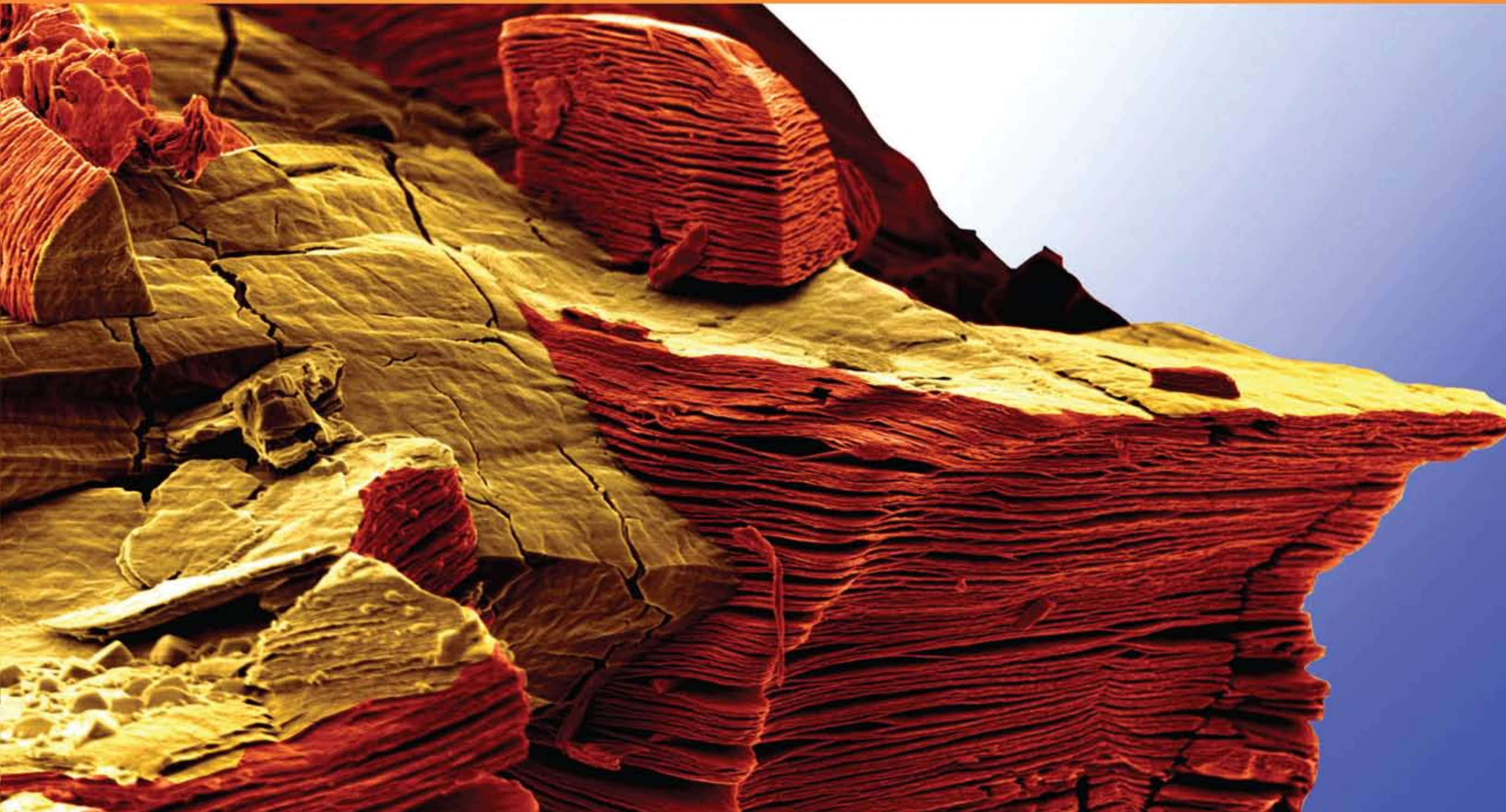
THE SCIENCE AND ENGINEERING OF MATERIALS

SEVENTH EDITION



DONALD R. ASKELAND | WENDELIN J. WRIGHT

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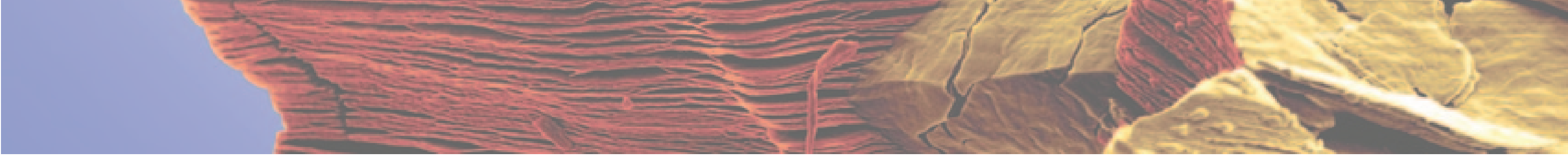

The Science and Engineering of Materials

Seventh Edition

Donald R. Askeland
University of Missouri—Rolla, Emeritus

Wendelin J. Wright
Bucknell University

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The Science and Engineering of Materials, Seventh Edition

Donald R. Askeland and Wendelin J. Wright

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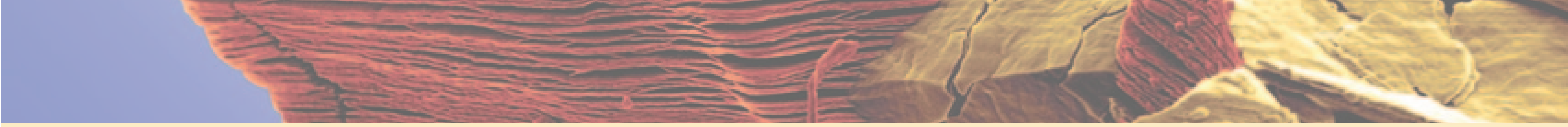
To Mary Sue and Tyler
–Donald R. Askeland

