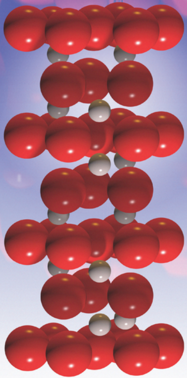
FUNDAMENTALS
OF MATERIALS SCIENCE AND ENGINEERING
AN INTEGRATED APPROACH

FIFTH EDITION



WILLIAM D. CALLISTER, JR. • DAVID G. RETHWISCH

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Characteristics of Selected Elements

Element	*Symbol*	*Atomic Number*	*Atomic Weight (amu)*	*Density of Solid, 20°C (g/cm³)*	*Crystal Structure,[a] 20°C*	*Atomic Radius (nm)*	*Ionic Radius (nm)*	*Most Common Valence*	*Melting Point (°C)*
Aluminum	Al	13	26.98	2.71	FCC	0.143	0.053	3+	660.4
Argon	Ar	18	39.95	—	—	—	—	Inert	−189.2
Barium	Ba	56	137.33	3.5	BCC	0.217	0.136	2+	725
Beryllium	Be	4	9.012	1.85	HCP	0.114	0.035	2+	1278
Boron	B	5	10.81	2.34	Rhomb.	—	0.023	3+	2300
Bromine	Br	35	79.90	—	—	—	0.196	1−	−7.2
Cadmium	Cd	48	112.41	8.65	HCP	0.149	0.095	2+	321
Calcium	Ca	20	40.08	1.55	FCC	0.197	0.100	2+	839
Carbon	C	6	12.011	2.25	Hex.	0.071	~0.016	4+	(sublimes at 3367)
Cesium	Cs	55	132.91	1.87	BCC	0.265	0.170	1+	28.4
Chlorine	Cl	17	35.45	—	—	—	0.181	1−	−101
Chromium	Cr	24	52.00	7.19	BCC	0.125	0.063	3+	1875
Cobalt	Co	27	58.93	8.9	HCP	0.125	0.072	2+	1495
Copper	Cu	29	63.55	8.94	FCC	0.128	0.096	1+	1085
Fluorine	F	9	19.00	—	—	—	0.133	1−	−220
Gallium	Ga	31	69.72	5.90	Ortho.	0.122	0.062	3+	29.8
Germanium	Ge	32	72.64	5.32	Dia. cubic	0.122	0.053	4+	937
Gold	Au	79	196.97	19.32	FCC	0.144	0.137	1+	1064
Helium	He	2	4.003	—	—	—	—	Inert	−272 (at 26 atm)
Hydrogen	H	1	1.008	—	—	—	0.154	1+	−259
Iodine	I	53	126.91	4.93	Ortho.	0.136	0.220	1−	114
Iron	Fe	26	55.85	7.87	BCC	0.124	0.077	2+	1538
Lead	Pb	82	207.2	11.35	FCC	0.175	0.120	2+	327
Lithium	Li	3	6.94	0.534	BCC	0.152	0.068	1+	181
Magnesium	Mg	12	24.31	1.74	HCP	0.160	0.072	2+	649
Manganese	Mn	25	54.94	7.44	Cubic	0.112	0.067	2+	1244
Mercury	Hg	80	200.59	—	—	—	0.110	2+	−38.8
Molybdenum	Mo	42	95.94	10.22	BCC	0.136	0.070	4+	2617
Neon	Ne	10	20.18	—	—	—	—	Inert	−248.7
Nickel	Ni	28	58.69	8.90	FCC	0.125	0.069	2+	1455
Niobium	Nb	41	92.91	8.57	BCC	0.143	0.069	5+	2468
Nitrogen	N	7	14.007	—	—	—	0.01–0.02	5+	−209.9
Oxygen	O	8	16.00	—	—	—	0.140	2−	−218.4
Phosphorus	P	15	30.97	1.82	Ortho.	0.109	0.035	5+	44.1
Platinum	Pt	78	195.08	21.45	FCC	0.139	0.080	2+	1772
Potassium	K	19	39.10	0.862	BCC	0.231	0.138	1+	63
Silicon	Si	14	28.09	2.33	Dia. cubic	0.118	0.040	4+	1410
Silver	Ag	47	107.87	10.49	FCC	0.144	0.126	1+	962
Sodium	Na	11	22.99	0.971	BCC	0.186	0.102	1+	98
Sulfur	S	16	32.06	2.07	Ortho.	0.106	0.184	2−	113
Tin	Sn	50	118.71	7.27	Tetra.	0.151	0.071	4+	232
Titanium	Ti	22	47.87	4.51	HCP	0.145	0.068	4+	1668
Tungsten	W	74	183.84	19.3	BCC	0.137	0.070	4+	3410
Vanadium	V	23	50.94	6.1	BCC	0.132	0.059	5+	1890
Zinc	Zn	30	65.41	7.13	HCP	0.133	0.074	2+	420
Zirconium	Zr	40	91.22	6.51	HCP	0.159	0.079	4+	1852

[a]Dia. = Diamond; Hex. = Hexagonal; Ortho. = Orthorhombic; Rhomb. = Rhombohedral; Tetra. = Tetragonal.

