lb/in.^3$

Fatigue failure Failure of a material due to repeated loading and unloading.

Glass An amorphous material derived from the molten state, typically, but not always, based on silica.

Glass-ceramics A special class of crystalline materials obtained by forming a glass and then heat treating it to form small crystals.

Grains Crystals in a polycrystalline material.

Grain boundaries Regions between grains of a polycrystalline material.

Materials engineering An engineering oriented field that focuses on how to translate or transform materials into a useful device or structure.

Materials science and engineering (MSE) An interdisciplinary field concerned with inventing new materials and improving previously known materials by developing a deeper understanding of the microstructure-composition-synthesis-processing relationships between different materials.

Materials science A field of science that emphasizes studies of relationships between the internal or microstructure, synthesis and processing and the properties of materials.

Materials science and engineering tetrahedron A tetrahedron diagram showing how the performance-to-cost ratio of materials depends upon the composition, microstructure, synthesis, and processing.

Mechanical properties Properties of a material, such as strength, that describe how well a material withstands applied forces, including tensile or compressive forces, impact forces, cyclical or fatigue forces, or forces at high temperatures.

Metal An element that has metallic bonding and generally good ductility, strength, and electrical conductivity.

Microstructure The structure of a material at a length scale of 10 nm to 1000 nm (1 μm).

Physical properties Describe characteristics such as color, elasticity, electrical or thermal conductivity, magnetism, and optical behavior that generally are not significantly influenced by forces acting on a material.

Polycrystalline material A material comprised of many crystals (as opposed to a single-crystal material that has only one crystal). The crystals are also known as grains.

Polymerization The process by which organic molecules are joined into giant molecules, or polymers.

Polymers A group of materials normally obtained by joining organic molecules into giant molecular chains or networks. Polymers are characterized by low strengths, low melting temperatures, and poor electrical conductivity.

Plastics These are polymeric materials consisting of other additives that enhance their properties.

Processing Different ways for shaping materials into useful components or changing their properties.

Semiconductors A group of materials having electrical conductivity between metals and typical ceramics (e.g., Si, GaAs).

Single crystal A crystalline material that is made of only one crystal (there are no grain boundaries).

Smart material A material that can sense and respond to an external stimulus such as change in temperature, application of a stress, or change in humidity or chemical environment.

Strength-to-weight ratio The strength of a material divided by its density; materials with a high strength-to-weight ratio are strong but lightweight.

Structure Description of the arrangements of atoms or ions in a material. The structure of materials has a profound influence on many properties of materials, even if the overall composition does not change!

Synthesis The process by which materials are made from naturally occurring or other chemicals.

Thermoplastics A special group of polymers in which molecular chains are entangled but not interconnected. They can be easily melted and formed into useful shapes. Normally, these polymers have a chainlike structure (e.g., polyethylene).

Thermosets A special group of polymers that decompose rather than melt upon heating. They are normally quite brittle due to a relatively rigid, three-dimensional network structure comprising chains that are bonded to one another (e.g., polyurethane).

PROBLEMS

Section 1-1 What is Materials Science and Engineering?

1-1 Define Material Science and Engineering (MSE).

1-2 Define the following terms: **(a)** composition, **(b)** structure, **(c)** synthesis, **(d)** processing, and **(e)** microstructure.

1-3 Explain the difference between the terms materials science and materials engineering.

1-4 Name one revolutionary discovery of a material. Name one evolutionary discovery of a material.

Section 1-2 Classification of Materials

Section 1-3 Functional Classification of Materials

Section 1-4 Classification of Materials Based on Structure

Section 1-5 Environmental and Other Effects

1-5 Steel is often coated with a thin layer of zinc if it is to be used outside. What characteristics do you think the zinc provides to this coated, or galvanized, steel? What precautions should be considered in producing this product? How will the recyclability of the steel be affected as a result of the galvanization?

1-6 We would like to produce a transparent canopy for an aircraft. If we were to use a ceramic (that is, traditional window glass) canopy, rocks or birds might cause it to shatter. Design a material that would minimize damage or at least keep the canopy from breaking into pieces.

1-7 Coiled springs ought to be very strong and stiff. Silicon nitride (Si_3N_4) is a strong, stiff material. Would you select this material for a spring? Explain.

1-8 Temperature indicators are sometimes produced from a coiled metal strip that uncoils a specific amount when the temperature increases. How does this work; from what kind of material would the indicator be made; and what are the important properties that the material in the indicator must possess?

Section 1-6 Materials Design and Selection

1-9 You would like to design an aircraft that can be flown by human power nonstop for a distance of 30 km. What types of material properties would you recommend? What materials might be appropriate?

1-10 You would like to place a three-foot diameter microsatellite into orbit. The satellite will contain delicate electronic equipment that will send and receive radio signals from earth. Design the outer shell within which the electronic equipment is contained. What properties will be required, and what kind of materials might be considered?

1-11 What properties should the head of a carpenter's hammer possess? How would you manufacture a hammer head?

1-12 The hull of the space shuttle consists of ceramic tiles bonded to an aluminum skin. Discuss the design requirements of the shuttle hull that led to the use of this combination of materials. What problems in producing the hull might the designers and manufacturers have faced?

1-13 You would like to select a material for the electrical contacts in an electrical switching device which opens and closes frequently and forcefully. What properties should the contact material possess? What type of material might you recommend? Would Al_2O_3 be a good choice? Explain.

1-14 Aluminum has a density of 2.7 g/cm^3. Suppose you would like to produce a composite material based on aluminum having a density of 1.5 g/cm^3. Design a material that would have this density. Would introducing beads of polyethylene, with a density of 0.95 g/cm^3, into the aluminum be a likely possibility? Explain.

1-15 You would like to be able to identify different materials without resorting to chemical analysis or lengthy testing procedures. Describe some possible testing and sorting techniques you might be able to use based on the physical properties of materials.

1-16 You would like to be able to physically separate different materials in a scrap recycling plant. Describe some possible methods that might be used to separate materials such as polymers, aluminum alloys, and steels from one another.

1-17 Some pistons for automobile engines might be produced from a composite material containing small, hard silicon carbide particles in an aluminum alloy matrix. Explain what benefits each material in the composite may provide to the overall part. What problems might the different properties of the two materials cause in producing the part?

1-18 Look up information on materials known as Geofoam. How are these materials used to reinforce ground that may be otherwise unstable?

1-19 An airplane made using primarily aluminum alloys weighs 5000 lbs. What will be the weight of this airplane if it is made using primarily carbon-fiber composites?

1-20 Ladders can be made using aluminum alloy, fiberglass, and wood. What will be the pros and cons of using each of these materials? One thing to keep in mind is that aluminum alloys are good conductors of electricity.

1-21 Replacing about half of the steel-based materials in a car can reduce the weight of the car by almost 60%. This can lead to nearly a 30% increase in fuel efficiency. What kinds of materials could replace steel in cars? What would be the advantages and disadvantages in using these materials?