To John, my love
–Wendelin J. Wright



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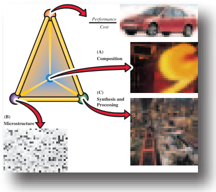
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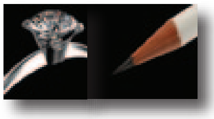

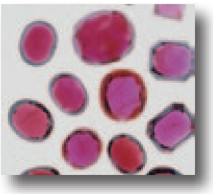

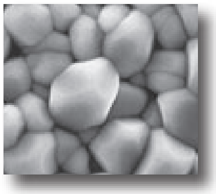

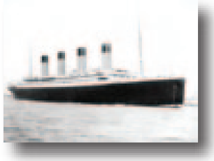

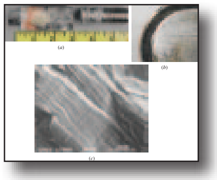

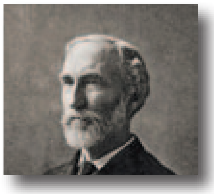

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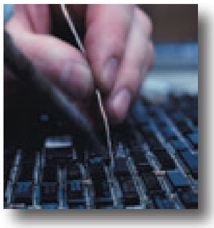

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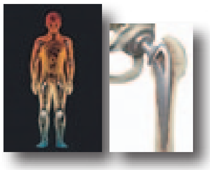

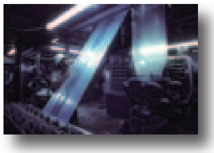

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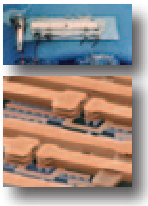

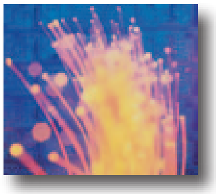

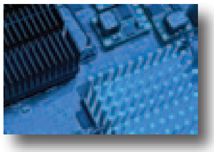

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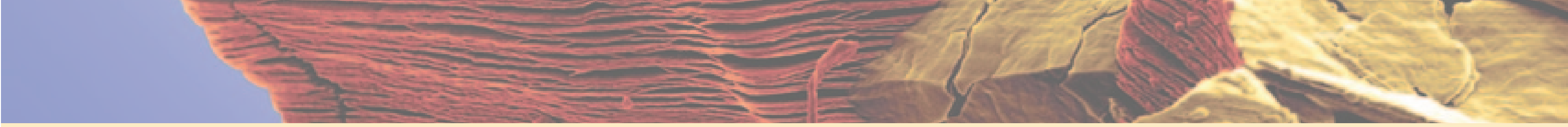

PREFACE

The copper age, the iron age, the silicon age . . . eras defined by the materials found in nature, but manipulated by the engineers of their day. The fundamental principles of structure, defects, kinetics, and processing are generally applicable to all materials, while over time our understanding has advanced and incorporated new ideas. As a result, the observable and macroscopic behavior of materials, spanning such varied characteristics as mechanical strength and toughness, electrical conductivity, refractive index, and corrosion resistance, is both understood more deeply and related more directly to underlying atomic-level phenomena.

Our tools for characterizing and manipulating materials have also grown vastly more sophisticated, allowing for deeper insights into materials structures and phenomena. At the edge of innovation we find the discovery—or even the creation—of entirely new materials, often made possible by new processing techniques, by circumventing equilibrium to cause materials to exist in metastable states, and by developing the tools to assemble, form, and study materials at the nanoscale. It is now routine, for instance, to examine materials at the near-atomic level for both structure and composition, using techniques such as high resolution transmission electron microscopy, grazing incidence x-ray diffraction, and electron energy loss spectroscopy. At the same time, materials processing has advanced to the point where thin films just a few atomic layers thick can in many instances be grown or deposited, while three-dimensional structures with dimensions of only a few tens of nanometers or less can also be manufactured. The entire electronics industry, for instance, is based on these types of advances. Flat screen televisions, high-speed wireless data systems, portable computation and telecommunication devices, automobiles and other transportation systems . . . these and countless other technologies are all dependent on our contemporary understanding of materials.

While not all students who study materials science will be practicing materials engineers, most engineers will in fact work with a diverse materials set, comprising metals, ceramics, plastics, composites, and semiconductors, and across lengths scales from the nanoscale to the macroscale, all within a context of myriad and diverse applications. Materials are an enabling component of what engineers imagine, design, and build. The ability to *innovate* and to incorporate materials *safely* in a design is rooted in an understanding of how to manipulate materials properties and functionality through the control of materials structure and processing techniques. The objective of this textbook, then, is to describe the foundations and applications of materials science for college-level engineering students as predicated upon the structure-processing-properties paradigm.

The challenge of any textbook is to provide the proper balance of breadth and depth for the subject at hand, to provide rigor at the appropriate level, to provide meaningful examples and up to date content, and to stimulate the intellectual excitement of the reader. Our goal here is to provide enough *science* so that the reader may understand basic materials phenomena, and enough *engineering* to prepare a wide range of students for competent professional practice.