Values of Selected Physical Constants

Quantity	*Symbol*	*SI Units*	*cgs Units*
Avogadro's number	N_A	6.022×10^{23} molecules/mol	6.022×10^{23} molecules/mol
Boltzmann's constant	k	1.38×10^{-23} J/atom·K	1.38×10^{-16} erg/atom·K 8.62×10^{-5} eV/atom·K
Bohr magneton	μ_B	9.27×10^{-24} A·m^2	9.27×10^{-21} erg/gauss[a]
Electron charge	e	1.602×10^{-19} C	4.8×10^{-10} statcoul[b]
Electron mass	—	9.11×10^{-31} kg	9.11×10^{-28} g
Gas constant	R	8.31 J/mol·K	1.987 cal/mol·K
Permeability of a vacuum	μ_0	1.257×10^{-6} henry/m	Unity[a]
Permittivity of a vacuum	ε_0	8.85×10^{-12} farad/m	Unity[b]
Planck's constant	h	6.63×10^{-34} J·s	6.63×10^{-27} erg·s 4.13×10^{-15} eV·s
Velocity of light in a vacuum	c	3×10^{8} m/s	3×10^{10} cm/s

[a] In cgs-emu units.

[b] In cgs-esu units.

Unit Abbreviations

A = ampere	in. = inch	N = newton
Å = angstrom	J = joule	nm = nanometer
Btu = British thermal unit	K = degrees Kelvin	P = poise
C = Coulomb	kg = kilogram	Pa = Pascal
°C = degrees Celsius	lb_f = pound force	s = second
cal = calorie (gram)	lb_m = pound mass	T = temperature
cm = centimeter	m = meter	μm = micrometer (micron)
eV = electron volt	Mg = megagram	W = watt
°F = degrees Fahrenheit	mm = millimeter	psi = pounds per square inch
ft = foot	mol = mole	
g = gram	MPa = megapascal	

SI Multiple and Submultiple Prefixes

Factor by Which Multiplied	*Prefix*	*Symbol*
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi[a]	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

[a] Avoided when possible.

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WileyPLUS is a research-based online environment for effective teaching and learning.

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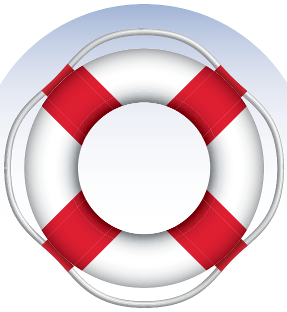

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Fundamentals of Materials Science and Engineering

An Integrated Approach

5th Edition

Fundamentals of Materials Science and Engineering

AN INTEGRATED APPROACH

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WILEY

Front Cover: Depiction of a unit cell for α-aluminum oxide (Al_2O_3). Red and gray spheres represent oxygen and aluminum ions, respectively.
Back Cover: (Top) Representation of a unit cell for iron sulfide (FeS). Yellow and brown spheres denote, respectively, sulfur and iron atoms. (Bottom) Depiction of a unit cell for wurtzite, which is the mineralogical name for one form of zinc sulfide (ZnS). Sulfur and zinc atoms are represented by yellow and blue spheres, respectively.

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This book was set in Times Ten LT Std Roman 9.5/11.5 by Aptara, Inc., and printed and bound by Quad Graphics/Versailles. The cover was printed by Quad Graphics/Versailles.

