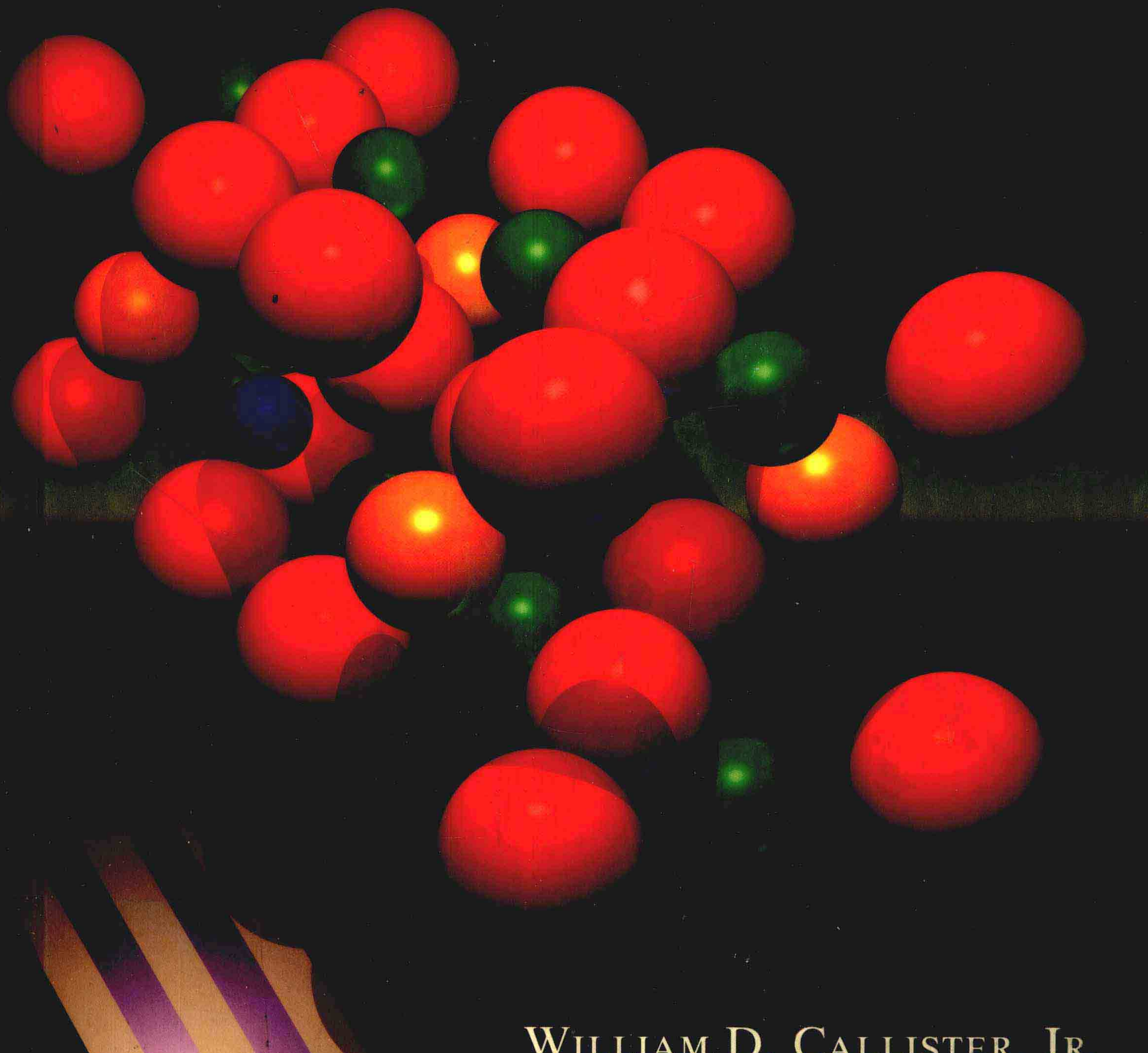
MATERIALS SCIENCE AND ENGINEERING
AN INTRODUCTION

FOURTH EDITION



WILLIAM D. CALLISTER, JR.