Cover Art

The cover art for the seventh edition of the text is a scanning electron microscope image showing two-dimensional (2-D) layers of Ti_3C_2, which were formed by selectively extracting Al from Ti_3AlC_2. Ti_3C_2 is a member of a new family of 2-D materials called MXenes, which was first discovered at Drexel University in 2011. Single and multilayer MXenes show attractive properties, such as a combination of metallic conductivity within the carbide layer and hydrophilicity of the oxygen terminated surface. MXenes comprise a growing family of 2-D materials with great promise in many applications, such as batteries and supercapacitor electrodes, transparent conducting coatings, and composite reinforcement. The width of the image is about 20 μm. The color is false; it has been added for artistic effect. The image is titled "The Cliff of the Two-Dimensional World" by Babak Anasori, Michael Naguib, Yury Gogotsi, and Michel W. Barsoum from the Department of Materials Science and Engineering and A. J. Drexel Nanotechnology Institute at Drexel University.

Audience and Prerequisites

This text is intended for an introductory science of materials class taught at the sophomore or junior level. A first course in college level chemistry is assumed, as is some coverage of first year college physics. A calculus course is helpful, but certainly not required. The text does not presume that students have taken other introductory engineering courses such as statics, dynamics, or mechanics of materials.

New to this Edition

The beginning of each chapter includes learning objectives to guide students in their studies. New problems have been added to the end of each chapter to increase the number of problems by 15%. The breadth of Chapter 15 on ceramic materials has been extended to include crystalline ceramics, silica and silicate compounds, and other topics of interest to provide a more comprehensive view of this important class of engineering materials. Other portions of the chapter have been revised for clarity. The cost of common engineering materials in Chapter 14 has been updated. As always, we have taken great care to provide the most error-free text possible.

Knovel™ Problems

At the conclusion of the end of chapter problems, you will find a special section with problems that require the use of Knovel (**www.knovel.com**). Knovel is an online aggregator of engineering references including handbooks, encyclopedias, dictionaries, textbooks, and databases from leading technical publishers and engineering societies such as the American Society of Mechanical Engineers (ASME) and the American Institute of Chemical Engineers (AIChE).

The Knovel problems build on material found in the textbook and require familiarity with online information retrieval. The problems are also available online at **www.cengage.com/engineering.** In addition, the solutions are accessible by registered instructors. If your institution does not have a subscription to Knovel or if you have any questions about Knovel, please contact

support@knovel.com
(210) 340-1944
(866) 324-5163

The Knovel problems were created by a team of engineers led by Sasha Gurke, senior vice president and co-founder of Knovel.

Supplements for the Instructor

Supplements to the text include the Instructor's Solutions Manual that provides complete solutions to selected problems and annotated Powerpoint™ slides.

MindTap

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap version have access to the book's MindTap Reader and are able to complete homework and assessment material online, through their desktop, laptop, or iPad. If you are using a Learning Management System (such as Blackboard or Moodle) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

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- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension
- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes, create their own flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and homework.

Acknowledgments

We thank all those who have contributed to the success of past editions and also the reviewers who provided detailed and constructive feedback on the sixth edition:

Cynthia W. Barnicki, Milwaukee School of Engineering

Deborah Chung, University of Buffalo, SUNY

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Stephen W. Stafford, University of Texas, El Paso

We also thank Jeffrey Florando of Lawrence Livermore National Laboratory for comments on the revisions to Chapter 15.

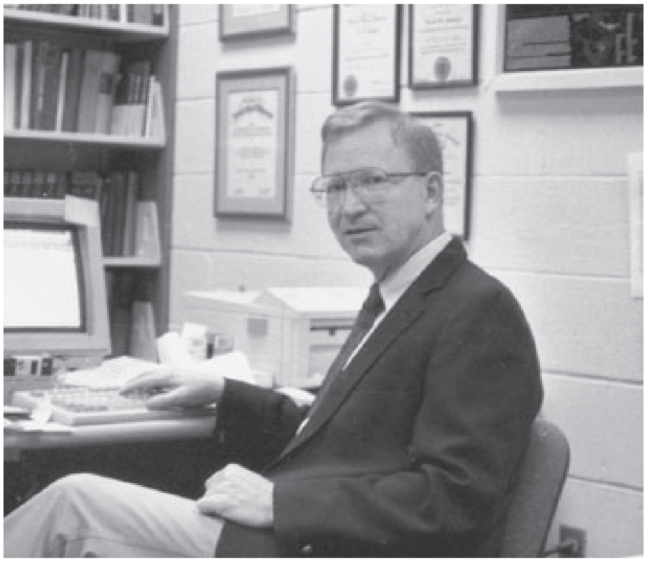
We are grateful to the team at Cengage Learning who has carefully guided this seventh edition through all stages of the publishing process. In particular, we thank Timothy Anderson, publisher for Global Engineering; Eavan Cully and Hilda Gowans, development editors; Rose Kernan, production editor; Kristiina Paul, permissions and photo researcher; Ashley Kaupert, media assistant; and Sam Roth, team assistant. We also thank Stephen Stafford and Keith McIver for new end of chapter problems in this edition.

Wendelin Wright thanks Briana King and Joanne Mowen for their assistance during the revision process as well as John Bravman of Bucknell University for his feedback, contributed illustrations, patience, and constant support.