This book is printed on acid-free paper. ∞

ISBN 978-1-119-17548-3

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Dedicated to
Wayne Anderson
Former editor and mentor

Preface

In this fifth 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 who have completed their freshmen calculus, chemistry, and physics courses.
- Present the subject matter in a logical order, from the simple to the more complex. Each chapter builds on the content of previous ones.
- 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; in addition, in most cases, some practical relevance is provided.
- Inclusion of features in the book that expedite the learning process, to include the following: photographs/illustrations (some in full color); learning objectives; "Why Study . . ." and "Materials of Importance" items (to provide relevance); "Concept Check" questions (to test conceptual understanding); end-of-chapter questions and problems (to develop understanding of concepts and problem-solving skills); end-of-book Answers to Selected Problems (to check accuracy of work); end-of-chapter 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:

- Two new case studies: "Liberty Ship Failures" (Chapter 1) and "Use of Composites in the Boeing 787 Dreamliner" (Chapter 15)
- Bond hybridization in carbon (Chapter 2)
- Revision of discussions on crystallographic planes and directions to include the use of equations for the determination of planar and directional indices (Chapter 3)
- Revised discussion on determination of grain size (Chapter 5)
- New section on the structure of carbon fibers (Chapter 13)
- Revised/expanded discussions on structures, properties, and applications of the nanocarbons: fullerenes, carbon nanotubes, and graphene; also on ceramic refractories and abrasives (Chapter 13)

- Revised/expanded discussion on structural composites: laminar composites and sandwich panels (Chapter 15)
- New section on structure, properties, and applications of nanocomposite materials (Chapter 15)
- Revised/expanded discussion on recycling issues in materials science and engineering (Chapter 20)
- Numerous new and revised example problems. In addition, all homework problems requiring computations have been refreshed.

ONLINE RESOURCES

Associated with the textbook are a number of 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*?

- ***The complete digital textbook*** that saves students up to 60% of the cost of the in-print text.
- ***Direct access to online self-assessment exercises.*** This is a web-based assessment program that contains questions and problems similar to those found in the text; these problems/questions are organized and labeled according to textbook sections. An answer/solution that is entered by the user in response to a question/problem is graded immediately, and comments are offered for incorrect responses. The student may use this electronic resource to review course material, and to assess his/her mastery and understanding of topics covered in the text.
- ***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.
- ***"Muddiest Point" Tutorial Videos.*** These videos (narrated by a student) help students with concepts that are difficult to understand and with solving troublesome problems.
- ***Answers to Concept Check questions.*** Students can visit the web site to find the correct answers to the Concept Check questions posed in the print textbook.

What do instructors receive with *WileyPLUS*?

- The ability to effectively and efficiently personalize and manage their course.
- The ability to track student performance and progress, and easily identify those who are falling behind.
- The ability to assign algorithmic problems with computer generated values that can vary from student to student, encouraging the student to develop problem-solving skills rather than simply reporting results found in a web search.

STUDENT COMPANION SITE (www.wiley.com/college/callister)

Posted on the Student Companion site are several important instructional elements that complement the text; these include the following:

- **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.
- **Mechanical Engineering (ME) Module.** This module treats materials science/engineering topics not covered in the printed text that are relevant to mechanical engineering.
- **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.
- **Student Lecture PowerPoint® Slides.** These slides (in both Adobe Acrobat® PDF and PowerPoint® 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.

INSTRUCTOR COMPANION SITE (www.wiley.com/college/callister)

The Instructor Companion Site is available for instructors who have adopted this text. Please visit the website to register for access. Resources that are available include the following:

- **All resources found on the Student Companion Site.**
- **Instructor Solutions Manual.** Detailed solutions for all end-of-chapter questions and problems (in both Word® and Adobe Acrobat® PDF formats).
- **Homework Problem Correlation Guide—4th edition to 5th edition.** This guide notes, for each homework problem or question (by number), whether it appeared in the fourth edition and, if so, its number in this previous edition.
- **Image Gallery.** Illustrations from the book. Instructors can use them in assignments, tests, or other exercises they create for students.
- **Art PowerPoint Slides.** Book art loaded into PowerPoints, so instructors can more easily use them to create their own PowerPoint Slides.
- **Lecture Note PowerPoints.** These slides, developed by the authors and Peter M. Anderson (The Ohio State University), follow the flow of topics in the text, and

include materials taken from the text as well as other sources. Slides are available in both Adobe Acrobat® PDF and PowerPoint® formats. [*Note:* If an instructor doesn't have available all fonts used by the developer, special characters may not be displayed correctly in the PowerPoint version (i.e., it is not possible to embed fonts in PowerPoints); however, in the PDF version, these characters will appear correctly.]

- **Solutions to Case Study Problems.**
- **Solutions to Problems in the Mechanical Engineering Web Module.**
- **Suggested Course Syllabi for the Various Engineering Disciplines.** Instructors may consult these syllabi for guidance in course/lecture organization and planning.
- **Experiments and Classroom Demonstrations.** Instructions and outlines for experiments and classroom demonstrations that portray phenomena and/or illustrate principles that are discussed in the book; references are also provided that give more detailed accounts of these demonstrations.

Feedback

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

ACKNOWLEDGMENTS

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.