FOURTH EDITION

Materials Science and Engineering

An Introduction

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John Wiley & Sons, Inc.

New York Chichester Brisbane Toronto Singapore Weinheim

Front Cover: The aggregate of sphere-like objects on the front cover represents a unit cell of the high critical temperature superconducting material $YBa_2Cu_3O_7$. Red, green, orange, and purple spheres represent oxygen, copper, barium, and yttrium ions, respectively. This material has a superconducting critical temperature of about 92 K, and was the first of this new generation of superconductors to have been recently discovered.

Back Cover: Top view of the $YBa_2Cu_3O_7$ unit cell that is shown on the front cover.

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Library of Congress Cataloging-in-Publication Data

Callister, William D., 1940–
Materials science and engineering : an introduction / William D. Callister, Jr.—4th ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-471-13459-7 (cloth : alk. paper)
1. Materials. I. Title.
TA403.C23 1996
620.1′1—dc20 96-1878
CIP

Printed in the United States of America

10 9 8 7 6 5 4 3 2

Dedicated to the Memory of Rose Anne Callister Gordon

Preface

In this fourth edition I have retained the objectives and philosophies of the previous editions. The primary objective is to present the basic fundamentals of materials science and engineering on a level appropriate for university/college students who have completed their freshmen calculus, chemistry, and physics courses. 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.

A second objective is to present the material in a logical order, from the simple to the more complex. The first twelve chapters are primarily concerned with metallic materials and their alloys, which, structurally, are the most simple of the four material types. The next five chapters treat ceramic materials, polymers, and, finally, composites in that order. Furthermore, each chapter builds on the content of previous ones. This is especially true for Chapters 2 through 11, which treat atomic bonding, crystal structures, imperfections, diffusion, mechanical properties, dislocations, failure, phase diagrams, phase transformations, and thermal processing, in that sequence.

The third objective, or philosophy, that I have strived to maintain throughout the text is that if a topic or concept is worth treating, then it is worth discussing in sufficient detail and to the extent that students have the opportunity to fully understand it without having to consult other sources; also, in most cases, some practical relevance is provided. Discussions are clear and concise and begin at appropriate levels of understanding.

A fourth objective is to include features in the book that expedite the learning process. These learning aids include copious illustrations and photographs, end-of-chapter questions and problems, answers to selected problems, references, a glossary, a list of symbols, and computer software. Relative to the questions and problems, most of the problems require computations leading to numerical solutions; in some cases, the students are 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 better comprehend and understand the associated concept. The questions are of two types: For some, the student needs only to restate in his or 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.

New Features

The most significant change from the previous edition is the incorporation of a new chapter, Chapter 24, "Economic, Environmental, and Societal Issues in Materials Science and Engineering." This inclusion was in response to a poll taken of a number of faculty in the United States and Canada who teach introductory materials science and engineering courses.

Chapter 23 has been retitled "Materials Selection and Design Considerations," and the cantilever beam case study has been replaced by a torsionally stressed cylindrical shaft case study, which incorporates Ashby's materials selection charts. The design element has been strengthened by the addition of ten diverse design examples (found in Chapters 5, 6, 7, 8, 11, 17, 19, and 21). In addition, numerous design problems are included at the conclusion of end-of-chapter Questions and Problems sections; these are designated by a "D" in the numbering scheme (e.g., 3.D4).

To each of the chapters that has a predominant materials science component (i.e., Chapters 2, 3, 4, 5, and 9), an "Implications" section has been added following the Summary; these sections are intended to provide some relevance and rationale for the topics that are treated.