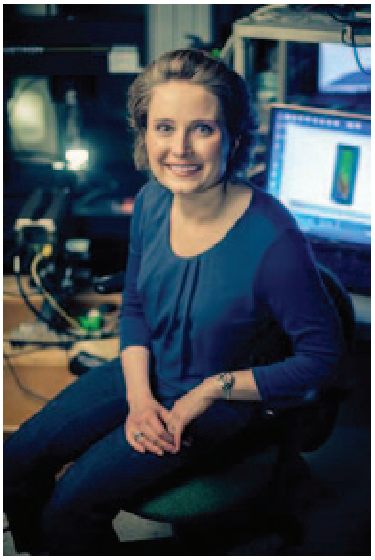
Donald R. Askeland
University of Missouri — Rolla, Emeritus

Wendelin J. Wright
Bucknell University

ABOUT THE AUTHORS

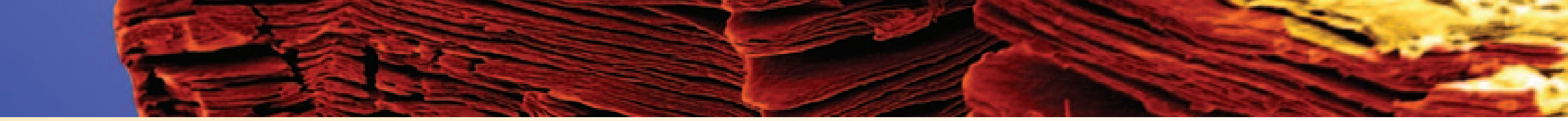


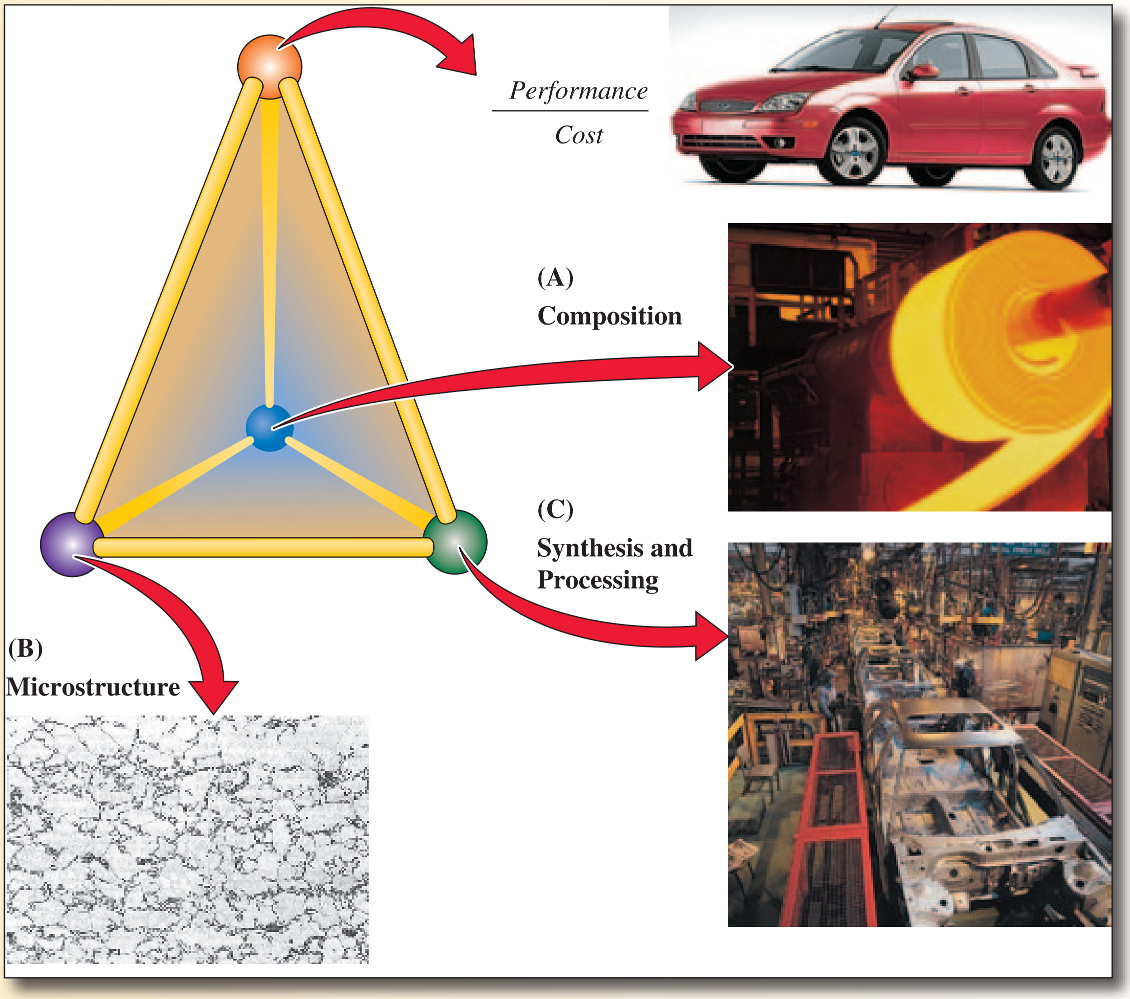
Donald R. Askeland is a Distinguished Teaching Professor Emeritus of Metallurgical Engineering at the University of Missouri–Rolla. He received his degrees from the Thayer School of Engineering at Dartmouth College and the University of Michigan prior to joining the faculty at the University of Missouri–Rolla 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.



Wendelin Wright is an associate professor at Bucknell University with a joint appointment in the departments of Mechanical Engineering and Chemical Engineering. She received her B.S., M.S., and Ph.D. in Materials Science and Engineering from Stanford University. Following graduation, she served a post–doctoral term at the Lawrence Livermore National Laboratory in the Manufacturing and Materials Engineering Division and then returned to Stanford as an Acting Assistant Professor in 2005. She joined the Santa Clara University faculty in 2006 as a tenure-track assistant professor and assumed her position at Bucknell in the fall of 2010.