We express our appreciation to those who have made contributions to this edition. We are especially indebted to the following:

Audrey Butler of The University of Iowa, and Bethany Smith and Stephen Krause of Arizona State University, for helping to develop material in the WileyPLUS course.

Grant Head for his expert programming skills, which he used in developing the *Virtual Materials Science and Engineering* software.

Eric Hellstrom and Theo Siegrist of Florida State University, as well as Norman E. Dowling and Maureen Julian of Virginia Tech for their feedback and suggestions for this edition.

We are also indebted to Dan Sayre and Linda Ratts, Executive Editors, Jennifer Welter, Senior Product Designer, and Wendy Ashenberg, Associate Product Designer, for their guidance and assistance on this revision.

Last, but certainly not least, we deeply and sincerely appreciate the continual encouragement and support of our families and friends.

William D. Callister, Jr.

David G. Rethwisch

October 2015

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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 (9.5)
at% = atom percent (5.6)
B = magnetic flux density (induction) (18.2)
B_r = magnetic remanence (18.7)
BCC = body-centered cubic crystal structure (3.4)
b = lattice parameter: unit cell y-axial length (3.11)
b = Burgers vector (5.7)
C = capacitance (12.18)
C_i = concentration (composition) of component i in wt% (5.6)
C'_i = concentration (composition) of component i in at% (5.6)
C_v, C_p = heat capacity at constant volume, pressure (17.2)
CPR = corrosion penetration rate (16.3)
CVN = Charpy V-notch (9.8)
%CW = percent cold work (8.11)
c = lattice parameter: unit cell z-axial length (3.11)
c_v, c_p = specific heat at constant volume, pressure (17.2)
D = diffusion coefficient (6.3)
D = dielectric displacement (12.19)
DP = degree of polymerization (4.5)
d = diameter
d = average grain diameter (8.9)
d_{hkl} = interplanar spacing for planes of Miller indices h, k, and l (3.20)
E = energy (2.5)
E = modulus of elasticity or Young's modulus (7.3)
$\mathscr{E}$ = electric field intensity (12.3)
E_f = Fermi energy (12.5)
E_g = band gap energy (12.6)
$E_r(t)$ = relaxation modulus (7.15)
%EL = ductility, in percent elongation (7.6)
e = electric charge per electron (12.7)
e^- = electron (16.2)
erf = Gaussian error function (6.4)
exp = e, the base for natural logarithms
F = force, interatomic or mechanical (2.5, 7.2)
$\mathscr{F}$ = Faraday constant (16.2)
FCC = face-centered cubic crystal structure (3.4)
G = shear modulus (7.3)
H = magnetic field strength (18.2)
H_c = magnetic coercivity (18.7)
HB = Brinell hardness (7.16)
HCP = hexagonal close-packed crystal structure (3.4)
HK = Knoop hardness (7.16)
HRB, HRF = Rockwell hardness: B and F scales (7.16)
HR15N, HR45W = superficial Rockwell hardness: 15N and 45W scales (7.16)
HV = Vickers hardness (7.16)
h = Planck's constant (19.2)
(hkl) = Miller indices for a crystallographic plane (3.14)
I = electric current (12.2)
I = intensity of electromagnetic radiation (19.3)
i = current density (16.3)
i_C = corrosion current density (16.4)