There have been some significant changes to the appendices. Appendix C, "Properties of Selected Engineering Materials," has been expanded significantly. Approximately eighty representative materials of all types (metals and metal alloys; graphite, ceramics, and semiconducting materials; polymers; composites; and fibers) were selected; values of ten different properties (e.g., density, modulus of elasticity, Poisson's ratio, etc.) for each material were collected (when available) and then tabulated by property. Appendix D contains the mer structures for thirty-one common polymeric materials. Two taxonomic charts are found in Appendix E. One is a classification scheme according to strengthening technique for metals, ceramics, and polymers that have been discussed in this book; the other chart classifies heat treatments for metals and ceramics.

Considerable effort has been expended to make this edition as current as possible. Several sections have been added to incorporate relatively new materials, technologies, and processes; these include: tape casting (Section 14.16); advanced polymeric materials (ultrahigh molecular weight polyethylene, thermoplastic elastomers, and liquid crystal polymers, Section 16.17); polymer-, metal-, and ceramic-matrix composites (Sections 17.8, 17.9, and 17.10); high-energy hard magnetic materials (Section 21.9); thin film magnetic storage media (Section 21.10); and optical fibers in communications (Section 22.14). Furthermore, virtually all metallic and ceramic phase diagrams, and most property tables have been updated to be as current as possible.

Relative to the use of units, in previous editions SI units were preferred in some instances, and Customary U.S. in others. For this edition, with very few exceptions, SI units are given preference.

And finally, most of the problems requiring computations that were new to the second edition have been changed; numerical values for these problems were altered.

The university engineering community is justifiably concerned about the increased length (and associated increase in cost) with each new edition of a textbook. The author shares this concern and has endeavored to minimize the inclusion of new material that would make this edition longer and more expensive. However, there is a consensus with engineering faculty that today's introductory materials science and engineering text should, among other things, 1) be current and up-to-date, 2) include a significant design component, and 3) discuss economic, environmental, and societal topics. Most of the changes and additions in this edition deal with these three issues. Furthermore, I do not feel it appropriate to eliminate book sections, the loss of which would compromise the science content, just to make it shorter.

SUPPLEMENTS

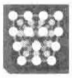
An *Instructor's Manual* is available to adopters of this book. All of the end-of-chapter questions and problems have been solved or answered in detail, which are presented in word-processed form. Accompanying some of the chapters are examination questions/problems that have been used by the author. Furthermore, several suggested course syllabi are provided.

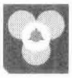
In addition, a number of color transparencies have been prepared; these are of photomicrographs and of complex and commonly used illustrations that appear in the book.

For the student, a computer software supplement is also available with this edition. This interactive software was developed by a professional software company; it (the software) will generate on a computer monitor three-dimensional projections of figures and processes that are difficult to represent on the two-dimensional textbook page (i.e., unit cells, crystallographic planes and directions, polymer molecules, and dislocations). Images associated with some of the homework problems are also included so as to facilitate their solutions. In addition, a diffusion design problem is included; the student is allowed to specify values of several diffusion parameters, upon which the software performs the appropriate computations and then provides a graphical solution.

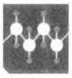
Throughout this book, whenever there is some text or a problem that is supplemented by the software, a small "icon" that denotes the associated module is included in one of the margins. These modules and their corresponding icons are as follows:

Crystallography and Unit Cells 

Dislocations 

Ceramic Structures 

Tensile Tests 

Polymer Structures 

Diffusion and Design Problem 

ACKNOWLEDGMENTS

Appreciation is expressed to those who have made contributions to this edition. I am indebted to the following individuals: Carl Wood, of Weber State University; Martin Searcy, of the Hewlett-Packard Company; Robert Scheer, Natalya Rapoport, Rishikesh K. Bharadwaj, Sivaraman Guruswamy, Jeffrey E. Shield, and Douglas Chinn, of the University of Utah; W. Roger Cannon of Rutgers University; David V. Ragone, of Massachusetts Institute of Technology; Hugh W. Kerr, of the University of Waterloo; Jianping Shen, of Santa Monica College; David Erickson and

