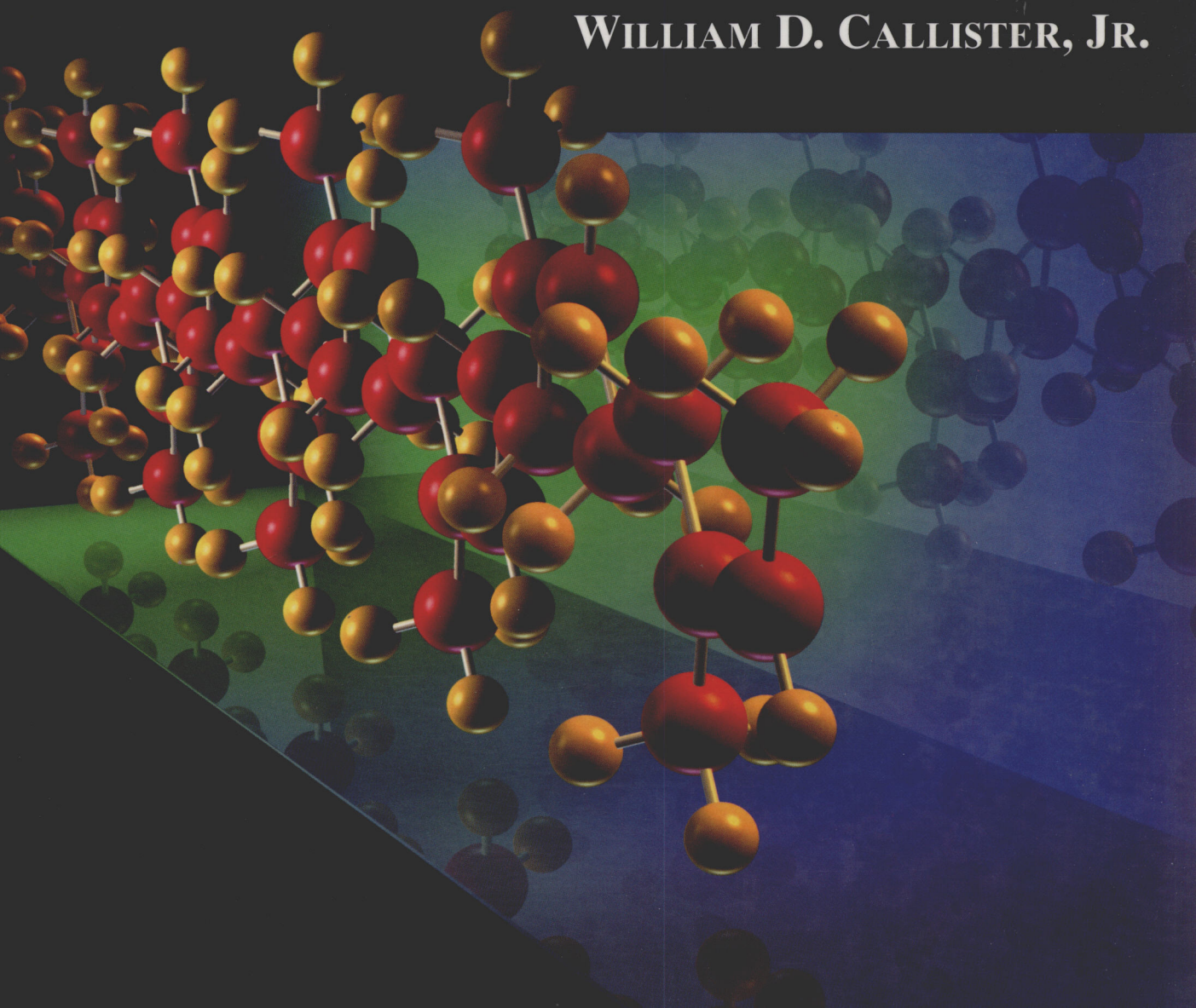
# Materials Science and Engineering

## An Introduction

Fifth Edition

William D. Callister, Jr.



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FIFTH EDITION

# Materials Science and Engineering

## An Introduction

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**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 molecular segment of natural rubber or *cis* polyisoprene. Red and yellow spheres represent carbon and hydrogen atoms, respectively.

**Back Cover:** Depiction of a molecular segment of *trans* polyisoprene (or gutta percha). Again, the red and yellow spheres represent carbon and hydrogen atoms.

