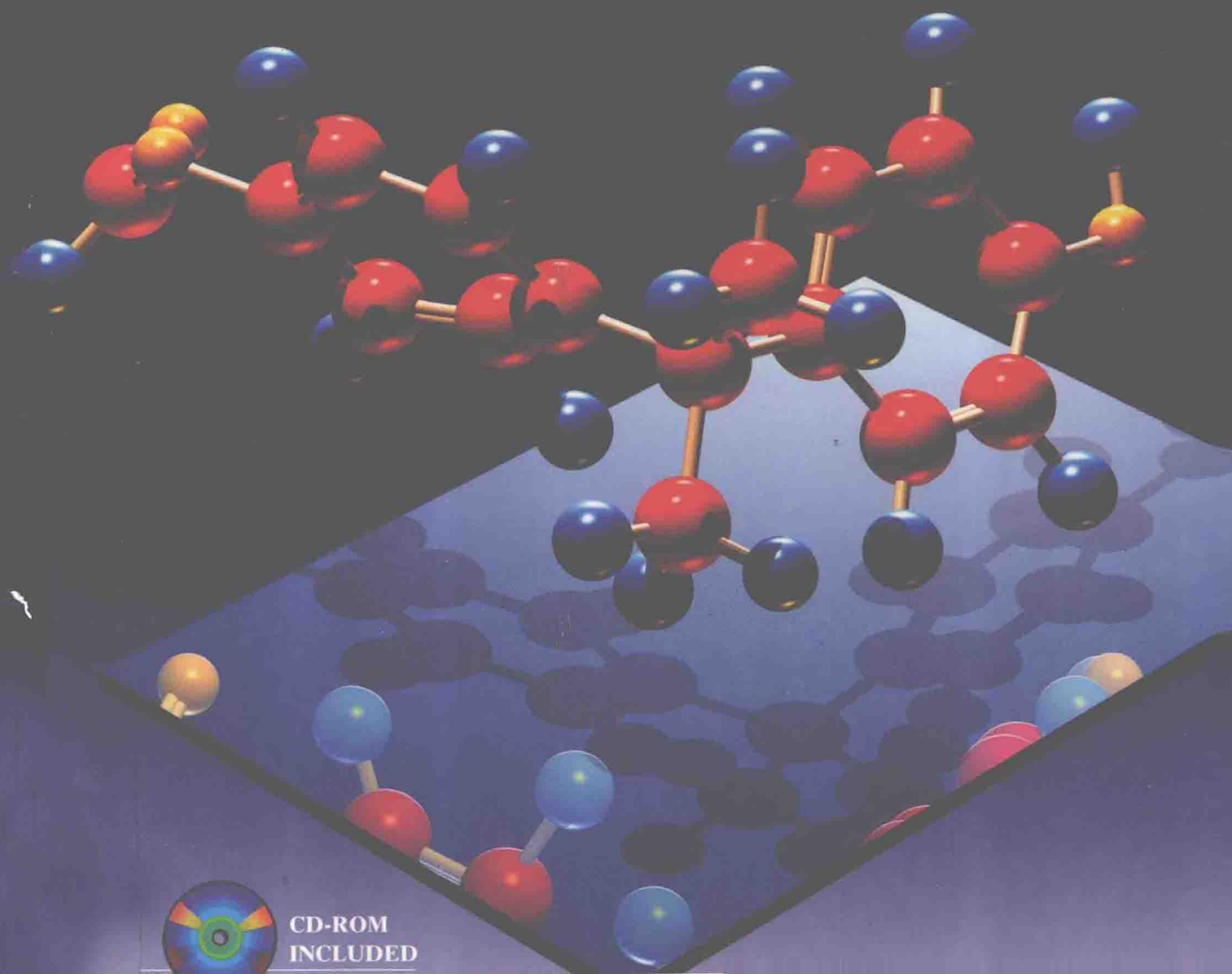
WILLIAM D. CALLISTER, JR.