J = diffusion flux (6.3)
J = electric current density (12.3)
K_c = fracture toughness (9.5)
K_{Ic} = plane strain fracture toughness for mode I crack surface displacement (9.5)
k = Boltzmann's constant (5.2)
k = thermal conductivity (17.4)
l = length
l_c = critical fiber length (15.4)
ln = natural logarithm
log = logarithm taken to base 10
M = magnetization (18.2)
$\overline{M}_n$ = polymer number-average molecular weight (4.5)
$\overline{M}_w$ = polymer weight-average molecular weight (4.5)
mol% = mole percent
N = number of fatigue cycles (9.10)
N_A = Avogadro's number (3.5)
N_f = fatigue life (9.10)
n = principal quantum number (2.3)
n = number of atoms per unit cell (3.5)
n = strain-hardening exponent (7.7)
n = number of electrons in an electrochemical reaction (16.2)
n = number of conducting electrons per cubic meter (12.7)
n = index of refraction (19.5)
n' = for ceramics, the number of formula units per unit cell (3.7)
n_i = intrinsic carrier (electron and hole) concentration (12.10)
P = dielectric polarization (12.19)
P–B ratio = Pilling–Bedworth ratio (16.10)
p = number of holes per cubic meter (12.10)
Q = activation energy
Q = magnitude of charge stored (12.18)
R = atomic radius (3.4)
R = gas constant
%RA = ductility, in percent reduction in area (7.6)
r = interatomic distance (2.5)
r = reaction rate (16.3)
r_A, r_C = anion and cation ionic radii (3.6)
S = fatigue stress amplitude (9.10)
SEM = scanning electron microscopy or microscope
T = temperature
T_c = Curie temperature (18.6)
T_C = superconducting critical temperature (18.12)
T_g = glass transition temperature (11.15)
T_m = melting temperature
TEM = transmission electron microscopy or microscope
TS = tensile strength (7.6)
t = time
t_r = rupture lifetime (9.15)
U_r = modulus of resilience (7.6)
$[uvw]$ = indices for a crystallographic direction (3.13)
V = electrical potential difference (voltage) (12.2)
V_C = unit cell volume (3.4)
V_C = corrosion potential (16.4)
V_H = Hall voltage (12.14)
V_i = volume fraction of phase i (10.8)
v = velocity
vol% = volume percent
W_i = mass fraction of phase i (10.8)
wt% = weight percent (5.6)
x = length
x = space coordinate
Y = dimensionless parameter or function in fracture toughness expression (9.5)
y = space coordinate
z = space coordinate
α = lattice parameter: unit cell y–z interaxial angle (3.11)
α, β, γ = phase designations
α_l = linear coefficient of thermal expansion (17.3)
β = lattice parameter: unit cell x–z interaxial angle (3.11)
γ = lattice parameter: unit cell x–y interaxial angle (3.11)
γ = shear strain (7.2)
Δ = precedes the symbol of a parameter to denote finite change
ε = engineering strain (7.2)
ε = dielectric permittivity (12.18)
ε_r = dielectric constant or relative permittivity (12.18)
$\dot{\varepsilon}_s$ = steady-state creep rate (9.16)
ε_T = true strain (7.7)
η = viscosity (8.16)
η = overvoltage (16.4)
θ = Bragg diffraction angle (3.20)
θ_D = Debye temperature (17.2)
λ = wavelength of electromagnetic radiation (3.20)
μ = magnetic permeability (18.2)
μ_B = Bohr magneton (18.2)
μ_r = relative magnetic permeability (18.2)
μ_e = electron mobility (12.7)
μ_h = hole mobility (12.10)
ν = Poisson's ratio (7.5)
ν = frequency of electromagnetic radiation (19.2)
ρ = density (3.5)
ρ = electrical resistivity (12.2)

ρ_t = radius of curvature at the tip of a crack (9.5)
σ = engineering stress, tensile or compressive (7.2)
σ = electrical conductivity (12.3)
σ^* = longitudinal strength (composite) (15.5)
σ_c = critical stress for crack propagation (9.5)
σ_{fs} = flexural strength (7.10)
σ_m = maximum stress (9.5)
σ_m = mean stress (9.9)
σ'_m = stress in matrix at composite failure (15.5)
σ_T = true stress (7.7)
σ_w = safe or working stress (7.20)
σ_y = yield strength (7.6)
τ = shear stress (7.2)
τ_c = fiber–matrix bond strength/matrix shear yield strength (15.4)
τ_{crss} = critical resolved shear stress (8.6)
χ_m = magnetic susceptibility (18.2)

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

Materials are probably more deep seated in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, and food production—virtually every segment of our everyday lives is influenced to one degree or another by materials. 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*.

1.2 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

[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.

properties of materials. 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.[2] 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. *Subatomic structure* involves electrons within the individual atoms and interactions with their nuclei. On an atomic level, structure encompasses the organization of atoms or molecules relative to one another. The next larger structural realm, which contains large groups of atoms that are normally agglomerated together, is termed *microscopic,* meaning that which is subject to direct observation using some type of microscope. Finally, structural elements that can be viewed with the naked eye are termed *macroscopic*.

The notion of *property* deserves elaboration. While in service use, all materials are exposed to external stimuli that evoke some type of response. 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. Mechanical properties relate deformation to an applied load or force; examples include elastic modulus (stiffness), strength, and toughness. For electrical properties, such as electrical conductivity and dielectric constant, the stimulus is an electric field. The thermal behavior of solids can be represented in terms of heat capacity and thermal conductivity. Magnetic properties demonstrate the response of a material to the application of a magnetic field. For optical properties, the stimulus is electromagnetic or light radiation; index of refraction and reflectivity are representative optical properties. Finally, deteriorative characteristics relate to the chemical reactivity of materials. 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. Thus, the interrelationship between processing, structure, properties, and performance is as depicted in the schematic illustration shown in Figure 1.1. Throughout this text, we draw attention to the relationships among these four components in terms of the design, production, and utilization of materials.

