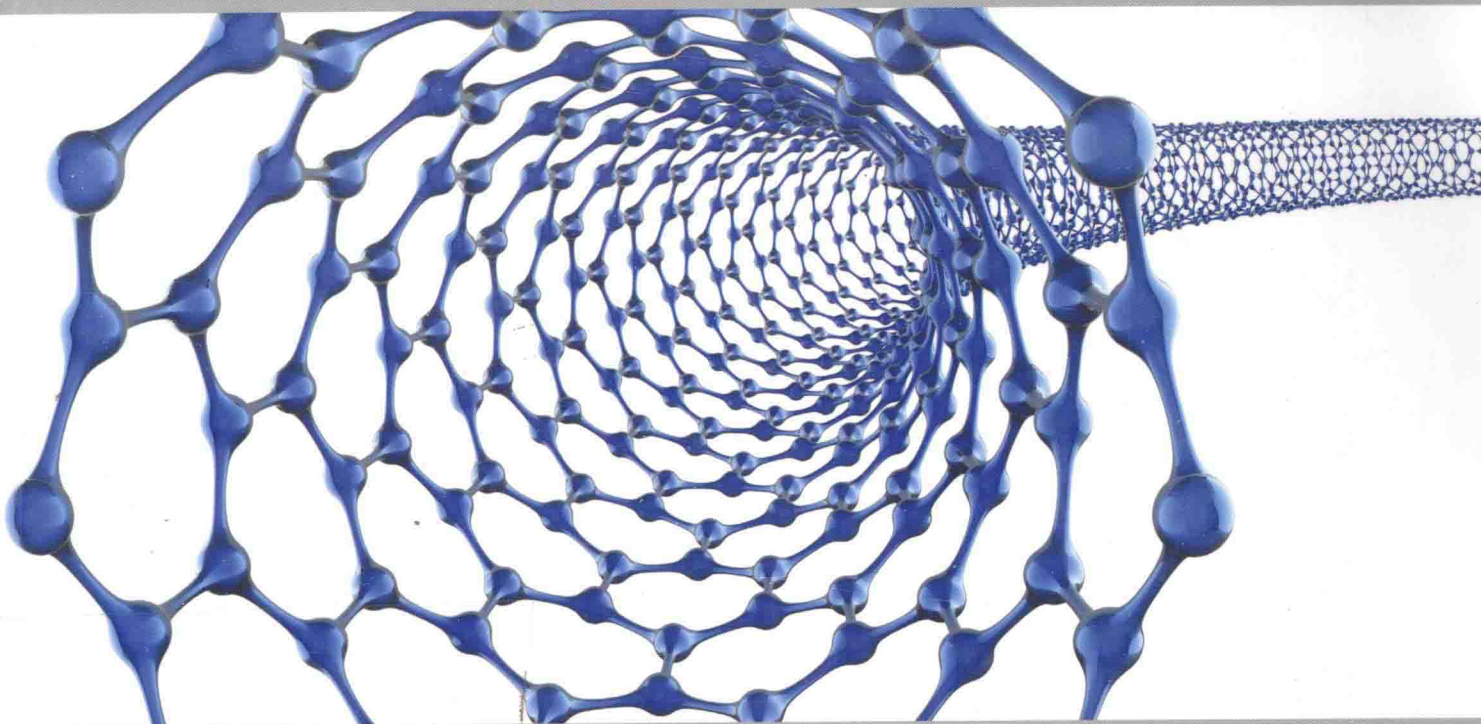WILLIAM D. CALLISTER, JR. | DAVID G. RETHWISCH

Materials Science and Engineering

Ninth Edition

EXCLUSIVE TO THIS VERSION

- New Problem Sets
- New Content Structure
- Use of Metric Units Only

SI VERSION

WILEY

9th E

Materials Science and Engineering

SI Version

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WILEY

Characteristics of Selected Elements

Element	Symbol	Atomic Number	Atomic Weight (amu)	Density of Solid, 20°C (g/cm³)	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	72.64	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

