10th Edition

Materials Science and Engineering

AN INTRODUCTION

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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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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