We present an example of these processing-structure-properties-performance principles in Figure 1.2, 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

Figure 1.1 The four components of the discipline of materials science and engineering and their interrelationship.

[2] Throughout this text we draw attention to the relationships between material properties and structural elements.

Figure 1.2 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.

Specimen preparation, P. A. Lessing.

all of the reflected light 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 also effectively scatter the reflected light 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.

1.3 WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

Why do we study materials? Many an applied scientist or engineer, whether mechanical, civil, chemical, or electrical, is at one time or another exposed to a design problem involving materials, such as 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, a materials problem is one of selecting the right material from the thousands available. The final decision is normally based on several criteria. First of all, the in-service conditions must be characterized, for these dictate the properties required of the material. On only rare occasions does a material possess the maximum 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 ideal 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.

CASE STUDY

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[3] is a well-known and dramatic example of the brittle fracture of steel that was thought to be ductile.[4] 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[5]:

- 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. 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.[6]
- 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.

[3]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.

[4]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 9.3 and 9.4.

[5]Sections 9.2 through 9.5 discuss various aspects of failure.

[6]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 9.8.

(*continued*)

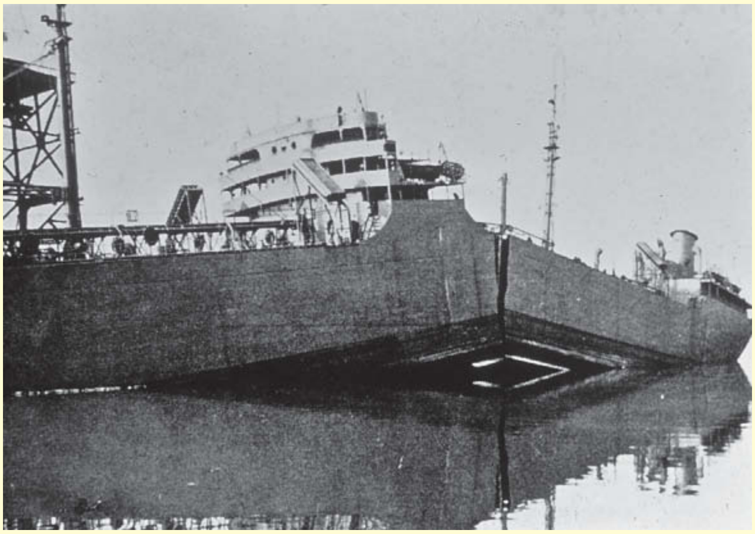

Figure 1.3 The Liberty ship *S.S. Schenectady,* which, in 1943, failed before leaving the shipyard.
(Reprinted with permission of Earl R. Parker, *Brittle Behavior of Engineering Structures,* National Academy of Sciences, National Research Council, John Wiley & Sons, New York, 1957.)

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.[7]
- 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.

[7]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

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Tutorial Video: What are the Different Classes 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, which 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.

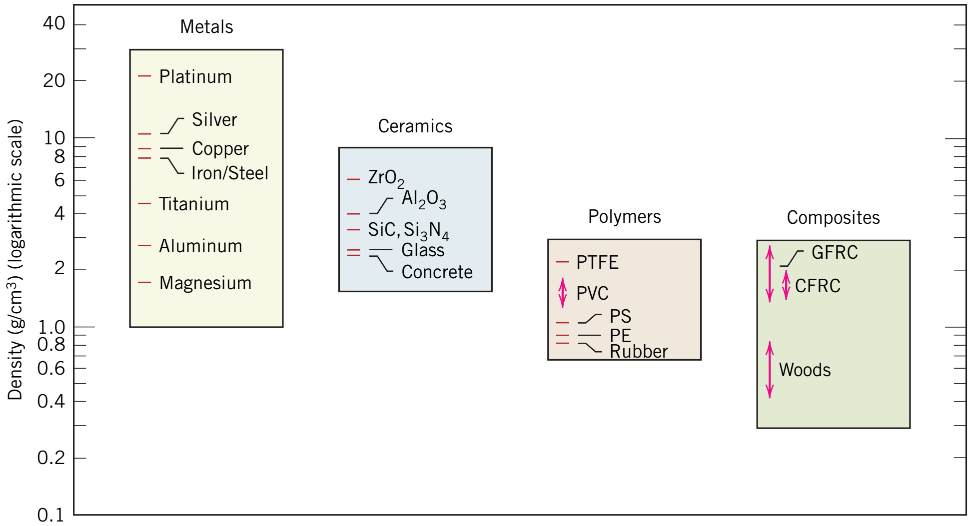

Figure 1.4 Bar chart of room-temperature density values for various metals, ceramics, polymers, and composite materials.

