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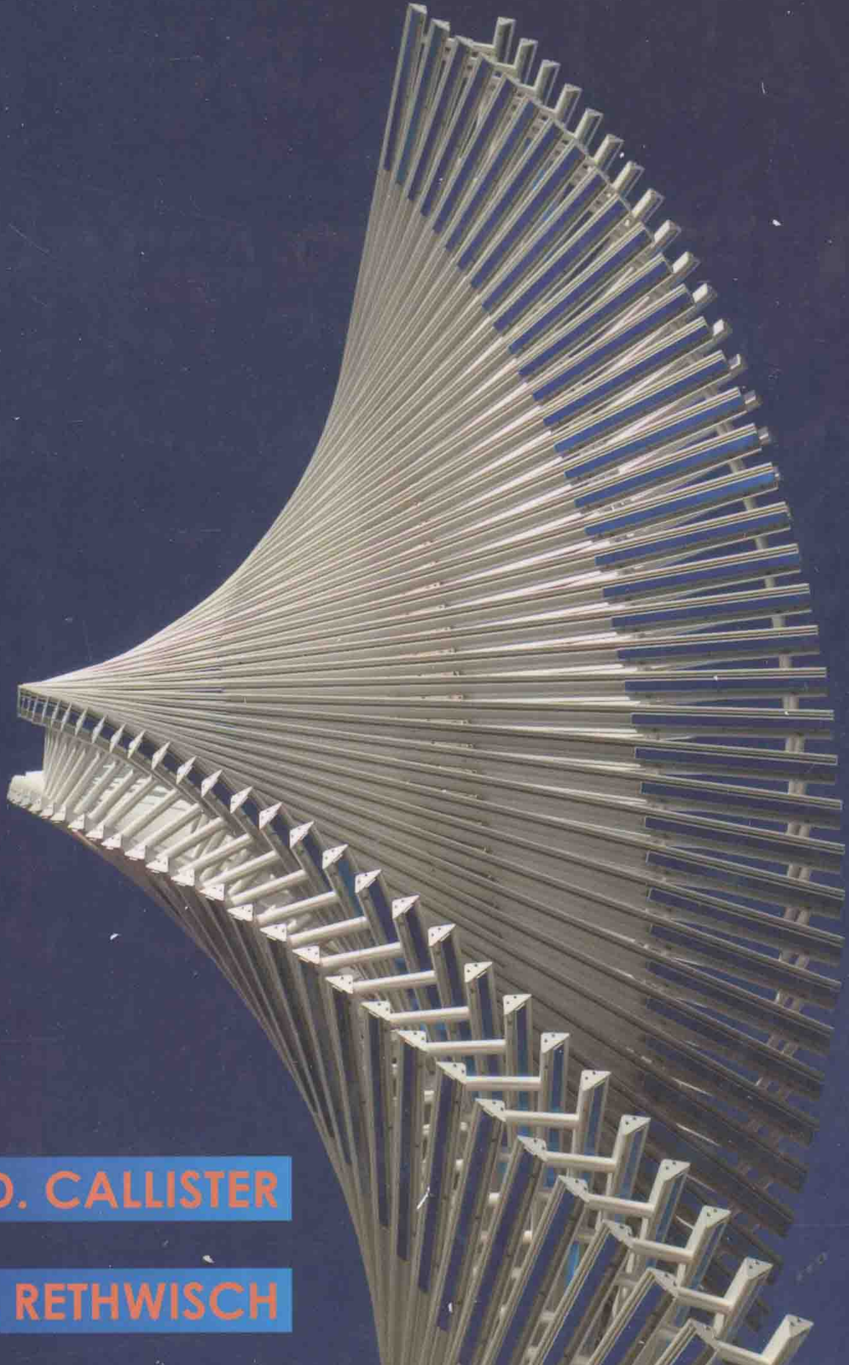
Materials Science and Engineering



WILLIAM D. CALLISTER

DAVID G. RETHWISCH

SI Version

EIGHTH EDITION

Materials Science and Engineering

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SI Version

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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