Unit Conversion Factors

Length

$1 \text{ m} = 10^{10} \text{ Å}$	$1 \text{ Å} = 10^{-10} \text{ m}$
$1 \text{ m} = 10^9 \text{ nm}$	$1 \text{ nm} = 10^{-9} \text{ m}$
$1 \text{ m} = 10^6 \text{ μm}$	$1 \text{ μm} = 10^{-6} \text{ m}$
$1 \text{ m} = 10^3 \text{ mm}$	$1 \text{ mm} = 10^{-3} \text{ m}$
$1 \text{ m} = 10^2 \text{ cm}$	$1 \text{ cm} = 10^{-2} \text{ m}$
$1 \text{ mm} = 0.0394 \text{ in.}$	$1 \text{ in.} = 25.4 \text{ mm}$
$1 \text{ cm} = 0.394 \text{ in.}$	$1 \text{ in.} = 2.54 \text{ cm}$
$1 \text{ m} = 3.28 \text{ ft}$	$1 \text{ ft} = 0.3048 \text{ m}$

Area

$1 \text{ m}^2 = 10^4 \text{ cm}^2$	$1 \text{ cm}^2 = 10^{-4} \text{ m}^2$
$1 \text{ mm}^2 = 10^{-2} \text{ cm}^2$	$1 \text{ cm}^2 = 10^2 \text{ mm}^2$
$1 \text{ m}^2 = 10.76 \text{ ft}^2$	$1 \text{ ft}^2 = 0.093 \text{ m}^2$
$1 \text{ cm}^2 = 0.1550 \text{ in.}^2$	$1 \text{ in.}^2 = 6.452 \text{ cm}^2$

Volume

$1 \text{ m}^3 = 10^6 \text{ cm}^3$	$1 \text{ cm}^3 = 10^{-6} \text{ m}^3$
$1 \text{ mm}^3 = 10^{-3} \text{ cm}^3$	$1 \text{ cm}^3 = 10^3 \text{ mm}^3$
$1 \text{ m}^3 = 35.32 \text{ ft}^3$	$1 \text{ ft}^3 = 0.0283 \text{ m}^3$
$1 \text{ cm}^3 = 0.0610 \text{ in.}^3$	$1 \text{ in.}^3 = 16.39 \text{ cm}^3$

Mass

$1 \text{ Mg} = 10^3 \text{ kg}$	$1 \text{ kg} = 10^{-3} \text{ Mg}$
$1 \text{ kg} = 10^3 \text{ g}$	$1 \text{ g} = 10^{-3} \text{ kg}$
$1 \text{ kg} = 2.205 \text{ lb}_m$	$1 \text{ lb}_m = 0.4536 \text{ kg}$
$1 \text{ g} = 2.205 \times 10^{-3} \text{ lb}_m$	$1 \text{ lb}_m = 453.6 \text{ g}$

Density

$1 \text{ kg/m}^3 = 10^{-3} \text{ g/cm}^3$	$1 \text{ g/cm}^3 = 10^3 \text{ kg/m}^3$
$1 \text{ Mg/m}^3 = 1 \text{ g/cm}^3$	$1 \text{ g/cm}^3 = 1 \text{ Mg/m}^3$
$1 \text{ kg/m}^3 = 0.0624 \text{ lb}_m/\text{ft}^3$	$1 \text{ lb}_m/\text{ft}^3 = 16.02 \text{ kg/m}^3$
$1 \text{ g/cm}^3 = 62.4 \text{ lb}_m/\text{ft}^3$	$1 \text{ lb}_m/\text{ft}^3 = 1.602 \times 10^{-2} \text{ g/cm}^3$
$1 \text{ g/cm}^3 = 0.0361 \text{ lb}_m/\text{in.}^3$	$1 \text{ lb}_m/\text{in.}^3 = 27.7 \text{ g/cm}^3$

Force

$1 \text{ N} = 10^5 \text{ dynes}$	$1 \text{ dyne} = 10^{-5} \text{ N}$
$1 \text{ N} = 0.2248 \text{ lb}_f$	$1 \text{ lb}_f = 4.448 \text{ N}$