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.[8] Atoms in metals and their alloys are arranged in a 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

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Tutorial Video: Metals

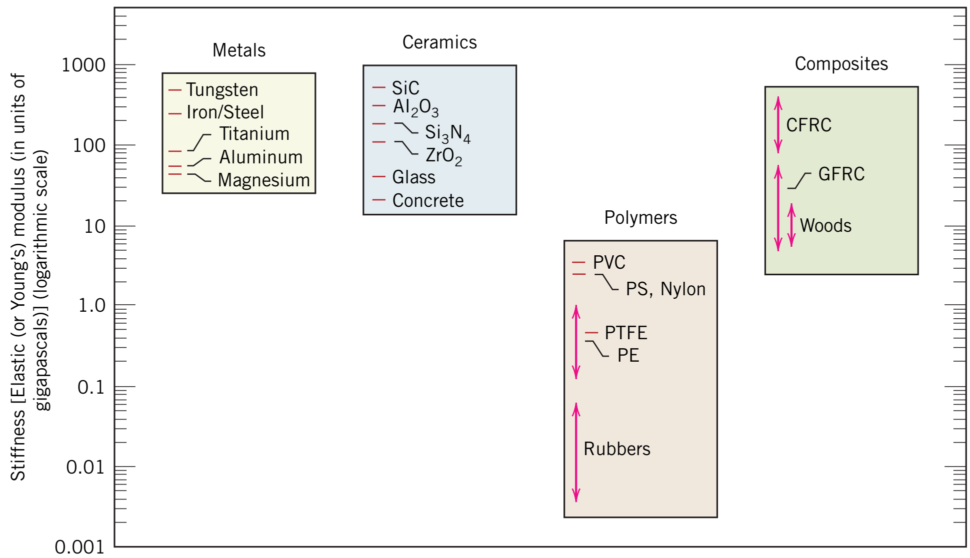

Figure 1.5 Bar chart of room-temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.

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

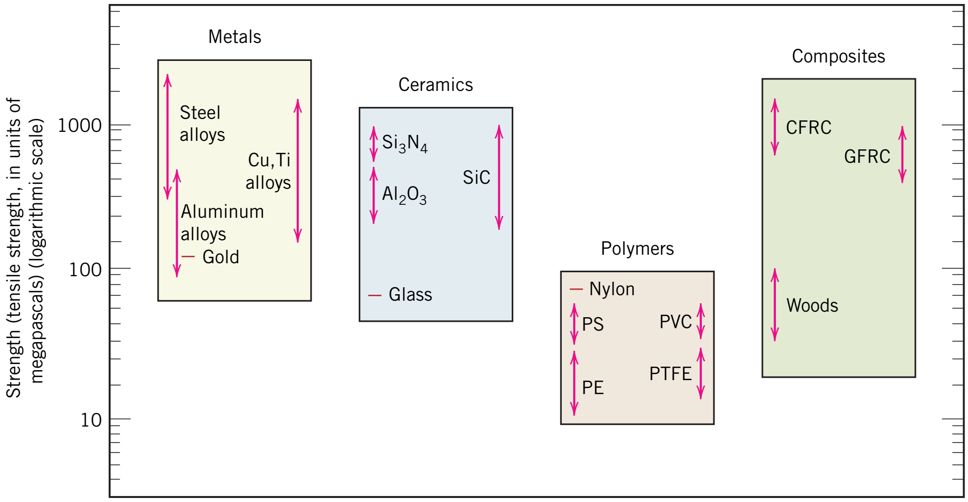

Figure 1.6 Bar chart of room-temperature strength (i.e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

(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.

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 13.