FUNDAMENTALS OF MATERIALS SCIENCE AND ENGINEERING / AN INTERACTIVE *e* • TEXT



CD-ROM INCLUDED

FIFTH EDITION

Fundamentals of Materials Science and Engineering

An Interactive *e* • Text

William D. Callister, Jr.

Department of Metallurgical Engineering
The University of Utah

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Front Cover: The object that appears on the front cover depicts a monomer unit for polycarbonate (or PC, the plastic that is used in many eyeglass lenses and safety helmets). Red, blue, and yellow spheres represent carbon, hydrogen, and oxygen atoms, respectively.

Back Cover: Depiction of a monomer unit for polyethylene terephthalate (or PET, the plastic used for beverage containers). Red, blue, and yellow spheres represent carbon, hydrogen, and oxygen atoms, respectively.

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DEDICATED TO THE MEMORY OF
DAVID A. STEVENSON

MY ADVISOR, A COLLEAGUE,
AND FRIEND AT
STANFORD UNIVERSITY

Preface

Fundamentals of Materials Science and Engineering is an alternate version of my text, **Materials Science and Engineering: An Introduction, Fifth Edition.** The contents of both are the same, but the order of presentation differs and **Fundamentals** utilizes newer technologies to enhance teaching and learning.

With regard to the order of presentation, there are two common approaches to teaching materials science and engineering—one that I call the "traditional" approach, the other which most refer to as the "integrated" approach. With the traditional approach, structures/characteristics/properties of metals are presented first, followed by an analogous discussion of ceramic materials and polymers. **Introduction, Fifth Edition** is organized in this manner, which is preferred by many materials science and engineering instructors. With the integrated approach, one particular structure, characteristic, or property for all three material types is presented before moving on to the discussion of another structure/characteristic/property. This is the order of presentation in **Fundamentals.**

Probably the most common criticism of college textbooks is that they are too long. With most popular texts, the number of pages often increases with each new edition. This leads instructors and students to complain that it is impossible to cover all the topics in the text in a single term. After struggling with this concern (trying to decide what to delete without limiting the value of the text), we decided to divide the text into two components. The first is a set of "core" topics—sections of the text that are most commonly covered in an introductory materials course, and second, "supplementary" topics—sections of the text covered less frequently. Furthermore, we chose to provide only the core topics in print, but the entire text (both core and supplementary topics) is available on the CD-ROM that is included with the print component of **Fundamentals.** Decisions as to which topics to include in print and which to include only on the CD-ROM were based on the results of a recent survey of instructors and confirmed in developmental reviews. The result is a printed text of approximately 525 pages and an *Interactive eText* on the CD-ROM, which consists of, in addition to the complete text, a wealth of additional resources including interactive software modules, as discussed below.

The text on the CD-ROM with all its various links is navigated using Adobe Acrobat™. These links within the *Interactive eText* include the following: (1) from the Table of Contents to selected *eText* sections; (2) from the index to selected topics within the *eText;* (3) from reference to a figure, table, or equation in one section to the actual figure/table/equation in another section (all figures can be enlarged and printed); (4) from end-of-chapter Important Terms and Concepts to their definitions within the chapter; (5) from in-text boldfaced terms to their corresponding glossary definitions/explanations; (6) from in-text references to the corresponding appendices; (7) from some end-of-chapter problems to their answers; (8) from some answers to their solutions; (9) from software icons to the corresponding interactive modules; and (10) from the opening splash screen to the supporting web site.

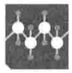
The interactive software included on the CD-ROM and noted above is the same that accompanies **Introduction, Fifth Edition.** This software, *Interactive Materials Science and Engineering, Third Edition* consists of interactive simulations and animations that enhance the learning of key concepts in materials science and engineering, a materials selection database, and *E-Z Solve: The Engineer's Equation Solving and Analysis Tool.* Software components are executed when the user clicks on the icons in the margins of the *Interactive eText;* icons for these several components are as follows:

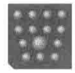
Crystallography and Unit Cells 

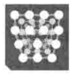
Tensile Tests 

Ceramic Structures 

Diffusion and Design Problem 

Polymer Structures 

Solid Solution Strengthening 

Dislocations 

Phase Diagrams 

E-Z Solve 

Database 

My primary objective in **Fundamentals** as in **Introduction, Fifth Edition** is to present the basic fundamentals of materials science and engineering on a level appropriate for university/college students who are well grounded in the fundamentals of calculus, chemistry, and physics. In order to achieve this goal, I have endeavored to use terminology that is familiar to the student who is encountering the discipline of materials science and engineering for the first time, and also to define and explain all unfamiliar terms.