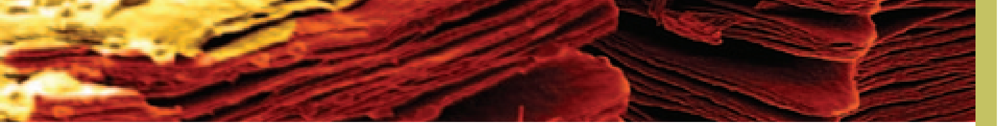
Professor Wright's research interests focus on the mechanical behavior of materials, particularly of metallic glasses. She is the recipient of the 2003 Walter J. Gores Award for Excellence in Teaching, which is Stanford University's highest teaching honor, a 2005 Presidential Early Career Award for Scientists and Engineers, and a 2010 National Science Foundation CAREER Award. Professor Wright is a licensed professional engineer in metallurgy in California. She is married to John Bravman and is the mother of two young sons, Cole and Cooper.





The principal goals of a materials scientist and engineer are to (1) make existing materials better and (2) invent or discover new phenomena, materials, devices, and applications. Breakthroughs in the materials science and engineering field are applied to many other fields of study such as biomedical engineering, physics, chemistry, environmental engineering, and information technology. The materials science and engineering tetrahedron shown here represents the heart and soul of this field, and its use is illustrated for the production of steel for an automotive chassis. As shown in this diagram, a materials scientist and engineer's main objective is to develop materials or devices that have the best performance for a particular application. In most cases, the performance-to-cost ratio, as opposed to the performance alone, is of utmost importance. This concept is shown as the apex of the tetrahedron and the three corners are representative of *A*—the composition, *B*—the microstructure, and *C*—the synthesis and processing of materials. These are all interconnected and ultimately affect the performance-to-cost ratio of a material or a device. The accompanying micrograph shows the microstructure of a dual phase steel. The microstructure of dual phase steels is engineered to absorb energy during automotive collisions. Hard particles of a phase called martensite (dark) are dispersed in a matrix of relatively soft, ductile ferrite (light).

For materials scientists and engineers, materials are like a palette of colors to an artist. Just as an artist can create different paintings using different colors, materials scientists create and improve upon different materials using different elements of the periodic table, and different synthesis and processing routes. (*Michael Shake/Shutterstock.com / Digital Vision/Getty Images / Digital Vision/Getty Images /* Metals Handbook, *Desk Edition (1998), ASM International, Materials Park, OH 44073-0002. Reprinted with permission of ASM International. All rights reserved. www.asminternational.org.*)



CHAPTER 1

Introduction to Materials Science and Engineering

Have You Ever Wondered?

- *What do materials scientists and engineers study?*
- *From a materials stand point, how do you significantly improve the fuel efficiency of a commercial jet airliner?*
- *Can we make flexible and lightweight electronic circuits using plastics?*
- *Why do jewelers add copper to gold?*
- *What is a "smart material?"*

Chapter Learning Objectives

The key objectives of this chapter are to

- Understand the primary concepts that define materials science and engineering.
- Understand the role of materials science in the design process.
- Classify materials by properties.
- Classify materials by function.

In this chapter, we will first introduce you to the field of materials science and engineering using different real-world examples. We will then provide an introduction to the classification of materials. Although most engineering programs require students to take a materials science course, you should approach your study of materials science as more than a mere requirement. A thorough knowledge of materials science and engineering will make you a better engineer and designer. Materials science underlies all technological advances, and an understanding of 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. You need to be capable of choosing the right material for your application based on its properties, and you must recognize how and why these properties might change over time and due to processing. Any engineer can look up materials properties in a book or search databases for a material that meets design specifications, but the *ability to innovate* and to *incorporate materials safely* in a design is rooted in an understanding of how to manipulate materials properties and functionality through the control of the material's structure and processing techniques.

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.