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## Characteristics of Selected Elements

| *Element* | *Symbol* | *Atomic Number* | *Atomic Weight (amu)* | *Density of Solid, 20°C ($g/cm^3$)* | *Crystal Structure, 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 | 72.59 | 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 | 118.69 | 7.17 | Tetra. | 0.151 | 0.071 | 4+ | 232 |
| Titanium | Ti | 22 | 47.88 | 4.51 | HCP | 0.145 | 0.068 | 4+ | 1668 |
| Tungsten | W | 74 | 183.85 | 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 | 65.39 | 7.13 | HCP | 0.133 | 0.074 | 2+ | 420 |
| Zirconium | Zr | 40 | 91.22 | 6.51 | HCP | 0.159 | 0.079 | 4+ | 1852 |

## Values of Selected Physical Constants

| *Quantity* | *Symbol* | *SI Units* | *cgs Units* |
|---|---|---|---|
| Avogadro's number | $N_A$ | $6.023 \times 10^{23}$ molecules/mol | $6.023 \times 10^{23}$ molecules/mol |
| Boltzmann's constant | $k$ | $1.38 \times 10^{-23}$ J/atom-K | $1.38 \times 10^{-16}$ erg/atom-K<br>$8.62 \times 10^{-5}$ eV/atom-K |
| Bohr magneton | $\mu_B$ | $9.27 \times 10^{-24}$ A-m$^2$ | $9.27 \times 10^{-21}$ erg/gauss[a] |
| Electron charge | $e$ | $1.602 \times 10^{-19}$ C | $4.8 \times 10^{-10}$ statcoul[b] |
| Electron mass | — | $9.11 \times 10^{-31}$ kg | $9.11 \times 10^{-28}$ g |
| Gas constant | $R$ | 8.31 J/mol-K | 1.987 cal/mol-K |
| Permeability of a vacuum | $\mu_0$ | $1.257 \times 10^{-6}$ henry/m | unity[a] |
| Permittivity of a vacuum | $\epsilon_0$ | $8.85 \times 10^{-12}$ farad/m | unity[b] |
| Planck's constant | $h$ | $6.63 \times 10^{-34}$ J-s | $6.63 \times 10^{-27}$ erg-s<br>$4.13 \times 10^{-15}$ eV-s |
| Velocity of light in a vacuum | $c$ | $3 \times 10^8$ m/s | $3 \times 10^{10}$ 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 | $\mu$m = micrometer (micron) |
| eV = electron volt | Mg = megagram | |
| °F = degrees Fahrenheit | mm = millimeter | W = watt |
| ft = foot | mol = mole | psi = pounds per square inch |
| 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 | $\mu$ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |

[a] Avoided when possible.

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# Materials Science and Engineering
## An Introduction

Dedicated to the Memory of
Cliff Robichaud and Nancy Prinz
I worked with these
wonderful People at Wiley
on Previous Editions

# Preface

In this Fifth Edition I have retained the objectives and approaches for teaching materials science and engineering that were presented in previous editions. The first, and primary, objective is to present the basic fundamentals on a level appropriate for university/college students who have completed their freshman 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.

The second objective is to present the subject matter 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 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 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; also, 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; end-of-chapter questions and problems, and answers to selected problems to help in self-assessment; a glossary, list of symbols, and references to facilitate understanding the subject matter; and computer software that provides (1) an interactive component that facilitates concept visualization, (2) a database that may be used to solve design and materials selection problems, and (3) an equation-solving capability.

Regarding questions and problems, most problems 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 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.

## Features That Are New to This Edition

First, each chapter now begins with two new sections: "Why Study . . ." and "Chapter Objectives." Each "Why Study . . ." section states the relevance of topics that are discussed in the chapter, and in most instances gives at least one example. The "Chapter Objectives" section provides a brief list of general learning objectives relevant to the key principles and concepts that the student should come to understand and then, in many instances, be able to apply.

Second, in order to enhance the understanding of the materials selection process, I made significant changes to the appendices and added several materials selection exercises. Appendix B, "Properties of Selected Engineering Materials," now contains values of eleven properties (e.g., density, strength, electrical conductivity, etc.) for a set of approximately one hundred materials. Some of this database was in the Fourth Edition (as Appendix C); however, property data were not always for the same materials. Furthermore, a new Appendix C has been included that contains the prices for all the materials listed in Appendix B; materials selection criteria almost always involve cost considerations.

Third, I have tried to limit the addition of new material in this revision. The university engineering community is justifiably concerned about the increased length (and associated increased cost) with each new edition of a textbook. I share this concern and have endeavored to minimize the inclusion of new material that would make this edition longer. However, some updating was necessary in order to keep the book current. A number of new homework problems were added, most of which are design-type problems, and many of the other problems have been refreshed. Given the consensus among engineering faculty that today's introductory materials science and engineering text should, among other things, be current and include a significant design component, I did not feel it appropriate to eliminate book sections, the loss of which would compromise the science content, just to make this edition shorter.

## Accompanying Software

*IMSE: Interactive Materials Science and Engineering,* Third Edition, is available on CD-ROM with this new edition of the text. The software that was available with previous editions has been updated and expanded. It now has the following features and capabilities:

1. It 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).
2. Images associated with some of the homework problems are included to facilitate their solutions.
3. A diffusion design problem is included; the student is allowed to specify values of several diffusion parameters, on which the software performs the appropriate computations and then provides a graphical solution.
4. New animations (with audio) illustrate the phenomenon of solid solution strengthening and concepts that may be explained using phase diagrams (i.e., solid solutions and two-phase situations).
5. The material property and cost databases that appear in Appendices B and C are also included on the CD-ROM. The user can sort through each property or cost list, and the materials will be ranked by property/cost value. In addition, the

user can use these databases for materials selection exercises. For up to three properties (or two properties and cost), maximum and minimum values may be specified, and the software will select all materials that fall within these ranges. Several materials selection homework problems have been designed that can be solved using this feature in the software.

