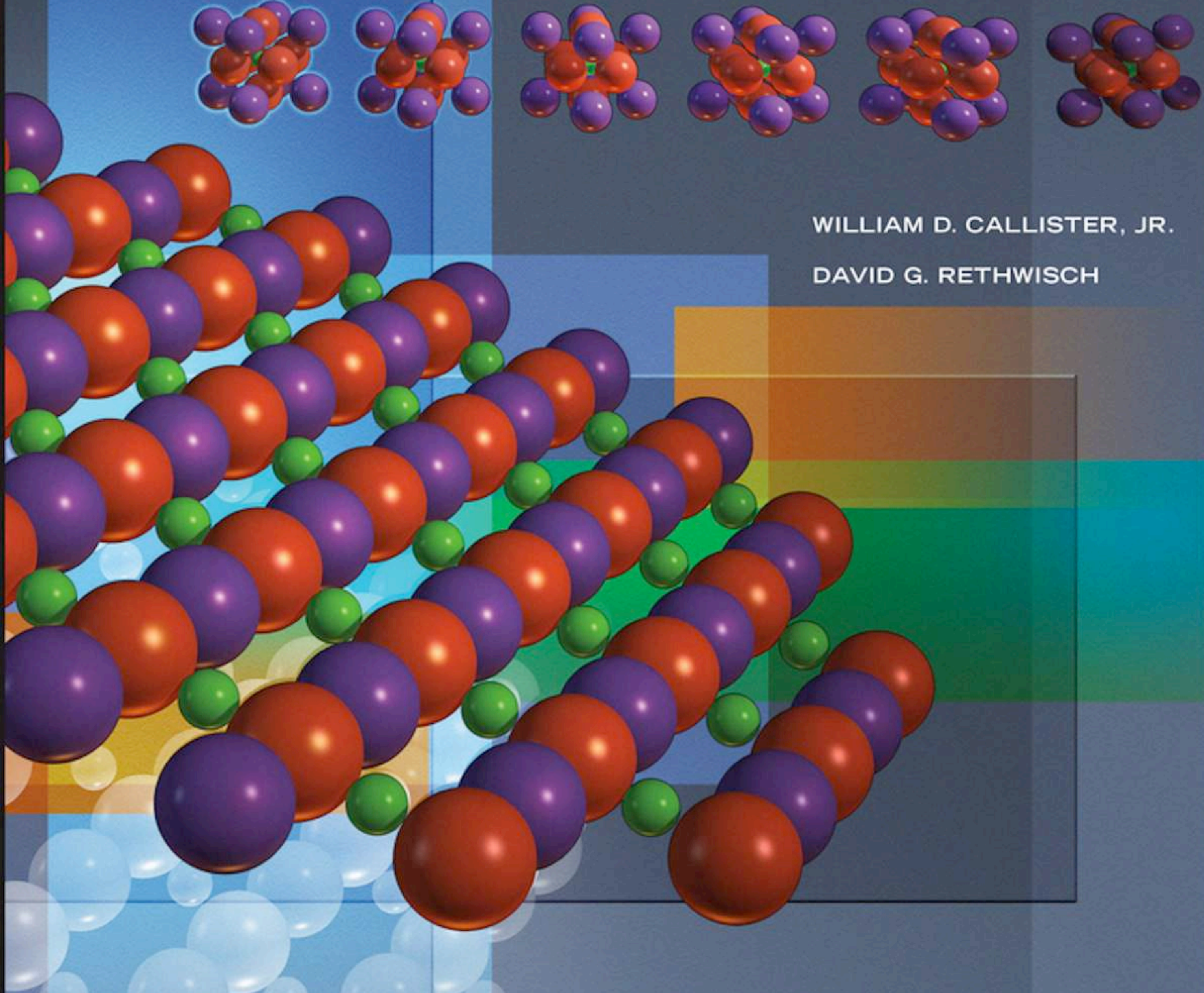
MATERIALS SCIENCE AND ENGINEERING

AN INTRODUCTION

TENTH EDITION



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WILEY

10th Edition

Materials Science and Engineering

AN INTRODUCTION

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WILEY

Front Cover: Representation of a (110) plane for barium titanate ($BaTiO_3$), which has the perovskite crystal structure. Red, purple, and green spheres represent, respectively, oxygen, barium, and titanium ions.
Back Cover: Depiction of a (123) plane for sodium chloride (NaCl), which has the rock salt crystal structure. Green and brown spheres denote chlorine and sodium ions, respectively.

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Dedicated to the memory of
Peter Joseph Rethwisch
Father, lumberman, and friend

Preface

In this tenth edition we have retained the objectives and approaches for teaching materials science and engineering that were presented in previous editions. These objectives are as follows:

- Present the basic fundamentals on a level appropriate for university/college students.
- Present the subject matter in a logical order, from the simple to the more complex.
- If a topic or concept is worth treating, then it is worth treating in sufficient detail and to the extent that students have the opportunity to fully understand it without having to consult other sources.
- Inclusion of features in the book that expedite the learning process, to include the following: photographs/illustrations; learning objectives; "Why Study . . ." and "Materials of Importance" items; "Concept Check" questions; questions and problems; Answers to Selected Problems; summary tables containing key equations and equation symbols; and a glossary (for easy reference).
- Employment of new instructional technologies to enhance the teaching and learning processes.

New/Revised Content

This new edition contains a number of new sections, as well as revisions/amplifications of other sections. These include the following:

- New discussions on the Materials Paradigm and Materials Selection (Ashby) Charts (Chapter 1)
- Revision of Design Example 8.1—"Materials Specification for a Pressurized Cylindrical Tank" (Chapter 8)
- New discussions on 3D printing (additive manufacturing)—Chapter 11 (metals), Chapter 13 (ceramics), and Chapter 15 (polymers)
- New discussions on biomaterials—Chapter 11 (metals), Chapter 13 (ceramics), and Chapter 15 (polymers)
- New section on polycrystalline diamond (Chapter 13)
- Revised discussion on the Hall effect (Chapter 18)
- Revised/expanded discussion on recycling issues in materials science and engineering (Chapter 22)
- All homework problems requiring computations have been refreshed

BOOK VERSIONS

There are three versions of this textbook as follows:

- Digital (for purchase)—formatted as print; contains entire content

- Digital (in WileyPLUS)—formatted by section; contains entire content
- Abridged Print (Companion)—binder ready form; problem statements omitted

ONLINE RESOURCES

Associated with the textbook are online learning resources, which are available to both students and instructors. These resources are found on three websites: (1) WileyPLUS, (2) a Student Companion Site, and (3) an Instructor Companion Site.