Stress

$1 \text{ MPa} = 145 \text{ psi}$	$1 \text{ psi} = 6.90 \times 10^{-3} \text{ MPa}$
$1 \text{ MPa} = 0.102 \text{ kg/mm}^2$	$1 \text{ kg/mm}^2 = 9.806 \text{ MPa}$
$1 \text{ Pa} = 10 \text{ dynes/cm}^2$	$1 \text{ dyne/cm}^2 = 0.10 \text{ Pa}$
$1 \text{ kg/mm}^2 = 1422 \text{ psi}$	$1 \text{ psi} = 7.03 \times 10^{-4} \text{ kg/mm}^2$

Fracture Toughness

$1 \text{ psi}\sqrt{\text{in.}} = 1.099 \times 10^{-3} \text{ MPa}\sqrt{\text{m}}$	$1 \text{ MPa}\sqrt{\text{m}} = 910 \text{ psi}\sqrt{\text{in.}}$

Energy

$1 \text{ J} = 10^7 \text{ ergs}$	$1 \text{ erg} = 10^{-7} \text{ J}$
$1 \text{ J} = 6.24 \times 10^{18} \text{ eV}$	$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$
$1 \text{ J} = 0.239 \text{ cal}$	$1 \text{ cal} = 4.184 \text{ J}$
$1 \text{ J} = 9.48 \times 10^{-4} \text{ Btu}$	$1 \text{ Btu} = 1054 \text{ J}$
$1 \text{ J} = 0.738 \text{ ft} \cdot \text{lb}_f$	$1 \text{ ft} \cdot \text{lb}_f = 1.356 \text{ J}$
$1 \text{ eV} = 3.83 \times 10^{-20} \text{ cal}$	$1 \text{ cal} = 2.61 \times 10^{19} \text{ eV}$
$1 \text{ cal} = 3.97 \times 10^{-3} \text{ Btu}$	$1 \text{ Btu} = 252.0 \text{ cal}$

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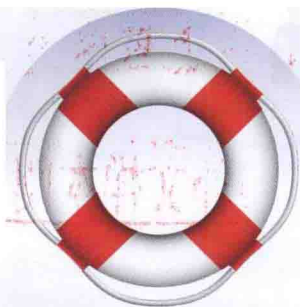
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Dedicated to
Bill Stenquist, editor and friend

Preface

In this ninth edition we 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 freshmen calculus, chemistry, and physics courses.

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 we 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 addition, in most cases, some practical relevance is provided.

The fourth objective is to include features in the book that will expedite the learning process. These learning aids include the following:

- Numerous illustrations, now presented in full color, and photographs to help visualize what is being presented
- Learning objectives, to focus students' attention on what they should be getting from each chapter
- "Why Study ..." and "Materials of Importance" items as well as case studies that provide relevance to topic discussions
- "Concept Check" questions that test whether a student understands the subject matter on a conceptual level
- Key terms, and descriptions of key equations, highlighted in the margins for quick reference
- End-of-chapter questions and problems designed to progressively develop students' understanding of concepts and facility with skills
- Answers to selected problems, so students can check their work
- A glossary, a global list of symbols, and references to facilitate understanding of the subject matter
- End-of-chapter summary tables of important equations and symbols used in these equations
- Processing/Structure/Properties/Performance correlations and summary concept maps for four materials (steels, glass-ceramics, polymer fibers, and silicon semiconductors), which integrate important concepts from chapter to chapter
- Materials of Importance sections that lend relevance to topical coverage by discussing familiar and interesting materials and their applications

The fifth objective is to enhance the teaching and learning process by using the newer technologies that are available to most instructors and today's engineering students.

New/Revised Content

Several important changes have been made with this ninth edition. One of the most significant is the incorporation of several new sections, as well as revisions/amplifications of other sections. These include the following:

- Reorganization in the sequencing and content of several chapters. These changes were made in response to suggestions from adopters of previous editions.
- Numerous new and revised example problems
- Revised, expanded, and updated tables
- Two new case studies: "Liberty Ship Failures" (Chapter 1) and "Use of Composites in the Boeing 787 Dreamliner" (Chapter 16)
- 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 6)
- New section on the structure of carbon fibers (Chapter 14)
- Revised/expanded discussions on structures, properties, and applications of the nanocarbons: fullerenes, carbon nanotubes, and graphene (Chapter 14)
- Revised/expanded discussion on structural composites: laminar composites and sandwich panels (Chapter 16)
- New section on structure, properties, and applications of nanocomposite materials (Chapter 16)
- Tutorial videos. In *WileyPLUS*, Tutorial Videos help students with their "muddiest points" in conceptual understanding and problem-solving.
- Exponents and logarithms. In *WileyPLUS*, the exponential functions and natural logarithms have been added to the Exponents and Logarithms section of the Math Skills Review.