The second objective is to present the subject matter in a logical order, from the simple to the more complex. Each chapter builds on the content of previous ones.

The third objective, or philosophy, that I strive to maintain throughout the text is that 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 most cases, some practical relevance is provided. Discussions are intended to be clear and concise and to begin at appropriate levels of understanding.

The fourth objective is to include features in the book that will expedite the learning process. These learning aids include numerous illustrations and photographs to help visualize what is being presented, learning objectives, "Why Study . . ." items that provide relevance to topic discussions, end-of-chapter questions and problems, answers to selected problems, and some problem solutions to help in self-assessment, a glossary, list of symbols, and references to facilitate understanding the subject matter.

The fifth objective, specific to **Fundamentals,** is to enhance the teaching and learning process using the newer technologies that are available to most instructors and students of engineering today.

Most of the problems in **Fundamentals** require computations leading to numerical solutions; in some cases, the student is required to render a judgment on the basis of the solution. Furthermore, many of the concepts within the discipline of materials science and engineering are descriptive in nature. Thus, questions have also been included that require written, descriptive answers; having to provide a written answer helps the student to better comprehend the associated concept. The questions are of two types: with one type, the student needs only to restate in his/her own words an explanation provided in the text material; other questions require the student to reason through and/or synthesize before coming to a conclusion or solution.

The same engineering design instructional components found in **Introduction, Fifth Edition** are incorporated in **Fundamentals.** Many of these are in Chapter 20, "Materials Selection and Design Considerations," that is on the CD-ROM. This chapter includes five different case studies (a cantilever beam, an automobile valve spring, the artificial hip, the thermal protection system for the Space Shuttle, and packaging for integrated circuits) relative to the materials employed and the rationale behind their use. In addition, a number of design-type (i.e., open-ended) questions/problems are found at the end of this chapter.

Other important materials selection/design features are Appendix B, "Properties of Selected Engineering Materials," and Appendix C, "Costs and Relative Costs for Selected Engineering Materials." The former contains values of eleven properties (e.g., density, strength, electrical resistivity, etc.) for a set of approximately one hundred materials. Appendix C contains prices for this same set of materials. The materials selection database on the CD-ROM is comprised of these data.

Supporting Web Site

The web site that supports **Fundamentals** can be found at *www.wiley.com/college/callister.* It contains student and instructor's resources which consist of a more extensive set of learning objectives for all chapters, an index of learning styles (an electronic questionnaire that accesses preferences on ways to learn), a glossary (identical to the one in the text), and links to other web resources. Also included with the Instructor's Resources are suggested classroom demonstrations and lab experiments. Visit the web site often for new resources that we will make available to help teachers teach and students learn materials science and engineering.

Instructors' Resources

Resources are available on another CD-ROM specifically for instructors who have adopted **Fundamentals.** These include the following: 1) detailed solutions of all end-of-chapter questions and problems; 2) a list (with brief descriptions) of possible classroom demonstrations and laboratory experiments that portray phenomena and/or illustrate principles that are discussed in the book (also found on the web site); references are also provided that give more detailed accounts of these demonstrations; and 3) suggested course syllabi for several engineering disciplines.

Also available for instructors who have adopted **Fundamentals** as well as **Introduction, Fifth Edition** is an online assessment program entitled *eGrade.* It is a browser-based program that contains a large bank of materials science/engineering problems/questions and their solutions. Each instructor has the ability to construct homework assignments, quizzes, and tests that will be automatically scored, recorded in a gradebook, and calculated into the class statistics. These self-scoring problems/questions can also be made available to students for independent study or pre-class review. Students work online and receive immediate grading and feedback.