WileyPLUS (www.wileyplus.com)

WileyPLUS is a research-based online environment for effective teaching and learning. It builds students' confidence by taking the guesswork out of studying by providing them with a clear roadmap: what is assigned, what is required for each assignment, and whether assignments are done correctly. Independent research has shown that students using WileyPLUS will take more initiative so the instructor has a greater impact on their achievement in the classroom and beyond. WileyPLUS also helps students study and progress at a pace that's right for them. Our integrated resources–available 24/7–function like a personal tutor, directly addressing each student's demonstrated needs by providing specific problem-solving techniques.

What do students receive with WileyPLUS?

They can browse the following WileyPLUS resources by chapter.

- ***The Complete Digital Textbook*** (at a savings up to 60% of the cost of the in-print text). Each chapter is organized and accessed by section (and end-of-chapter elements). (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/CHAPTER RESOURCES/Reading Content.)
- ***Virtual Materials Science and Engineering (VMSE).*** This web-based software package consists of interactive simulations and animations that enhance the learning of key concepts in materials science and engineering. Included in VMSE are eight modules and a materials properties/cost database. Titles of these modules are as follows: (1) Metallic Crystal Structures and Crystallography; (2) Ceramic Crystal Structures; (3) Repeat Unit and Polymer Structures; (4) Dislocations; (5) Phase Diagrams; (6) Diffusion; (7) Tensile Tests; and (8) Solid-Solution Strengthening. (Found under Read, Study & Practice.)
- ***Tutorial ("Muddiest Point") Videos.*** These videos (narrated by a student) help students with concepts that are difficult to understand and with solving troublesome problems. (Found under Read, Study & Practice.)
- ***Library of Case Studies.*** One way to demonstrate principles of *design* in an engineering curriculum is via case studies: analyses of problem-solving strategies applied to real-world examples of applications/devices/failures encountered by engineers. Six case studies are provided as follows: (1) Materials Selection for a Torsionally Stressed Cylindrical Shaft; (2) Automobile Valve Spring; (3) Failure of an Automobile Rear Axle; (4) Artificial Total Hip Replacement; (5) Intraocular Lens Implants; and (6) Chemical Protective Clothing. (Found under Read, Study & Practice.)
- ***Mechanical Engineering (ME) Online Module.*** This module treats materials science/engineering topics not covered in the printed text that are relevant to mechanical engineering. (Found under Read, Study & Practice.)
- ***Flash Cards.*** A set of flash-cards has been generated for most chapters. These can be used in drills to memorize definitions of terms. (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/CHAPTER RESOURCES/Flashcards.)

- ***Extended Learning Objectives.*** This is a more extensive list of learning objectives than is provided at the beginning of each chapter. These direct the student to study the subject material to a greater depth. (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/CHAPTER RESOURCES/Extended Learning Objectives.)
- ***Student Lecture Notes.*** These slides (in PowerPoint and PDF formats) are virtually identical to the lecture slides provided to an instructor for use in the classroom. The student set has been designed to allow for note taking on printouts. (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/CHAPTER RESOURCES/Student Lecture Notes.)
- ***Answers to Concept Check questions.*** Students can visit the web site to find the correct answers to the Concept Check questions posed in the textbook. (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/PRACTICE/Concept Check Questions/Concept Check Number/Show Solution.)
- ***Online Self-Assessment Exercises.*** A set of questions and problems for each chapter that are similar to those found in the text. An answer to each problem/question entered by the student is assessed as either correct or incorrect, after which both the solution and answer are provided. (Found under Read, Study & Practice/CONTENTS/Select Chapter Number/PRACTICE/Practice Questions and Problems.)
- ***Math Skills Review.*** This is a tutorial that includes instructions on how to solve a variety of mathematical equations, some of which appear in the homework problems. Examples are also provided. (Found under Read, Study & Practice/CONTENTS/Chapter 22.)

What do instructors receive with WileyPLUS?

WileyPLUS provides reliable, customizable resources that reinforce course goals inside and outside of the classroom as well as visibility into individual student progress. Prepared materials and activities help instructors optimize their time.

The same resources are provided as are found for students as noted above.

The opportunity to pre-prepare activities, including:

- Questions
- Readings and resources
- Presentations

Course materials and assessment content:

- ***Complete set of Lecture PowerPoint slides (or Lecture Notes).*** (Found under Prepare & Present/Resources/Select Chapter Number/All Sources/Instructor Resources/PowerPoint/GO/Lecture Notes.)
- ***Image Gallery.*** Digital repository of images from the text that instructors may use to generate their own PowerPoint slides. (Found under Prepare & Present/Resources/Select Chapter Number/All Sources/Instructor Resources/PowerPoint/GO/Image Gallery.)
- ***Solutions Manual (Textbook).*** The manuals contain solutions/answers for all problems/questions in the textbook. (Found under Prepare & Present/Resources/Select Chapter Number/All Sources/Instructor Resources/Document/GO/Chapter Solutions Manual.)
- ***Solutions Manual (ME Online Module).*** (Found under Prepare & Present/Resources/Mechanical Engineering Module/All Sources/Instructor Resources/Document/GO/Solutions for ME Module.)