Online Learning Resources—Student Companion Site at www.wiley.com/college/callister.

Also found on the book's website is a Students' Companion page on which are posted several important instructional elements for the student that complement the text; these include the following:

- **Answers to Concept Check questions**, questions which are found in the print book.
- **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. Five 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; and (5) 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.
- **Index of Learning Styles.** Upon answering a 44-item questionnaire, a user's learning-style preference (i.e., the manner in which information is assimilated and processed) is assessed.

Online Resources for Instructors—Instructors Companion Site at 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.** (Except for the Student Lecture PowerPoint® Slides.)
- **Instructor Solutions Manual.** Detailed solutions for all end-of-chapter questions and problems (in both Word® and Adobe Acrobat® PDF formats).
- *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.
- **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.

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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: billcallister@comcast.net.

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 for their feedback and suggestions for this edition.

List of Symbols

The number of the section in which a symbol is introduced or explained is given in parentheses.

A = area

$\mathring{A}$ = angstrom unit

A_i = atomic weight of element i (2.2)

APF = atomic packing factor (4.2)

a = lattice parameter: unit cell x-axial length (4.2)

a = crack length of a surface crack (10.5)

at% = atom percent (6.6)

B = magnetic flux density (induction) (21.2)

B_r = magnetic remanence (21.7)

BCC = body-centered cubic crystal structure (4.3)

b = lattice parameter: unit cell y-axial length (3.4)

$\mathbf{b}$ = Burgers vector (6.7)

C = capacitance (19.18)

C_i = concentration (composition) of component i in wt% (6.6)

C_i' = concentration (composition) of component i in at% (6.6)

C_v, C_p = heat capacity at constant volume, pressure (20.2)

CPR = corrosion penetration rate (18.3)

CVN = Charpy V-notch (10.6)

%CW = percent cold work (9.10)

c = lattice parameter: unit cell z-axial length (3.4)

c = velocity of electromagnetic radiation in a vacuum (22.2)

D = diffusion coefficient (7.3)

D = dielectric displacement (19.19)

DP = degree of polymerization (5.5)

d = diameter

d = average grain diameter (9.8)

d_{hkl} = interplanar spacing for planes of Miller indices h, k, and l (4.19)

E = energy (2.5)

E = modulus of elasticity or Young's modulus (8.3)

$\mathcal{E}$ = electric field intensity (19.3)

E_f = Fermi energy (19.5)

E_g = band gap energy (19.6)

$E_r(t)$ = relaxation modulus (15.4)

%EL = ductility, in percent elongation (8.4)

e = electric charge per electron (19.7)

e^- = electron (18.2)

erf = Gaussian error function (7.4)

exp = e, the base for natural logarithms

F = force, interatomic or mechanical (2.5, 8.2)

$\mathcal{F}$ = Faraday constant (18.2)

FCC = face-centered cubic crystal structure (4.2)

G = shear modulus (8.3)

H = magnetic field strength (21.2)

H_c = magnetic coercivity (21.7)

HB = Brinell hardness (8.5)

HCP = hexagonal close-packed crystal structure (4.4)

HK = Knoop hardness (8.5)

HRB, HRF = Rockwell hardness: B and F scales (8.5)

HR15N, HR45W = superficial Rockwell hardness: 15N and 45W scales (8.5)

HV = Vickers hardness (8.5)

h = Planck's constant (22.2)

(hkl) = Miller indices for a crystallographic plane (3.7)

$(hkil)$ = Miller indices for a crystallographic plane, hexagonal crystals (3.7)

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 (7.3)

J = electric current density (19.3)

K_c = fracture toughness (10.5)