6. Also new to this version of the software is the inclusion of *E-Z Solve: The Engineer's Equation Solving and Analysis Tool.* It can be used to solve numerical algebraic and ordinary differential equations with ease. Several such problems have been incorporated into this edition. And, of course, *E-Z Solve* can be used to solve computationally complex problems encountered in other engineering courses.

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 | | Tensile Tests | |
| Ceramic Structures | | Diffusion and Design Problem | |
| Polymer Structures | | Solid Solution Strengthening | |
| Dislocations | | Phase Diagrams | |

## Supporting Web Site

The Web site that supports this text can be found at **www.wiley.com/college/callister.** It provides an extended list of learning objectives, updates, additional teaching and learning resources, links to other relevant Web sites, and other resources. Visit us often for new resources that we will make available to help teachers teach and to help students learn materials science and engineering.

## Instructors' Resources

The following resources are available on CD-ROM for instructors who have adopted this text: (1) detailed solutions of all end-of-chapter questions and problems; (2) key photographs and illustrations that appear in the book, so that the instructor can print them for handouts or prepare transparencies in his or her desired format; (3) new to this edition, a list (with brief descriptions) of possible classroom demonstrations that portray phenomena and/or illustrate principles that are discussed in the book (with references that give more detailed accounts of these demonstrations); (4) a new list of relevant laboratory experiments; and (5) suggested course syllabi for several engineering disciplines.

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WILLIAM D. CALLISTER, JR.

*Salt Lake City, Utah*
*January 1999*

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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)
%RA = ductility, in percent reduction in area (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 (16.7)
%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
vol% = volume percent
$W_i$ = mass fraction of phase $i$ (9.6)
wt% = weight percent (4.3)
$x$ = length
$x$ = space coordinate

$Y$ = dimensionless parameter or function in fracture toughness expression (8.5)
$y$ = space coordinate
$z$ = space coordinate
$\alpha$ = lattice parameter: unit cell $y$–$z$ interaxial angle (3.7)
$\alpha, \beta, \gamma$ = phase designations
$\alpha_l$ = linear coefficient of thermal expansion (20.3)
$\beta$ = lattice parameter: unit cell $x$–$z$ interaxial angle (3.7)
$\gamma$ = lattice parameter: unit cell $x$–$y$ interaxial angle (3.7)
$\gamma$ = shear strain (6.2)
$\Delta$ = finite change in a parameter the symbol of which it precedes
$\epsilon$ = engineering strain (6.2)
$\epsilon$ = dielectric permittivity (19.17)
$\epsilon_r$ = dielectric constant or relative permittivity (19.17)
$\dot{\epsilon}_s$ = steady-state creep rate (8.13)
$\epsilon_T$ = true strain (6.7)
$\eta$ = viscosity (13.9)
$\eta$ = overvoltage (18.4)
$\theta$ = Bragg diffraction angle (3.15)
$\theta_D$ = Debye temperature (20.2)
$\lambda$ = wavelength of electromagnetic radiation (3.15)
$\mu$ = magnetic permeability (21.2)
$\mu_B$ = Bohr magneton (21.2)
$\mu_r$ = relative magnetic permeability (21.2)
$\mu_e$ = electron mobility (19.7)
$\mu_h$ = hole mobility (19.10)
$\nu$ = Poisson's ratio (6.5)
$\nu$ = frequency of electromagnetic radiation (22.2)
$\rho$ = density (3.5)
$\rho$ = electrical resistivity (19.2)
$\rho_t$ = radius of curvature at the tip of a crack (8.5)
$\sigma$ = engineering stress, tensile or compressive (6.2)
$\sigma$ = electrical conductivity (19.3)
$\sigma^*$ = longitudinal strength (composite) (17.5)
$\sigma_c$ = critical stress for crack propagation (8.5)
$\sigma_{fs}$ = flexural strength (13.8)
$\sigma_m$ = maximum stress (8.5)
$\sigma_m$ = mean stress (8.7)
$\sigma'_m$ = stress in matrix at composite failure (17.5)
$\sigma_T$ = true stress (6.7)
$\sigma_w$ = safe or working stress (6.12)
$\sigma_y$ = yield strength (6.6)
$\tau$ = shear stress (6.2)
$\tau_c$ = fiber–matrix bond strength/ matrix shear yield strength (17.4)
$\tau_{crss}$ = critical resolved shear stress (7.5)
$\chi_m$ = magnetic susceptibility (21.2)

## 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

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