Randy Philpot, of Advanced Composites (Salt Lake City, Utah); Pat Vigil, of National Semiconductor Corporation; Dan L. Greenfield, of Allegheny Ludlum Corporation; and to Cliff Robichaud, Stephanie Davis, Nancy Prinz, Sigmund Malinowski, Karin Kincheloe, and Mary Ann Price at Wiley. Thanks and apologies to others whose contributions I have overlooked. 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 1996

Contents

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)
%AR = ductility, in percent area reduction (6.6)
a = lattice parameter: unit cell x-axial length (3.4)
a = crack length of a surface crack (8.5)
at% = atom percent (4.3)
B = magnetic flux density (induction) (21.2)
B_r = magnetic remanence (21.7)
BCC = body-centered cubic crystal structure (3.4)
b = lattice parameter: unit cell y-axial length (3.7)
$\mathbf{b}$ = Burgers vector (4.4)
C = capacitance (19.17)
C_i = concentration (composition) of component i in wt% (4.3)
C_i' = concentration (composition) of component i in at% (4.3)
C_v, C_p = heat capacity at constant volume, pressure (20.2)
CPR = corrosion penetration rate (18.3)
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 (22.2)
D = diffusion coefficient (5.3)
D = dielectric displacement (19.18)
d = diameter
d = average grain diameter (7.8)
d_{hkl} = interplanar spacing for planes of Miller indices h, k, and l (3.15)
E = energy (2.5)
E = modulus of elasticity or Young's modulus (6.3)
$\mathscr{E}$ = electric field intensity (19.3)
E_f = Fermi energy (19.5)
E_g = band gap energy (19.6)
$E_r(t)$ = relaxation modulus (16.6)
%EL = ductility, in percent elongation (6.6)
e = electric charge per electron (19.7)
e^- = electron (18.2)
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 (18.2)
FCC = face-centered cubic crystal structure (3.4)
G = shear modulus (6.3)
H = magnetic field strength (21.2)
H_c = magnetic coercivity (21.7)
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 (22.2)
(hkl) = Miller indices for a crystallographic plane (3.9)
I = electric current (19.2)
I = intensity of electromagnetic radiation (22.3)
i = current density (18.3)
i_C = corrosion current density (18.4)
J = diffusion flux (5.3)
J = electric current density (19.3)
K = stress intensity factor (8.5)
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 (20.4)
l = length
l_c = critical fiber length (17.4)
ln = natural logarithm
log = logarithm taken to base 10
M = magnetization (21.2)
$\overline{M}_n$ = polymer number-average molecular weight (15.5)
$\overline{M}_w$ = polymer weight-average molecular weight (15.5)
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 (18.2)
n = number of conducting electrons per cubic meter (19.7)
n = index of refraction (22.5)
n' = for ceramics, the number of formula units per unit cell (13.2)
n_n = number-average degree of polymerization (15.5)
n_w = weight-average degree of polymerization (15.5)
P = dielectric polarization (19.18)
P–B ratio = Pilling–Bedworth ratio (18.10)
p = number of holes per cubic meter (19.10)
Q = activation energy
Q = magnitude of charge stored (19.17)
R = atomic radius (3.4)
R = gas constant
r = interatomic distance (2.5)
r = reaction rate (10.3, 18.3)
r_A, r_C = anion and cation ionic radii (13.2)
S = fatigue stress amplitude (8.8)
SEM = scanning electron microscopy or microscope
T = temperature
T_c = Curie temperature (21.6)
T_C = superconducting critical temperature (21.11)
T_g = glass transition temperature (14.2)
T_m = melting temperature
TEM = transmission electron microscopy or microscope
TS = tensile strength (6.6)
t = time
t_r = rupture lifetime (8.13)
U_r = modulus of resilience (6.6)
$[uvw]$ = indices for a crystallographic direction (3.8)
V = electrical potential difference (voltage) (18.2)
V_C = unit cell volume (3.4)
V_C = corrosion potential (18.4)
V_H = Hall voltage (19.13)
V_i = volume fraction of phase i (9.6)
v = velocity