- ***Solutions Manual (Library of Case Studies).*** (Found under Prepare & Present/Resources/Select Any Chapter/All Sources/Instructor Resources/Document/GO/Solutions to the Library Case Studies/Word or PDF.)
- ***Problem Conversion Guide.*** This guide correlates homework problems/questions between the previous and current textbook editions. (Found under Prepare & Present/Resources/Select Any Chapter/All Sources/Instructor Resources/Document/GO/Problem Conversion Guide: 9th edition to 10th edition.)
- ***Problems/Questions.*** Selected problems coded algorithmically with hints, links to text, whiteboard/show work feature and instructor controlled problem solving help. [Found under Assignment/Questions/Select Chapter Number/Select Section Number (or All Sections)/Select Level (or All Levels)/All Sources/GO.]
- ***Answers to Concept Check Questions.*** (Found under Assignment/Questions/Select Chapter Number/All Sections/All Levels/All Sources/GO/Question Name.)
- ***List of Classroom Demonstrations and Laboratory Experiments.*** These demos and experiments portray phenomena and/or illustrate principles that are discussed in the book; references are also provided that give more detailed accounts of them. (Found under Prepare & Present/Resources/Select Any Chapter/All Sources/Instructor Resources/All File Types/GO/Experiments and Classroom Demonstrations.)
- ***Suggested Course Syllabi for the Various Engineering Disciplines.*** Instructors may consult these syllabi for guidance in course/lecture organization and planning. (Found under Prepare & Present/Resources/Select Any Chapter/All Sources/Instructor Resources/All File Types/GO/Sample Syllabi.)
- ***Gradebook.*** WileyPLUS provides instant access to reports on trends in class performance, student use of course materials and progress towards learning objectives, helping inform decisions and drive classroom discussions. (Found under Gradebook.)

STUDENT AND INSTRUCTOR COMPANION SITES (www.wiley.com/college/callister)

For introductory materials science and engineering courses that do not use WileyPLUS, print and digital (for purchase) versions of the book are available. In addition, online resources may be accessed on a Student Companion Site (for students) and an Instructor Companion Site (for instructors). Some, but not all of the WileyPLUS resources are found on these two sites.

The following resources may be accessed on the **STUDENT COMPANION SITE**:

- ***Student Lecture PowerPoint Slides***
- ***Answers to Concept Check Questions***
- ***Extended Learning Objectives***
- ***Mechanical Engineering (ME) Online Module***
- ***Math Skills Review***

Whereas for the **INSTRUCTOR COMPANION SITE** the following resources are available:

- ***Solutions Manuals (in PDF and Word formats)***
- ***Answers to Concept Check Questions***
- ***Problem Conversion Guide***
- ***Complete Set of Lecture PowerPoint Slides***
- ***Extended Learning Objectives***

- ***Image Gallery.***
- ***Mechanical Engineering (ME) Online Module***
- ***Solutions to Problems in the ME Online Module***
- ***Suggested Syllabi for the Introductory Materials Course***
- ***Math Skills Review***

Feedback

We have a sincere interest in meeting the needs of educators and students in the materials science and engineering community, and therefore solicit feedback on this edition. Comments, suggestions, and criticisms may be submitted to the authors via email at the following address: *billcallister2419@gmail.com.*

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Since we undertook the task of writing this and previous editions, instructors and students, too numerous to mention, have shared their input and contributions on how to make this work more effective as a teaching and learning tool. To all those who have helped, we express our sincere thanks.

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William D. Callister, Jr.
David G. Rethwisch
September 2017

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List of Symbols

The number of the section in which a symbol is introduced or explained is given in parentheses.

A = area
Å = angstrom unit
A_i = atomic weight of element i (2.2)
APF = atomic packing factor (3.4)
a = lattice parameter: unit cell x-axial length (3.4)
a = crack length of a surface crack (8.5)
at% = atom percent (4.4)
B = magnetic flux density (induction) (20.2)
B_r = magnetic remanence (20.7)
BCC = body-centered cubic crystal structure (3.4)
b = lattice parameter: unit cell y-axial length (3.7)
$\mathbf{b}$ = Burgers vector (4.5)
C = capacitance (18.18)
C_i = concentration (composition) of component i in wt% (4.4)
C_i' = concentration (composition) of component i in at% (4.4)
C_v, C_p = heat capacity at constant volume, pressure (19.2)
CPR = corrosion penetration rate (17.3)
CVN = Charpy V-notch (8.6)
%CW = percent cold work (7.10)
c = lattice parameter: unit cell z-axial length (3.7)
c = velocity of electromagnetic radiation in a vacuum (21.2)
D = diffusion coefficient (5.3)
D = dielectric displacement (18.19)
DP = degree of polymerization (14.5)
d = diameter
d = average grain diameter (7.8)
d_{hkl} = interplanar spacing for planes of Miller indices h, k, and l (3.16)
E = energy (2.5)
E = modulus of elasticity or Young's modulus (6.3)
$\mathscr{E}$ = electric field intensity (18.3)
E_f = Fermi energy (18.5)
E_g = band gap energy (18.6)
$E_r(t)$ = relaxation modulus (15.4)
%EL = ductility, in percent elongation (6.6)
e = electric charge per electron (18.7)
e^- = electron (17.2)
erf = Gaussian error function (5.4)
exp = e, the base for natural logarithms
F = force, interatomic or mechanical (2.5, 6.2)
$\mathscr{F}$ = Faraday constant (17.2)
FCC = face-centered cubic crystal structure (3.4)
G = shear modulus (6.3)
H = magnetic field strength (20.2)
H_c = magnetic coercivity (20.7)
HB = Brinell hardness (6.10)
HCP = hexagonal close-packed crystal structure (3.4)
HK = Knoop hardness (6.10)
HRB, HRF = Rockwell hardness: B and F scales (6.10)
HR15N, HR45W = superficial Rockwell hardness: 15N and 45W scales (6.10)
HV = Vickers hardness (6.10)
h = Planck's constant (21.2)
(hkl) = Miller indices for a crystallographic plane (3.10)