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

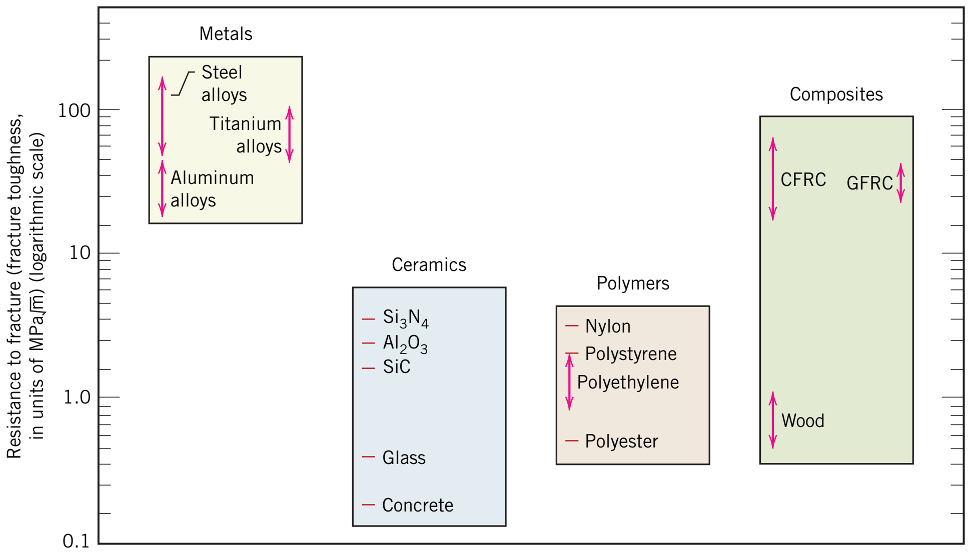

Figure 1.7 Bar chart of room-temperature resistance to fracture (i.e., fracture toughness) for various metals, ceramics, polymers, and composite materials. (Reprinted from *Engineering Materials 1: An Introduction to Properties, Applications and Design,* third edition, M. F. Ashby and D. R. H. Jones,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

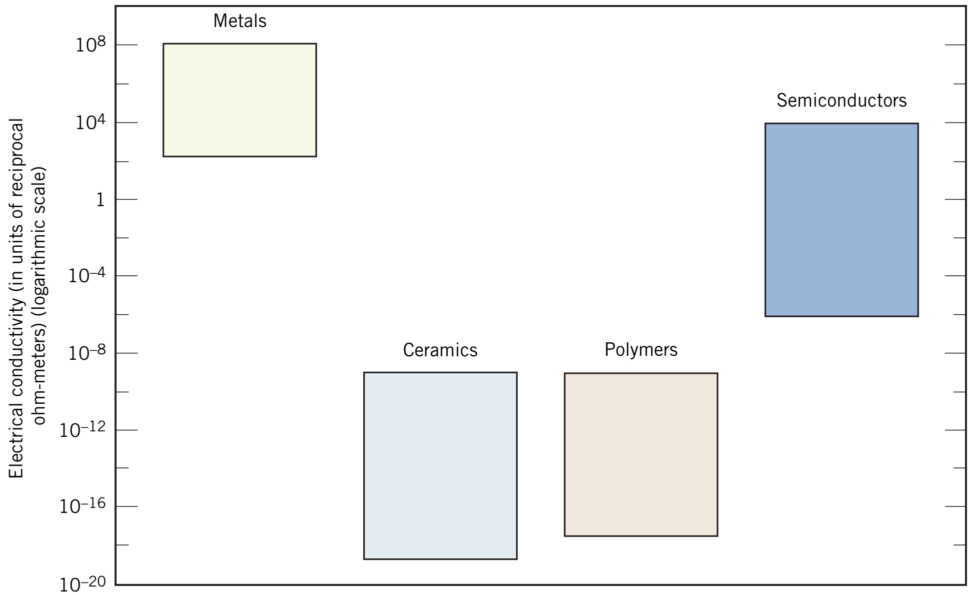

Figure 1.8 Bar chart of room-temperature electrical conductivity ranges for metals, ceramics, polymers, and semiconducting materials.

cookware, cutlery, and even automobile engine parts. Furthermore, ceramic materials are typically insulative to the passage of heat and electricity (i.e., have low electrical conductivities; Figure 1.8) and are more resistant to high temperatures and harsh environments than are metals and polymers. With regard to optical characteristics, ceramics may be transparent, translucent, or opaque (Figure 1.2), and some of the oxide ceramics (e.g., Fe_3O_4) exhibit magnetic behavior.

Several common ceramic objects are shown in Figure 1.10. The characteristics, types, and applications of this class of materials are also discussed in Chapter 13.

Polymers

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Tutorial Video: Polymers

Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other nonmetallic elements (i.e., O, N, and Si). Furthermore, they have very large molecular structures, often chainlike in nature, that often have a backbone of carbon atoms. Some common and familiar polymers are polyethylene (PE), nylon, poly(vinyl chloride) (PVC), polycarbonate (PC), polystyrene (PS), and silicone rubber. These materials typically have low densities (Figure 1.4), whereas their mechanical characteristics are generally dissimilar

Figure 1.9 Familiar objects made of metals and metal alloys (from left to right): silverware (fork and knife), scissors, coins, a gear, a wedding ring, and a nut and bolt.