Values of Selected Physical Constants

Quantity	*Symbol*	*SI Units*	*cgs Units*
Avogadro's number	N_A	6.022×10^{23} molecules/mol	6.022×10^{23} molecules/mol
Boltzmann's constant	k	1.38×10^{-23} J/atom · K	1.38×10^{-16} erg/atom · K 8.62×10^{-5} eV/atom · K
Bohr magneton	μ_B	9.27×10^{-24} A · m^2	9.27×10^{-21} erg/gauss[a]
Electron charge	e	1.602×10^{-19} C	4.8×10^{-10} statcoul[b]
Electron mass	—	9.11×10^{-31} kg	9.11×10^{-28} g
Gas constant	R	8.31 J/mol · K	1.987 cal/mol · K
Permeability of a vacuum	μ_0	1.257×10^{-6} henry/m	unity[a]
Permittivity of a vacuum	ϵ_0	8.85×10^{-12} farad/m	unity[b]
Planck's constant	h	6.63×10^{-34} J · s	6.63×10^{-27} erg · s 4.13×10^{-15} eV · s
Velocity of light in a vacuum	c	3×10^8 m/s (3×10^{10} cm/s)	9.8×10^8 ft/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	μm	= micrometer (micron)
eV	= electron volt	Mg	= megagram	W	= watt
°F	= degrees Fahrenheit	mm	= millimeter	psi	= pounds per square inch
ft	= foot	mol	= mole		
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	μ
10^{-9}	nano	n
10^{-12}	pico	p

[a] Avoided when possible.

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MAKE IT YOURS!

Dedicated to

our wives, Nancy and Ellen, whose love, patience, and understanding have helped make this volume possible

Preface

In this Eighth 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. In order to achieve this goal, we 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 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; 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, now presented in full color, and photographs to help visualize what is being presented;
- Learning objectives, to focus student attention on what they should be getting from each chapter;
- "Why Study . . ." and "Materials of Importance" items that provide relevance to topic discussions;
- "Concept Check" questions that test whether or not 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 that students can check their work;
- A glossary, list of symbols, and references to facilitate understanding the subject matter.

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

Features That Are New to This Edition

New/Revised Content

Several important changes have been made with this Eighth Edition. One of the most significant is the incorporation of a number of new sections, as well as revisions/amplifications of other sections. New sections/discussions are as follows:

- Diffusion in semiconductors (Section 5.6).
- Flash memory (in Section 18.15).
- "Biodegradable and Biorenewable Polymers/Plastics" Materials of Importance piece in Chapter 22.

Other revisions and additions include the following:

- Expanded discussion on nanomaterials (Section 1.5).
- A more comprehensive discussion on the construction of crystallographic directions in hexagonal unit cells—also of conversion from the three-index scheme to four-index (Section 3.9).
- Expanded discussion on titanium alloys (Section 11.3).
- Revised and enlarged treatment of hardness and hardness testing of ceramics (Section 12.11).
- Updated discussion on the process for making sheet glass (in Section 13.9).
- Updates on magnetic storage (hard disk drives and magnetic tapes—Section 20.11).
- Minor updates and revisions in Chapter 22 ("Economic, Environmental, and Societal Issues in Materials Science and Engineering"), especially on recycling.
- **Appendix C ("Costs and Relative Costs for Selected Engineering Materials")** has been updated.
- **End-of chapter summaries** have been revised to reflect answers/responses to the extended lists of learning objectives, to better serve students as a study guide.
- **Summary table of important equations** at the end of each chapter.
- **Summary list of symbols** at the end of each chapter.
- **New chapter-opener photos and layouts,** focusing on applications of materials science to help engage students and motivate a desire to learn more about materials science.
- Virtually all **Homework problems** requiring computations have been refreshed.

Processing/Structure/Properties/Performance Correlations

One new feature that has been incorporated throughout this new edition is a tracking of relationships among the processing, structure, properties, and performance components for four different materials: steel alloys, glass-ceramics, polymer fibers, and silicon semiconductors. This concept is outlined in Chapter 1 (Section 1.7), which includes the presentation of a "topic timeline." This timeline notes those locations (by section) where discussions involving the processing, structure, properties, and performance of each of these four material types are found.