$(hkil)$ = Miller indices for a crystallographic plane, hexagonal crystals (3.10)
I = electric current (18.2)
I = intensity of electromagnetic radiation (21.3)
i = current density (17.3)
i_C = corrosion current density (17.4)
J = diffusion flux (5.3)
J = electric current density (18.3)
K_c = fracture toughness (8.5)
K_{Ic} = plane strain fracture toughness for mode I crack surface displacement (8.5)
k = Boltzmann's constant (4.2)
k = thermal conductivity (19.4)
l = length
l_c = critical fiber length (16.4)
ln = natural logarithm
log = logarithm taken to base 10
M = magnetization (20.2)
$\overline{M}_n$ = polymer number-average molecular weight (14.5)
$\overline{M}_w$ = polymer weight-average molecular weight (14.5)
mol% = mole percent
N = number of fatigue cycles (8.8)
N_A = Avogadro's number (3.5)
N_f = fatigue life (8.8)
n = principal quantum number (2.3)
n = number of atoms per unit cell (3.5)
n = strain-hardening exponent (6.7)
n = number of electrons in an electrochemical reaction (17.2)
n = number of conducting electrons per cubic meter (18.7)
n = index of refraction (21.5)
n' = for ceramics, the number of formula units per unit cell (12.2)
n_i = intrinsic carrier (electron and hole) concentration (18.10)
P = dielectric polarization (18.19)
P–B ratio = Pilling–Bedworth ratio (17.10)
p = number of holes per cubic meter (18.10)
Q = activation energy
Q = magnitude of charge stored (18.18)
R = atomic radius (3.4)
R = gas constant
%RA = ductility, in percent reduction in area (6.6)
r = interatomic distance (2.5)
r = reaction rate (17.3)
r_A, r_C = anion and cation ionic radii (12.2)
S = fatigue stress amplitude (8.8)
SEM = scanning electron microscopy or microscope
T = temperature
T_c = Curie temperature (20.6)
T_C = superconducting critical temperature (20.12)
T_g = glass transition temperature (13.10, 15.12)
T_m = melting temperature
TEM = transmission electron microscopy or microscope
TS = tensile strength (6.6)
t = time
t_r = rupture lifetime (8.12)
U_r = modulus of resilience (6.6)
$[uvw]$ = indices for a crystallographic direction (3.9)
$[uvtw]$, $[UVW]$ = indices for a crystallographic direction, hexagonal crystals (3.9)
V = electrical potential difference (voltage) (17.2, 18.2)
V_C = unit cell volume (3.4)
V_C = corrosion potential (17.4)
V_H = Hall voltage (18.14)
V_i = volume fraction of phase i (9.8)
v = velocity
vol% = volume percent
W_i = mass fraction of phase i (9.8)
wt% = weight percent (4.4)
x = length
x = space coordinate
Y = dimensionless parameter or function in fracture toughness expression (8.5)
y = space coordinate
z = space coordinate
α = lattice parameter: unit cell y–z interaxial angle (3.7)
α, β, γ = phase designations
α_l = linear coefficient of thermal expansion (19.3)
β = lattice parameter: unit cell x–z interaxial angle (3.7)
γ = lattice parameter: unit cell x–y interaxial angle (3.7)
γ = shear strain (6.2)
Δ = precedes the symbol of a parameter to denote finite change
ε = engineering strain (6.2)
ε = dielectric permittivity (18.18)

ε_r = dielectric constant or relative permittivity (18.18)

$\dot{\varepsilon}_S$ = steady-state creep rate (8.12)

ε_T = true strain (6.7)

η = viscosity (12.10)

η = overvoltage (17.4)

2θ = Bragg diffraction angle (3.16)

θ_D = Debye temperature (19.2)

λ = wavelength of electromagnetic radiation (3.16)

μ = magnetic permeability (20.2)

μ_B = Bohr magneton (20.2)

μ_r = relative magnetic permeability (20.2)

μ_e = electron mobility (18.7)

μ_h = hole mobility (18.10)

ν = Poisson's ratio (6.5)

ν = frequency of electromagnetic radiation (21.2)

ρ = density (3.5)

ρ = electrical resistivity (18.2)

ρ_t = radius of curvature at the tip of a crack (8.5)

σ = engineering stress, tensile or compressive (6.2)

σ = electrical conductivity (18.3)

σ^* = longitudinal strength (composite) (16.5)

σ_c = critical stress for crack propagation (8.5)

σ_{fs} = flexural strength (12.9)

σ_m = maximum stress (8.5)

σ_m = mean stress (8.7)

σ'_m = stress in matrix at composite failure (16.5)

σ_T = true stress (6.7)

σ_w = safe or working stress (6.12)

σ_y = yield strength (6.6)

τ = shear stress (6.2)

τ_c = fiber–matrix bond strength/matrix shear yield strength (16.4)

τ_{crss} = critical resolved shear stress (7.5)

χ_m = magnetic susceptibility (20.2)

Subscripts

c = composite

cd = discontinuous fibrous composite

cl = longitudinal direction (aligned fibrous composite)

ct = transverse direction (aligned fibrous composite)

f = final

f = at fracture

f = fiber

i = instantaneous

m = matrix

m, max = maximum

min = minimum

0 = original

0 = at equilibrium

0 = in a vacuum

Chapter 1 Introduction

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A familiar item fabricated from three different material types is the beverage container. Beverages are marketed in aluminum (metal) cans (top), glass (ceramic) bottles (center), and plastic (polymer) bottles (bottom).

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Learning Objectives

After studying this chapter, you should be able to do the following:

1. **List six different property classifications of materials that determine their applicability.**
2. **Cite the four components that are involved in the design, production, and utilization of materials, and briefly describe the interrelationships between these components.**
3. **Cite three criteria that are important in the materials selection process.**
4. **(a) List the three primary classifications of solid materials, and then cite the distinctive chemical feature of each.**
   (b) Note the four types of advanced materials and, for each, its distinctive feature(s).
5. **(a) Briefly define *smart material/system*.**
   (b) Briefly explain the concept of *nanotechnology* as it applies to materials.

1.1 HISTORICAL PERSPECTIVE

Please take a few moments and reflect on what your life would be like without all of the materials that exist in our modern world. Believe it or not, without these materials we wouldn't have automobiles, cell phones, the internet, airplanes, nice homes and their furnishings, stylish clothes, nutritious (also "junk") food, refrigerators, televisions, computers . . . (and the list goes on). Virtually every segment of our everyday lives is influenced to one degree or another by materials. Without them our existence would be much like that of our Stone Age ancestors.