K_{Ic} = plane strain fracture toughness for mode I crack surface displacement (10.5)

k = Boltzmann's constant (6.2)

k = thermal conductivity (20.4)

l = length

l_c = critical fiber length (16.4)

$\ln$ = natural logarithm

$\log$ = logarithm taken to base 10

M = magnetization (21.2)

$\overline{M}_n$ = polymer number-average molecular weight (5.5)

$\overline{M}_w$ = polymer weight-average molecular weight (5.5)

mol% = mole percent

N = number of fatigue cycles (10.8)

N_A = Avogadro's number (4.5)

N_f = fatigue life (10.8)

n = principal quantum number (2.3)

n = number of atoms per unit cell (4.5)

n = strain-hardening exponent (8.4)

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 (4.10)

n_i = intrinsic carrier (electron and hole) concentration (19.10)

P = dielectric polarization (19.19)

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 (19.18)

R = atomic radius (4.2)

R = gas constant

%RA = ductility, in percent reduction in area (8.4)

r = interatomic distance (2.5)

r = reaction rate (18.3)

r_A, r_C = anion and cation ionic radii (4.6)

S = fatigue stress amplitude (10.8)

SEM = scanning electron microscopy or microscope

T = temperature

T_c = Curie temperature (21.6)

T_C = superconducting critical temperature (21.12)

T_g = glass transition temperature (15.12, 17.8)

T_m = melting temperature

TEM = transmission electron microscopy or microscope

TS = tensile strength (8.4)

t = time

t_r = rupture lifetime (10.12)

U_r = modulus of resilience (8.4)

$[uvw]$ = indices for a crystallographic direction (3.6)

$[uvtw], [UVW]$ = indices for a crystallographic direction, hexagonal crystals (3.6)

V = electrical potential difference (voltage) (18.2, 19.2)

V_C = unit cell volume (4.4)

V_C = corrosion potential (18.4)

V_H = Hall voltage (19.14)

V_i = volume fraction of phase i (11.8)

v = velocity

vol% = volume percent

W_i = mass fraction of phase i (11.8)

wt% = weight percent (6.6)

x = length

x = space coordinate

Y = dimensionless parameter or function in fracture toughness expression (10.5)

y = space coordinate

z = space coordinate

α = lattice parameter: unit cell y–z interaxial angle (3.4)

α, β, γ = phase designations

α_l = linear coefficient of thermal expansion (20.3)

β = lattice parameter: unit cell x–z interaxial angle (3.4)

γ = lattice parameter: unit cell x–y interaxial angle (3.4)

γ = shear strain (8.2)

Δ = precedes the symbol of a parameter to denote finite change

ϵ = engineering strain (8.2)

ϵ = dielectric permittivity (19.18)

ϵ_r = dielectric constant or relative permittivity (19.18)

$\dot{\epsilon}_s$ = steady-state creep rate (10.12)

ϵ_T = true strain (8.4)

η = viscosity (14.8)

η = overvoltage (18.4)

2θ = Bragg diffraction angle (4.20)

θ_D = Debye temperature (20.2)

λ = wavelength of electromagnetic radiation (4.19)

μ = magnetic permeability (21.2)

μ_B = Bohr magneton (21.2)

μ_r = relative magnetic permeability (21.2)

μ_e = electron mobility (19.7)

μ_h = hole mobility (19.10)

ν = Poisson's ratio (8.3)

ν = frequency of electromagnetic radiation (22.2)

ρ = density (4.5)

ρ = electrical resistivity (19.2)

ρ_t = radius of curvature at the tip of a crack (10.5)

σ = engineering stress, tensile or compressive (8.2)

σ = electrical conductivity (19.3)

σ^* = longitudinal strength (composite) (16.5)

σ_c = critical stress for crack propagation (10.5)

σ_{fs} = flexural strength (14.7)

σ_m = maximum stress (10.5)

σ_m = mean stress (10.7)

σ'_m = stress in matrix at composite failure (16.5)

σ_T = true stress (8.4)

σ_w = safe or working stress (8.7)

σ_y = yield strength (8.4)

τ = shear stress (8.2)

τ_c = fiber–matrix bond strength/ matrix shear yield strength (16.4)

τ_{crss} = critical resolved shear stress (9.5)

χ_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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