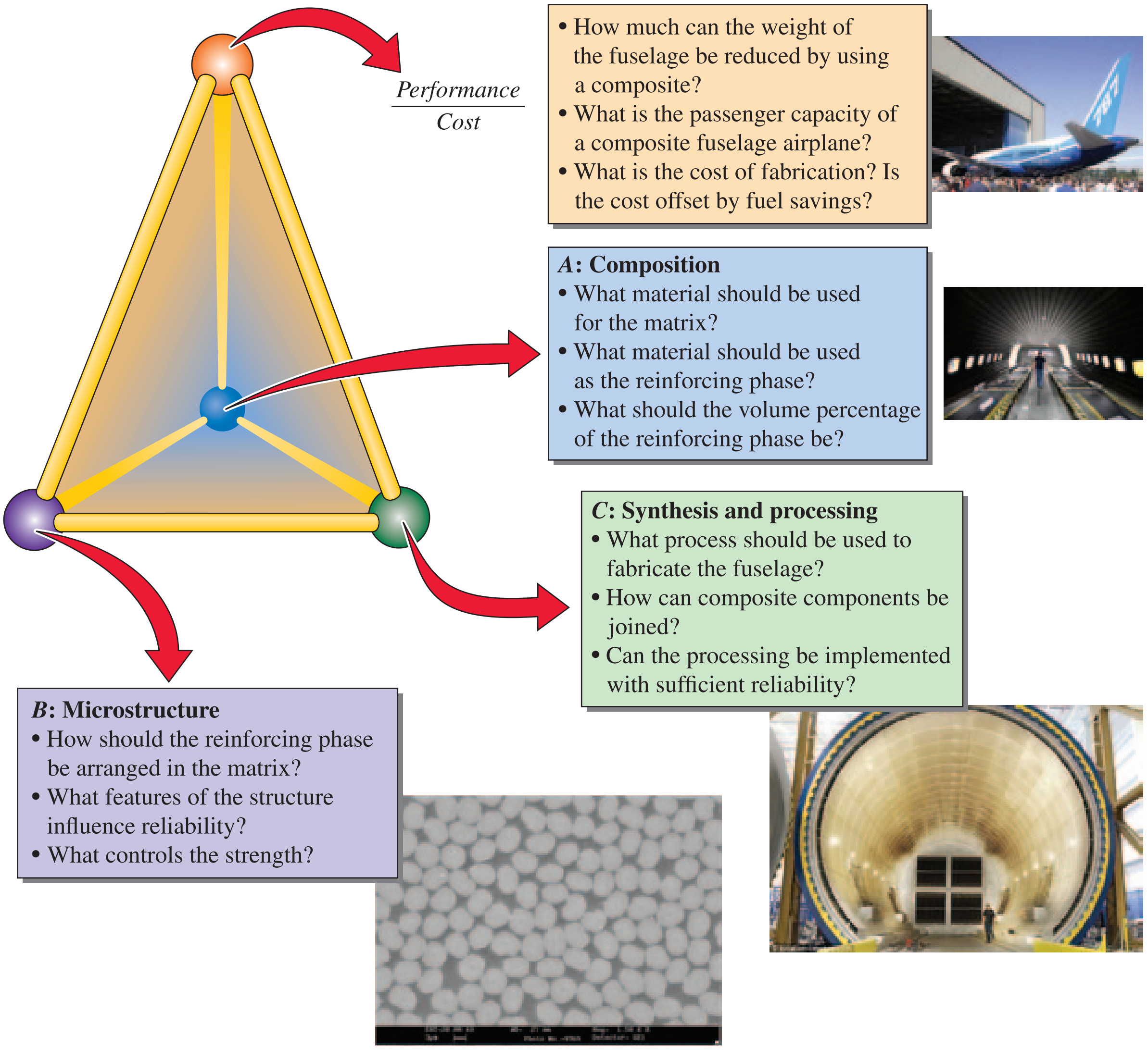
In this book, we provide compelling examples of real-world applications of engineered materials. The diversity of applications and the unique uses of materials illustrate why a good engineer needs to understand and know how to apply the principles of materials science and engineering.

1-1 What is Materials Science and Engineering?

Materials science and engineering (MSE) is an interdisciplinary field that studies and manipulates the composition and structure of materials across length scales to control materials properties through synthesis and processing. The term **composition** means the chemical make-up of a material. The term **structure** means 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 to cause changes in the properties of different materials. One of the most important functions of materials scientists and engineers is to establish the relationships between a material or a device's properties and performance and the microstructure of that material, its composition, and the way the material or the device was synthesized and processed. 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 useful devices or structures.

One of the most fascinating aspects of materials science involves the investigation of a material's structure. 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! The electrical resistivity of the wire will also increase as we bend it repeatedly. In this simple example, take note that we did not change the material's composition (i.e., its chemical make-up). The changes in the material's properties are due to a change in its internal structure. If you look at the wire after bending, it will look the same as before; however, its structure has been changed at the microscopic scale. The structure at the microscopic scale is known as the **microstructure**. If we can understand what has changed microscopically, we can begin to discover ways to control the material's properties.

Let's consider one example using the **materials science and engineering tetrahedron** shown in Figure 1-1. (Another example is shown on the chapter opening page.) For most of the history of commercial air travel, the fuselages of airplanes have been made using aluminum alloys. The fuselage material must possess sufficiently high strength, but must also be lightweight and formable into aerodynamic contours. Aluminum is one material that meets these requirements. In 2011, passengers began traveling on Boeing's 787 Dreamliner aircraft. One of the primary innovations of the Boeing 787 is the extensive use of **composites**; composite materials are formed by incorporating multiple components in a material in such a way that the properties of the resultant material are unique and not otherwise attainable. Composite materials comprise half of the Dreamliner's total weight, and in fact, the fuselage of the Boeing 787 is made from carbon fiber-reinforced plastic. Carbon fiber-reinforced plastic is a composite of carbon fiber in a polymer epoxy resin matrix.



- How much can the weight of the fuselage be reduced by using a composite?
- What is the passenger capacity of a composite fuselage airplane?
- What is the cost of fabrication? Is the cost offset by fuel savings?

***A*: Composition**
- What material should be used for the matrix?
- What material should be used as the reinforcing phase?
- What should the volume percentage of the reinforcing phase be?

***C*: Synthesis and processing**
- What process should be used to fabricate the fuselage?
- How can composite components be joined?
- Can the processing be implemented with sufficient reliability?

***B*: Microstructure**
- How should the reinforcing phase be arranged in the matrix?
- What features of the structure influence reliability?
- What controls the strength?

Figure 1-1 Application of the materials science and engineering tetrahedron to carbon fiber-reinforced plastic for the fabrication of aircraft fuselages. The composition, microstructure, and synthesis/processing are all interconnected and affect the performance-to-cost ratio. Clockwise from upper right: the Boeing 787; the interior of an empty Boeing 787 fuselage; a giant autoclave used to bake carbon fiber-reinforced plastic sections; carbon fiber in an epoxy matrix. (*Bloomberg via Getty Images / Srinivasa, Vinod, Shivakumar, Vinay, Nayaka, Vinay, Jagadeeshaiaih, Sunil, Seethram, Murali, Shenoy, Raghavendra, & Nafidi, Abdelhakim. (2010). Fracture morphology of carbon fiber reinforced plastic composite laminates.* Materials Research, *13(3), 417-424. Retrieved January 06, 2014, from http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-14392010000300022&lng=en&tlng=en. 10.1590/S1516-14392010000300022./ AFP/Getty Images / Aviation Images*)

After decades of success with their various models of aircraft, Boeing invested billions of dollars to develop a commercial airplane based on a new class of materials. Why would Boeing do this? The driving force behind the move to carbon fiber-reinforced plastic was to reduce the weight of the fuselage, thereby increasing fuel efficiency. This significantly increases the performance to cost ratio of the aircraft.