Historically, the development and advancement of societies have been intimately tied to the members' ability to produce and manipulate materials to fill their needs. In fact, early civilizations have been designated by the level of their materials development (Stone Age, Bronze Age, Iron Age).[1]

The earliest humans had access to only a very limited number of materials, those that occur naturally: stone, wood, clay, skins, and so on. With time, they discovered techniques for producing materials that had properties superior to those of the natural ones; these new materials included pottery and various metals. Furthermore, it was discovered that the properties of a material could be altered by heat treatments and by the addition of other substances. At this point, materials utilization was totally a selection process that involved deciding from a given, rather limited set of materials, the one best suited for an application by virtue of its characteristics. It was not until relatively recent times that scientists came to understand the relationships between the structural elements of materials and their properties. This knowledge, acquired over approximately the past 100 years, has empowered them to fashion, to a large degree, the characteristics of materials. Thus, tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society, including metals, plastics, glasses, and fibers.

The development of many technologies that make our existence so comfortable has been intimately associated with the accessibility of suitable materials. An advancement in the understanding of a material type is often the forerunner to the stepwise progression of a technology. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute. In the contemporary era, sophisticated electronic devices rely on components that are made from what are called *semiconducting materials*.

---

[1] The approximate dates for the beginnings of the Stone, Bronze, and Iron ages are 2.5 million BC, 3500 BC, and 1000 BC, respectively.

1.2 MATERIALS SCIENCE AND ENGINEERING

Sometimes it is useful to subdivide the discipline of materials science and engineering into *materials science* and *materials engineering* subdisciplines. Strictly speaking, materials science involves investigating the relationships that exist between the structures and properties of materials (i.e., why materials have their properties). In contrast, materials engineering involves, on the basis of these structure–property correlations, designing or engineering the structure of a material to produce a predetermined set of properties. From a functional perspective, the role of a materials scientist is to develop or synthesize new materials, whereas a materials engineer is called upon to create new products or systems using existing materials and/or to develop techniques for processing materials. Most graduates in materials programs are trained to be both materials scientists and materials engineers.

Structure is, at this point, a nebulous term that deserves some explanation. In brief, the structure of a material usually relates to the arrangement of its internal components. Structural elements may be classified on the basis of size and in this regard there are several levels:

- Subatomic structure—involves electrons within the individual atoms, their energies and interactions with the nuclei.
- Atomic structure—relates to the organization of atoms to yield molecules or crystals.
- Nanostructure—deals with aggregates of atoms that form particles (nanoparticles) that have nanoscale dimensions (less that about 100 nm).
- Microstructure—those structural elements that are subject to direct observation using some type of microscope (structural features having dimensions between 100 nm and several millimeters).
- Macrostructure—structural elements that may be viewed with the naked eye (with scale range between several millimeters and on the order of a meter).

Atomic structure, nanostructure, and microstructure of materials are investigated using microscopic techniques discussed in Section 4.10.

The notion of *property* deserves elaboration. While in service use, all materials are exposed to external stimuli that evoke some types of responses. For example, a specimen subjected to forces experiences deformation, or a polished metal surface reflects light. A property is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus. Generally, definitions of properties are made independent of material shape and size.

Virtually all important properties of solid materials may be grouped into six different categories: mechanical, electrical, thermal, magnetic, optical, and deteriorative. For each, there is a characteristic type of stimulus capable of provoking different responses. These are noted as follows:

- Mechanical properties—relate deformation to an applied load or force; examples include elastic modulus (stiffness), strength, and resistance to fracture.
- Electrical properties—the stimulus is an applied electric field; typical properties include electrical conductivity and dielectric constant.
- Thermal properties—are related to changes in temperature or temperature gradients across a material; examples of thermal behavior include thermal expansion and heat capacity.
- Magnetic properties—the responses of a material to the application of a magnetic field; common magnetic properties include magnetic susceptibility and magnetization.
- Optical properties—the stimulus is electromagnetic or light radiation; index of refraction and reflectivity are representative optical properties.

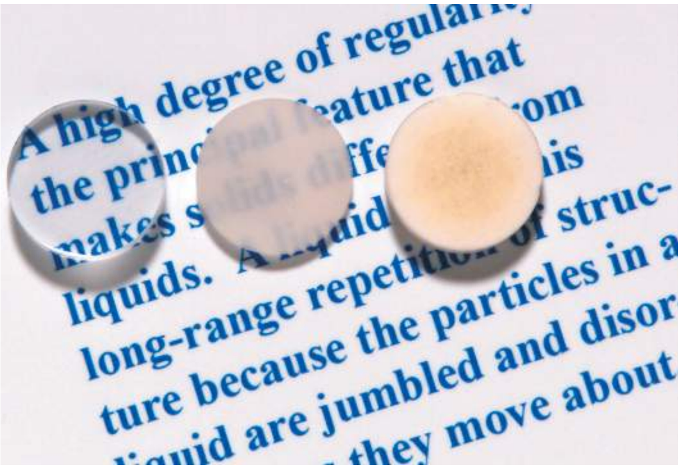

Figure 1.1 Three thin disk specimens of aluminum oxide that have been placed over a printed page in order to demonstrate their differences in light-transmittance characteristics. The disk on the left is *transparent* (i.e., virtually all light that is reflected from the page passes through it), whereas the one in the center is *translucent* (meaning that some of this reflected light is transmitted through the disk). The disk on the right is *opaque*—that is, none of the light passes through it. These differences in optical properties are a consequence of differences in structure of these materials, which have resulted from the way the materials were processed.

William D. Callister Jr./ Specimen preparation, P.A. Lessing

- Deteriorative characteristics—relate to the chemical reactivity of materials; for example, corrosion resistance of metals.

The chapters that follow discuss properties that fall within each of these six classifications.

In addition to structure and properties, two other important components are involved in the science and engineering of materials—namely, *processing* and *performance*. With regard to the relationships of these four components, the structure of a material depends on how it is processed. Furthermore, a material's performance is a function of its properties.

We present an example of these processing-structure-properties-performance principles in Figure 1.1, a photograph showing three thin disk specimens placed over some printed matter. It is obvious that the optical properties (i.e., the light transmittance) of each of the three materials are different; the one on the left is transparent (i.e., virtually all of the reflected light from the printed page passes through it), whereas the disks in the center and on the right are, respectively, translucent and opaque. All of these specimens are of the same material, aluminum oxide, but the leftmost one is what we call a *single crystal*—that is, has a high degree of perfection—which gives rise to its transparency. The center one is composed of numerous and very small single crystals that are all connected; the boundaries between these small crystals scatter a portion of the light reflected from the printed page, which makes this material optically translucent. Finally, the specimen on the right is composed not only of many small, interconnected crystals, but also of a large number of very small pores or void spaces. These pores scatter the reflected light to a greater degree than the crystal boundaries and render this material opaque. Thus, the structures of these three specimens are different in terms of crystal boundaries and pores, which affect the optical transmittance properties. Furthermore, each material was produced using a different processing technique. If optical transmittance is an important parameter relative to the ultimate in-service application, the performance of each material will be different.