These discussions are introduced in the "Why Study?" sections of appropriate chapters, and, in addition, end-of-chapter summaries with relational diagrams are also included. Finally, for each of the four materials a processing/structure/properties/

performance summary appears at the end of that chapter in which the last item on the topic timeline appears.

Discipline-Specific Modules

A set of discipline-specific modules appear on the book's web site (Student Companion Site). These modules treat materials science/engineering topics not covered in the print text that are relevant to specific engineering disciplines—mechanical and biomaterials.

All Chapters Now In Print

Five chapters of the previous edition were in electronic format only (i.e., not in print). In this edition, *all chapters are in print.*

Case Studies

In prior editions, "Materials Selection and Design Considerations" consisted of a series of case studies that were included as Chapter 22. These case studies will now appear as a library of case studies on the book's web site (Student Companion Site) at *www.wiley.com/go/global/callister.* This library includes the following:

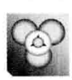
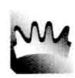
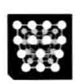
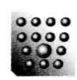
- Materials Selection for a Torsionally Stressed Cylindrical Shaft
- Automobile Valve Spring
- Failure of an Automobile Rear Axle
- Artificial Total Hip Replacement
- Chemical Protective Clothing
- Materials for Integrated Circuit Packages

Student Learning Resources (*www.wiley.com/go/global/callister*)

Also found on the book's web site (Student Companion Site) are several important instructional elements for the student that complement the text; these include the following:

1. *VMSE: Virtual Materials Science and Engineering.* This is an expanded version of the software program that accompanied the previous edition. It consists of interactive simulations and animations that enhance the learning of key concepts in materials science and engineering, and, in addition, a materials properties/cost database. Students can access *VMSE* via the registration code included on the inside front cover of the textbook.

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

Metallic Crystal Structures and Crystallography		Phase Diagrams	
Ceramic Crystal Structures		Diffusion	
Repeat Unit and Polymer Structures		Tensile Tests	
Dislocations		Solid-Solution Strengthening	

2. *Answers to Concept Check questions.* Students can visit the web site to find the correct answers to the Concept Check questions.

3. *Extended Learning Objectives*—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 degree of depth.

4. *Direct access to online self-assessment exercises.* This is a Web-based assessment program that contains questions and problems similar to those found in the text; these problems/questions are organized and labeled according to textbook sections. An answer/solution that is entered by the user in response to a question/problem is graded immediately, and comments are offered for incorrect responses. The student may use this electronic resource to review course material, and to assess his/her mastery and understanding of topics covered in the text.

5. *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.

Instructors' Resources

The Instructor Companion Site (*www.wiley.com/go/global/callister*) is available for instructors who have adopted this text. Please visit the web site to register for access. Resources that are available include the following:

1. *Instructor Solutions Manual.* Detailed solutions of all end-of-chapter questions and problems (in both Word® and Adobe Acrobat® PDF formats).

2. *Photographs, illustrations, and tables that appear in the book.* These are in both PDF and JPEG formats so that an instructor can print them for handouts or prepare transparencies in his/her desired format.

3. *A set of PowerPoint® lecture slides.* These slides, developed by Peter M. Anderson (The Ohio State University), and adapted by the text authors, follow the flow of topics in the text, and include materials from the text and from other sources. Instructors may use the slides as is or edit them to fit their teaching needs.

4. *A list of classroom demonstrations and laboratory experiments.* These portray phenomena and/or illustrate principles that are discussed in the book; references are also provided that give more detailed accounts of these demonstrations.

5. In addition, all of the student learning resources described above are available on the Instructor Companion Site.

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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, would like to solicit feedback on this eighth edition. Comments, suggestions, and criticisms may be submitted to the authors via e-mail at the following address: *billcallister@comcast.net.*

Acknowledgments

Since undertaking 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!

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William D. Callister, Jr.
David G. Rethwisch

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)
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, 6.3)
$\mathscr{F}$ = 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)
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 (13.9, 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)
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)
$\dot{\epsilon}_s$ = steady-state creep rate (8.12)
ϵ_T = true strain (6.7)
η = viscosity (12.10)
η = overvoltage (17.4)
θ = 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