Tutorial and Mastery modes provide the student with hints integrated within each problem/question or a tailored study session that recognizes the student's demonstrated learning needs. For more information, visit *www.wiley.com/college/egrade.*

ACKNOWLEDGMENTS

Appreciation is expressed to those who have reviewed and/or made contributions to this alternate version of my text. I am especially indebted to the following individuals: Carl Wood of Utah State University, Rishikesh K. Bharadwaj of Systran Federal Corporation, Martin Searcy of the Agilent Technologies, John H. Weaver of The University of Minnesota, John B. Hudson of Rensselaer Polytechnic Institute, Alan Wolfenden of Texas A & M University, and T. W. Coyle of the University of Toronto.

I am also indebted to Wayne Anderson, Sponsoring Editor, to Monique Calello, Senior Production Editor, Justin Nisbet, Electronic Publishing Analyst at Wiley, and Lilian N. Brady, my proofreader, for their assistance and guidance in developing and producing this work. In addition, I thank Professor Saskia Duyvesteyn, Department of Metallurgical Engineering, University of Utah, for generating the *e-Grade* bank of questions/problems/solutions.

Since I undertook the task of writing my first text on this subject in the early 1980's, 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, I express my sincere thanks!

Last, but certainly not least, the continual encouragement and support of my family and friends is deeply and sincerely appreciated.

WILLIAM D. CALLISTER, JR.
Salt Lake City, Utah
August 2000

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)
%RA = ductility, in percent reduction in area (7.6)
a = lattice parameter: unit cell x-axial length (3.4)
a = crack length of a surface crack (9.5a, 9.5b)
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 (12.17)
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 = velocity of electromagnetic radiation in a vacuum (19.2)
D = diffusion coefficient (6.3)
D = dielectric displacement (12.18)
d = diameter
d = average grain diameter (8.9)
d_{hkl} = interplanar spacing for planes of Miller indices h, k, and l (3.19)
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 (3.13)
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 = stress intensity factor (9.5a)
K_c = fracture toughness (9.5a, 9.5b)
K_{Ic} = plane strain fracture toughness for mode I crack surface displacement (9.5a, 9.5b)
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_n = number-average degree of polymerization (4.5)
n_w = weight-average degree of polymerization (4.5)
P = dielectric polarization (12.18)
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 (12.17)
R = atomic radius (3.4)
R = gas constant
r = interatomic distance (2.5)
r = reaction rate (11.3, 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 (18.11)
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 (9.16)
U_r = modulus of resilience (7.6)
$[uvw]$ = indices for a crystallographic direction (3.12)
V = electrical potential difference (voltage) (12.2)
V_C = unit cell volume (3.4)
V_C = corrosion potential (16.4)
V_H = Hall voltage (12.13)
V_i = volume fraction of phase i (10.7)
v = velocity
vol% = volume percent
W_i = mass fraction of phase i (10.7)
wt% = weight percent (5.6)

x = length
x = space coordinate
Y = dimensionless parameter or function in fracture toughness expression (9.5a, 9.5b)
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 = finite change in a parameter the symbol of which it precedes
ϵ = engineering strain (7.2)
ϵ = dielectric permittivity (12.17)
ϵ_r = dielectric constant or relative permittivity (12.17)
$\dot{\epsilon}_s$ = steady-state creep rate (9.16)
ϵ_T = true strain (7.7)
η = viscosity (8.16)
η = overvoltage (16.4)
θ = Bragg diffraction angle (3.19)
θ_D = Debye temperature (17.2)
λ = wavelength of electromagnetic radiation (3.19)
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 (9.5a, 9.5b)
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 (9.5a, 9.5b)
σ_{fs} = flexural strength (7.10)
σ_m = maximum stress (9.5a, 9.5b)
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

Contents

Chapters 1 through 13 discuss core topics (found in both print and on the CD-ROM) and supplementary topics (in the eText only)

8. Deformation and Strengthening Mechanisms 197

9. Failure 234

Chapters 14 through 21 discuss just supplementary topics, and are found only on the CD-ROM (and not in print)