This interrelationship among processing, structure, properties, and performance of materials may be depicted in linear fashion as in the schematic illustration shown in Figure 1.2. The model represented by this diagram has been called by some the *central paradigm of materials science and engineering* or sometimes just the *materials paradigm*. (The term "paradigm" means a model or set of ideas.) This paradigm, formulated in the 1990s is, in essence, the core of the discipline of materials science and engineering. It describes the protocol for selecting and designing materials for specific and well-defined

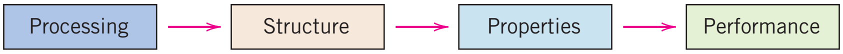

Figure 1.2 The four components of the discipline of materials science and engineering and their interrelationship.

applications, and has had a profound influence on the field of materials.[2] Previous to this time the materials science/engineering approach was to design components and systems using the existing palette of materials. The significance of this new paradigm is reflected in the following quotation: ". . . whenever a material is being created, developed, or produced, the properties or phenomena the material exhibits are of central concern. Experience shows that the properties and phenomena associated with a material are intimately related to its composition and structure at all levels, including which atoms are present and how the atoms are arranged in the material, and that this structure is the result of synthesis and processing."[3]

Throughout this text, we draw attention to the relationships among these four components in terms of the design, production, and utilization of materials.

1.3 WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

Why do engineers and scientists study materials? Simply, because things engineers design are made of materials. Many an applied scientist or engineer (e.g., mechanical, civil, chemical, electrical), is at one time or another exposed to a design problem involving materials—for example, a transmission gear, the superstructure for a building, an oil refinery component, or an integrated circuit chip. Of course, materials scientists and engineers are specialists who are totally involved in the investigation and design of materials.

Many times, an engineer has the option of selecting a best material from the thousands available. The final decision is normally based on several criteria. First, the in-service conditions must be characterized, for these dictate the properties required of the material. Only on rare occasions does a material possess the optimum or ideal combination of properties. Thus, it may be necessary to trade one characteristic for another. The classic example involves strength and ductility; normally, a material having a high strength has only a limited ductility. In such cases, a reasonable compromise between two or more properties may be necessary.

A second selection consideration is any deterioration of material properties that may occur during service operation. For example, significant reductions in mechanical strength may result from exposure to elevated temperatures or corrosive environments.

Finally, probably the overriding consideration is that of economics: What will the finished product cost? A material may be found that has the optimum set of properties but is prohibitively expensive. Here again, some compromise is inevitable. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired shape.

The more familiar an engineer or scientist is with the various characteristics and structure–property relationships, as well as the processing techniques of materials, the more proficient and confident he or she will be in making judicious materials choices based on these criteria.

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[2] This paradigm has recently been updated to include the component of material sustainability in the "Modified Paradigm of Materials Science and Engineering," as represented by the following diagram:

Processing → Structure → Properties → Performance → Reuse/Recyclability

[3] "*Materials Science and Engineering for the 1990s*," p. 27, National Academies Press, Washington, DC, 1998.

CASE STUDY 1.1

Liberty Ship Failures

The following case study illustrates one role that materials scientists and engineers are called upon to assume in the area of materials performance: analyze mechanical failures, determine their causes, and then propose appropriate measures to guard against future incidents.

The failure of many of the World War II Liberty ships[4] is a well-known and dramatic example of the brittle fracture of steel that was thought to be ductile.[5] Some of the early ships experienced structural damage when cracks developed in their decks and hulls. Three of them catastrophically split in half when cracks formed, grew to critical lengths, and then rapidly propagated completely around the ships' girths. Figure 1.3 shows one of the ships that fractured the day after it was launched.

Subsequent investigations concluded one or more of the following factors contributed to each failure:[6]

- When some normally ductile metal alloys are cooled to relatively low temperatures, they become susceptible to brittle fracture—that is, they experience a ductile-to-brittle transition upon cooling through a critical range of temperatures.

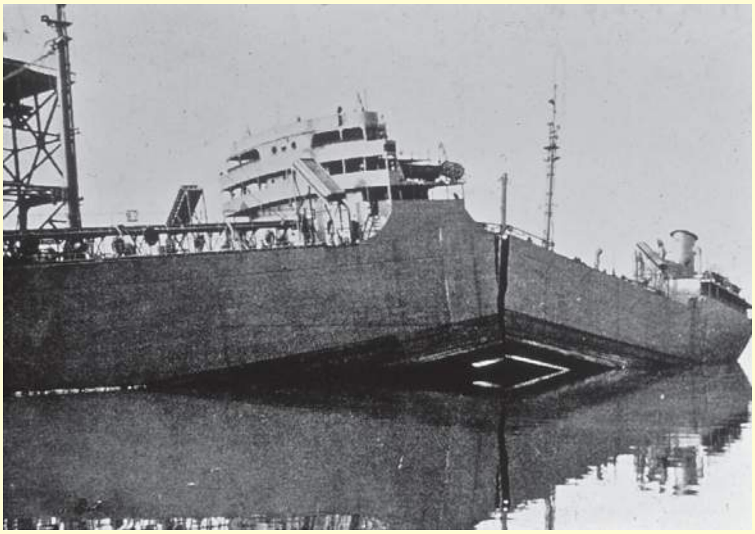

Figure 1.3 The Liberty ship *S.S. Schenectady,* which, in 1943, failed before leaving the shipyard.
(Reprinted with permission of Earl R. Parker, *Brittle Behavior of Engineering Structures,* National Academy of Sciences, National Research Council, John Wiley & Sons, New York, 1957.)

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[4] During World War II, 2,710 Liberty cargo ships were mass-produced by the United States to supply food and materials to the combatants in Europe.