The switch to a composite material involved numerous technical challenges. What would the composite material be? How would the composite fuselage be formed? Decades of data are available for the growth of cracks in aluminum under the cyclic loading of take-offs and landings. Would the composite fuselage be reliable? Would a carbon fiber-reinforced plastic also have the corrosion-resistance that aluminum has or would delamination between the fibers and plastic occur? Aluminum jets have structural panels that are riveted together. How can various structural components made from composites be joined? From this discussion, you can see that many issues need to be considered during the design and materials selection for any product and that the ratio of performance to cost, composition, microstructure, and synthesis and process are all critical factors.

Let's look at one more example of the application of the materials science and engineering tetrahedron by considering the use in microelectronic devices of a class of materials known as semiconducting polymers (Figure 1-2). Many types of displays such as those found in alarm clocks and watches utilize light emitting diodes (LEDs) made from inorganic compounds based on gallium arsenide (GaAs) and other materials; however, semiconducting polymers also have been used more recently. The advantages of using plastics for microelectronics include their flexibility and ease of processing. The questions materials scientists and engineers must answer with applications of semiconducting polymers are

- What are the relationships between the structure of polymers and their electrical properties?
- How can devices be made using these plastics?
- Will these devices be compatible with existing silicon chip technology?
- How robust are these devices?
- How will the performance and cost of these devices compare with traditional devices?

These are just a few of the factors that engineers and scientists must consider during the development, design, and manufacturing of semiconducting polymer devices.

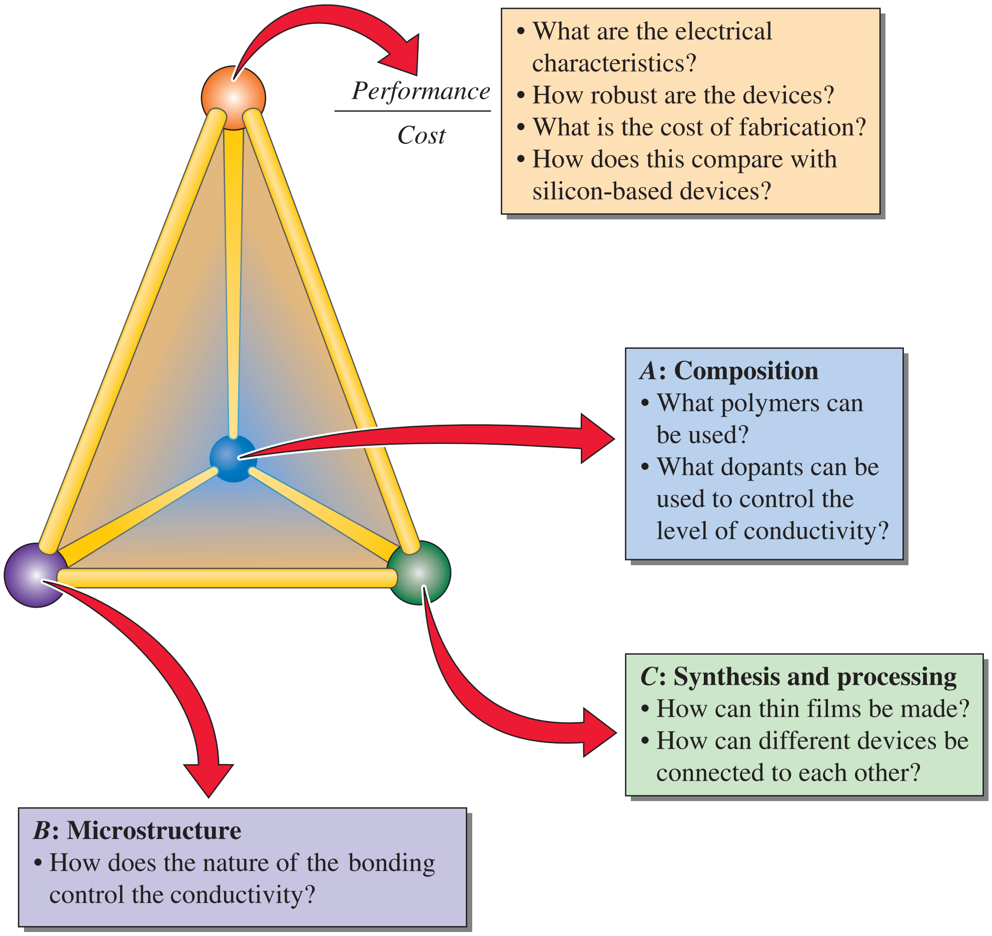


Figure 1-2 Application of the tetrahedron of materials science and engineering to semiconducting polymers for microelectronics.

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.

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	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	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	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, used in 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

Materials in each of these groups possess different structures and properties. The differences in strength, which are compared in Figure 1-3, illustrate the wide range of properties from which engineers can select. Since metallic materials are extensively used for load-bearing applications, their mechanical properties are of great practical interest. We briefly introduce these properties here. The term "stress" refers to load or force per unit area. "Strain" refers to elongation or change in dimension divided by the 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. The level of stress needed to initiate plastic deformation is known as the "yield strength." The maximum percent deformation that can be achieved is a measure of the ductility of a metallic material. These concepts are discussed further in Chapters 6 and 7.