[5] Ductile metals fail after relatively large degrees of permanent deformation; however, very little if any permanent deformation accompanies the fracture of brittle materials. Brittle fractures can occur very suddenly as cracks spread rapidly; crack propagation is normally much slower in ductile materials, and the eventual fracture takes longer. For these reasons, the ductile mode of fracture is usually preferred. Ductile and brittle fractures are discussed in Sections 8.3 and 8.4.

[6] Sections 8.2 through 8.6 discuss various aspects of failure.

These Liberty ships were constructed of steel that experienced a ductile-to-brittle transition. Some of them were deployed to the frigid North Atlantic, where the once ductile metal experienced brittle fracture when temperatures dropped to below the transition temperature.[7]

- The corner of each hatch (i.e., door) was square; these corners acted as points of stress concentration where cracks can form.
- German U-boats were sinking cargo ships faster than they could be replaced using existing construction techniques. Consequently, it became necessary to revolutionize construction methods to build cargo ships faster and in greater numbers. This was accomplished using prefabricated steel sheets that were assembled by welding rather than by the traditional time-consuming riveting. Unfortunately, cracks in welded structures may propagate unimpeded for large distances, which can lead to catastrophic failure. However, when structures are riveted, a crack ceases to propagate once it reaches the edge of a steel sheet.
- Weld defects and *discontinuities* (i.e., sites where cracks can form) were introduced by inexperienced operators.

Remedial measures taken to correct these problems included the following:

- Lowering the ductile-to-brittle temperature of the steel to an acceptable level by improving steel quality (e.g., reducing sulfur and phosphorus impurity contents).
- Rounding off hatch corners by welding a curved reinforcement strip on each corner.[8]
- Installing crack-arresting devices such as riveted straps and strong weld seams to stop propagating cracks.
- Improving welding practices and establishing welding codes.

In spite of these failures, the Liberty ship program was considered a success for several reasons, the primary reason being that ships that survived failure were able to supply Allied Forces in the theater of operations and in all likelihood shortened the war. In addition, structural steels were developed with vastly improved resistances to catastrophic brittle fractures. Detailed analyses of these failures advanced the understanding of crack formation and growth, which ultimately evolved into the discipline of fracture mechanics.

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[7] This ductile-to-brittle transition phenomenon, as well as techniques that are used to measure and raise the critical temperature range, are discussed in Section 8.6.

[8] The reader may note that corners of windows and doors for all of today's marine and aircraft structures are rounded.

1.4 CLASSIFICATION OF MATERIALS

Solid materials have been conveniently grouped into three basic categories: metals, ceramics, and polymers, a scheme based primarily on chemical makeup and atomic structure. Most materials fall into one distinct grouping or another. In addition, there are the composites that are engineered combinations of two or more different materials. A brief explanation of these material classifications and representative characteristics is offered next. Another category is advanced materials—those used in high-technology applications, such as semiconductors, biomaterials, smart materials, and nanoengineered materials; these are discussed in Section 1.5.

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Tutorial Video: What Are the Different Classes of Materials?

Metals

Metals are composed of one or more metallic elements (e.g., iron, aluminum, copper, titanium, gold, nickel), and often also nonmetallic elements (e.g., carbon, nitrogen, oxygen) in relatively small amounts.[9] Atoms in metals and their alloys are arranged in a

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[9] The term *metal alloy* refers to a metallic substance that is composed of two or more elements.

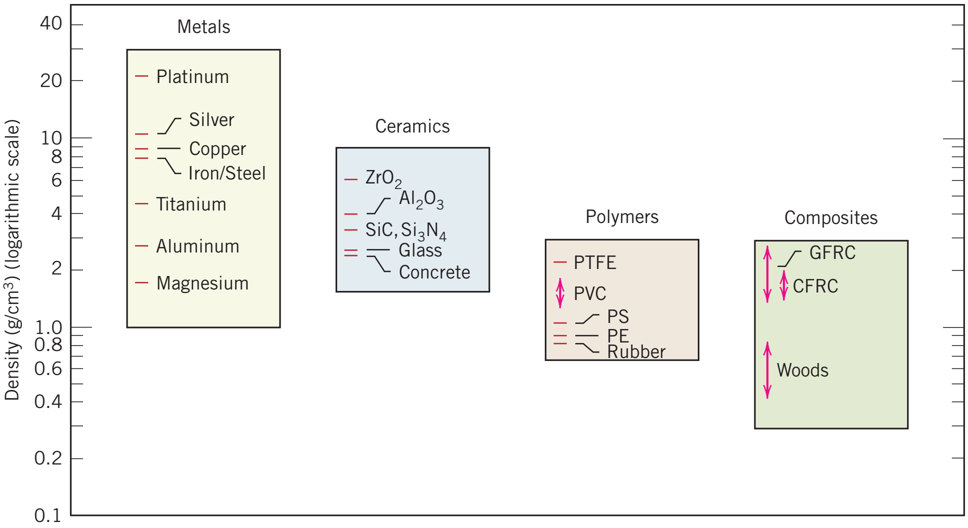

Figure 1.4 Bar chart of room-temperature density values for various metals, ceramics, polymers, and composite materials.

very orderly manner (as discussed in Chapter 3) and are relatively dense in comparison to the ceramics and polymers (Figure 1.4). With regard to mechanical characteristics, these materials are relatively stiff (Figure 1.5) and strong (Figure 1.6), yet are ductile (i.e., capable of large amounts of deformation without fracture), and are resistant to fracture (Figure 1.7), which accounts for their widespread use in structural applications. Metallic materials have large numbers of nonlocalized electrons—that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. For example, metals are extremely good conductors of electricity (Figure 1.8) and heat, and are not transparent to visible light; a polished metal surface has a lustrous appearance. In addition, some of the metals (i.e., Fe, Co, and Ni) have desirable magnetic properties.