Metals and Alloys Metals include aluminum, magnesium, zinc, iron, titanium, copper, and nickel. An alloy is a metal that contains additions of one or more metals or nonmetals, e.g., steel is an alloy of iron with carbon additions. In general, metals have good electrical and thermal conductivities. 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, alloys provide improvement in a particular desirable property or permit better combinations of properties. For example, pure gold is a soft metal; thus, jewelers add copper to gold to improve strength so that gold jewelry is not easily damaged.

Ceramics Ceramics can be defined as inorganic nonmetallic 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

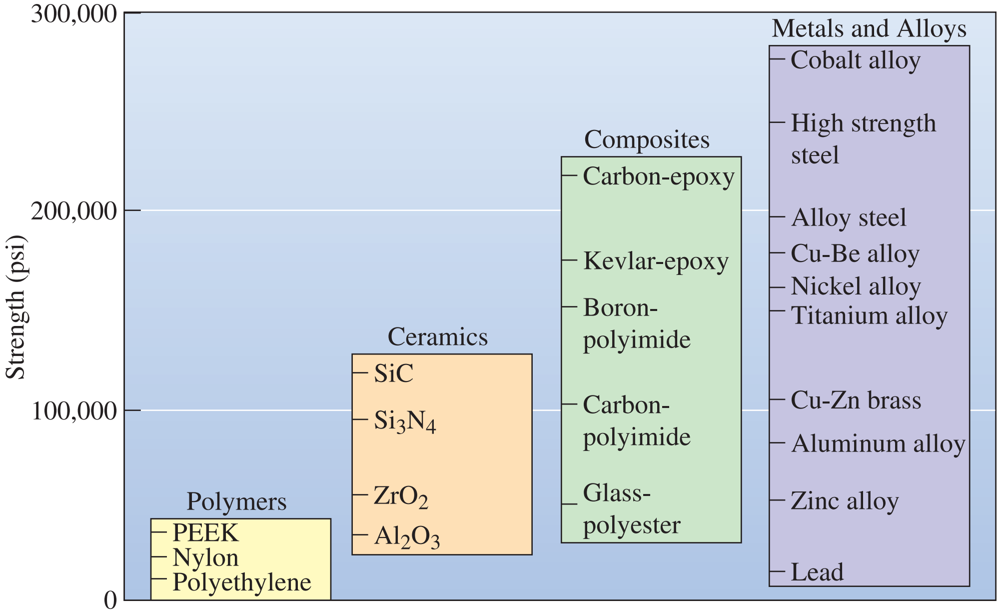


Figure 1-3 Representative strengths of various categories of materials. Compressive strengths are shown for ceramics.

actuators, capacitors, wireless communications, spark plugs, inductors, and electrical insulation. Some ceramics are used as barrier coatings to protect metallic substrates in turbine engines. Ceramics are also used in such consumer products as paints, plastics, and tires, and for industrial applications such as the oxygen sensors used in cars. Traditional ceramics are used to make bricks, tableware, bathroom fixtures, refractories (heat-resistant materials), and abrasives. In general, ceramics do not conduct heat well; they must be heated to very high temperatures before melting. Ceramics are strong and hard, but also very brittle. We normally prepare fine powders of ceramics and mold 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. Ceramics have exceptional strength under compression. Can you believe that 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 a molten liquid. The term "amorphous" refers to materials that do not have a regular, periodic arrangement of atoms. Amorphous materials will be discussed in Chapter 3. The fiber optics industry is founded on optical fibers based on high-purity silica glass. Glasses are also used in houses, cars, screens for computers, televisions, and smart phones, and hundreds of other applications. Glasses can be thermally treated (tempered) to make them stronger. Forming glasses and then nucleating (forming) 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. They are produced using a process known as **polymerization**. Polymeric materials include rubber (elastomers) and many types of adhesives. Polymers typically are good electrical and thermal insulators although there are exceptions. Although they have lower strengths than metals or ceramics, polymers have very good **strength-to-weight ratios**. 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 discs (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 1-4). Polymers are

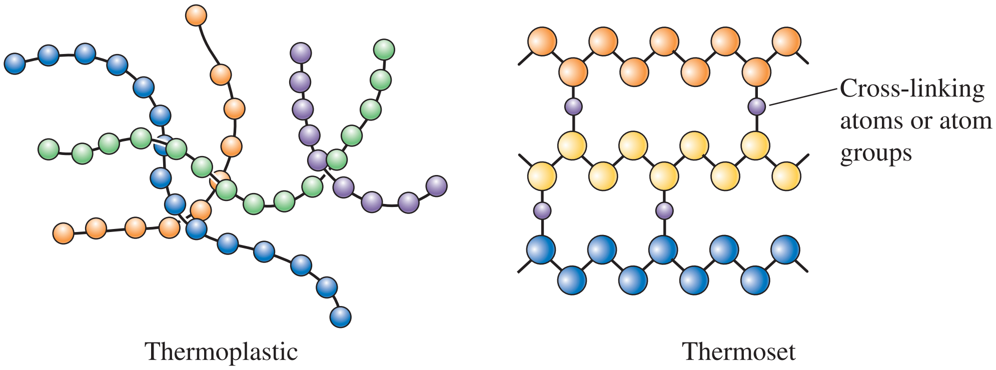


Figure 1-4 Polymerization occurs when small molecules, represented by the circles, combine to produce larger molecules, or polymers. The polymer molecules can have a structure that consists of many chains that are entangled but not connected (thermoplastics) or can form three-dimensional networks in which chains are cross-linked (thermosets).