WileyPLUS

Tutorial Video: Metals

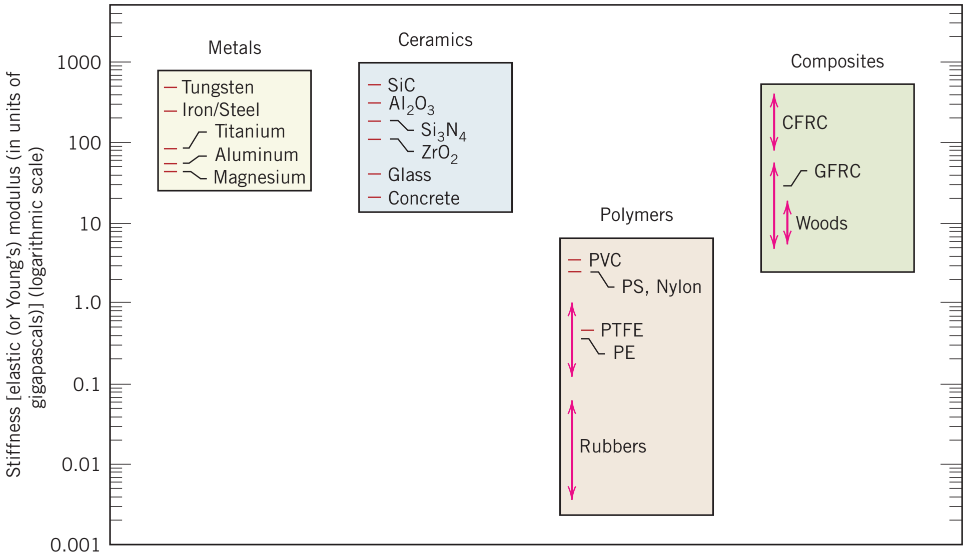

Figure 1.5 Bar chart of room-temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.

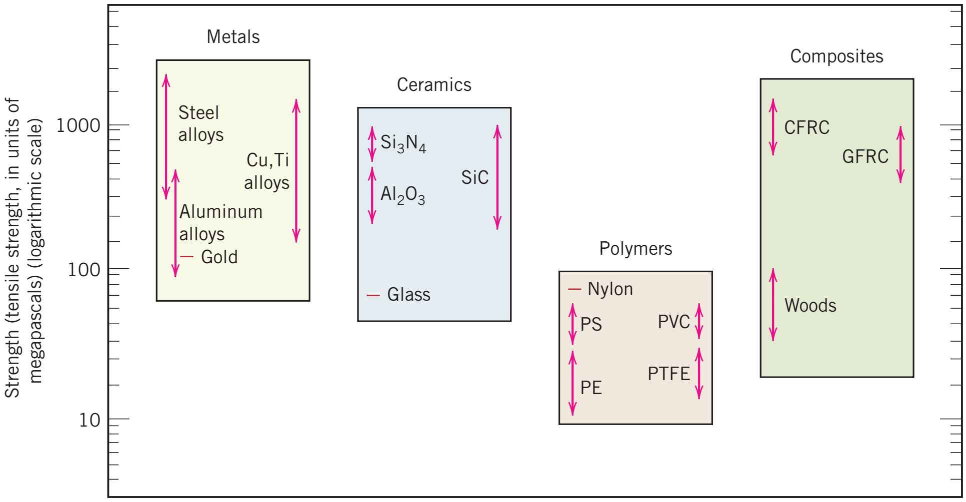

Figure 1.6 Bar chart of room-temperature strength (i.e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

Figure 1.9 shows several common and familiar objects that are made of metallic materials. Furthermore, the types and applications of metals and their alloys are discussed in Chapter 11.

Ceramics

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Tutorial Video: Ceramics

Ceramics are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, common ceramic materials include aluminum oxide (or *alumina,* Al_2O_3), silicon dioxide (or *silica,* SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and, in addition, what some refer to as the *traditional ceramics*—those composed of clay minerals (e.g., porcelain), as well as cement and glass. With regard to mechanical behavior, ceramic materials are relatively stiff and strong—stiffnesses and strengths are comparable to those of the metals (Figures 1.5 and 1.6). In addition, they are typically very hard. Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are highly susceptible to fracture (Figure 1.7). However, newer ceramics are being engineered to have improved resistance to fracture; these materials are used for cookware, cutlery, and even automobile engine parts. Furthermore, ceramic materials are typically insulative to the

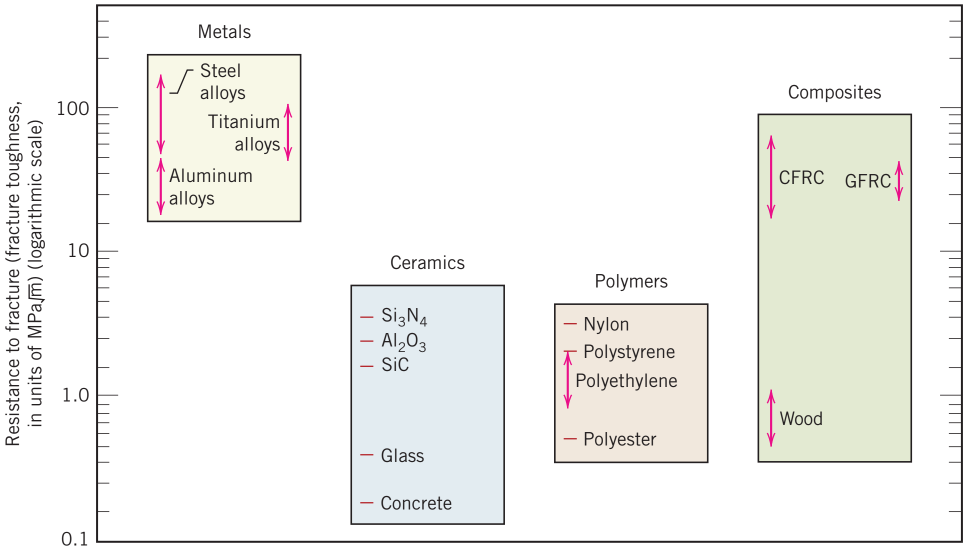

Figure 1.7 Bar chart of room-temperature resistance to fracture (i.e., fracture toughness) for various metals, ceramics, polymers, and composite materials. (Reprinted from *Engineering Materials 1: An Introduction to Properties, Applications and Design,* third edition, M. F. Ashby and D. R. H. Jones, pages 177 and 178. Copyright 2005, with permission from Elsevier.)