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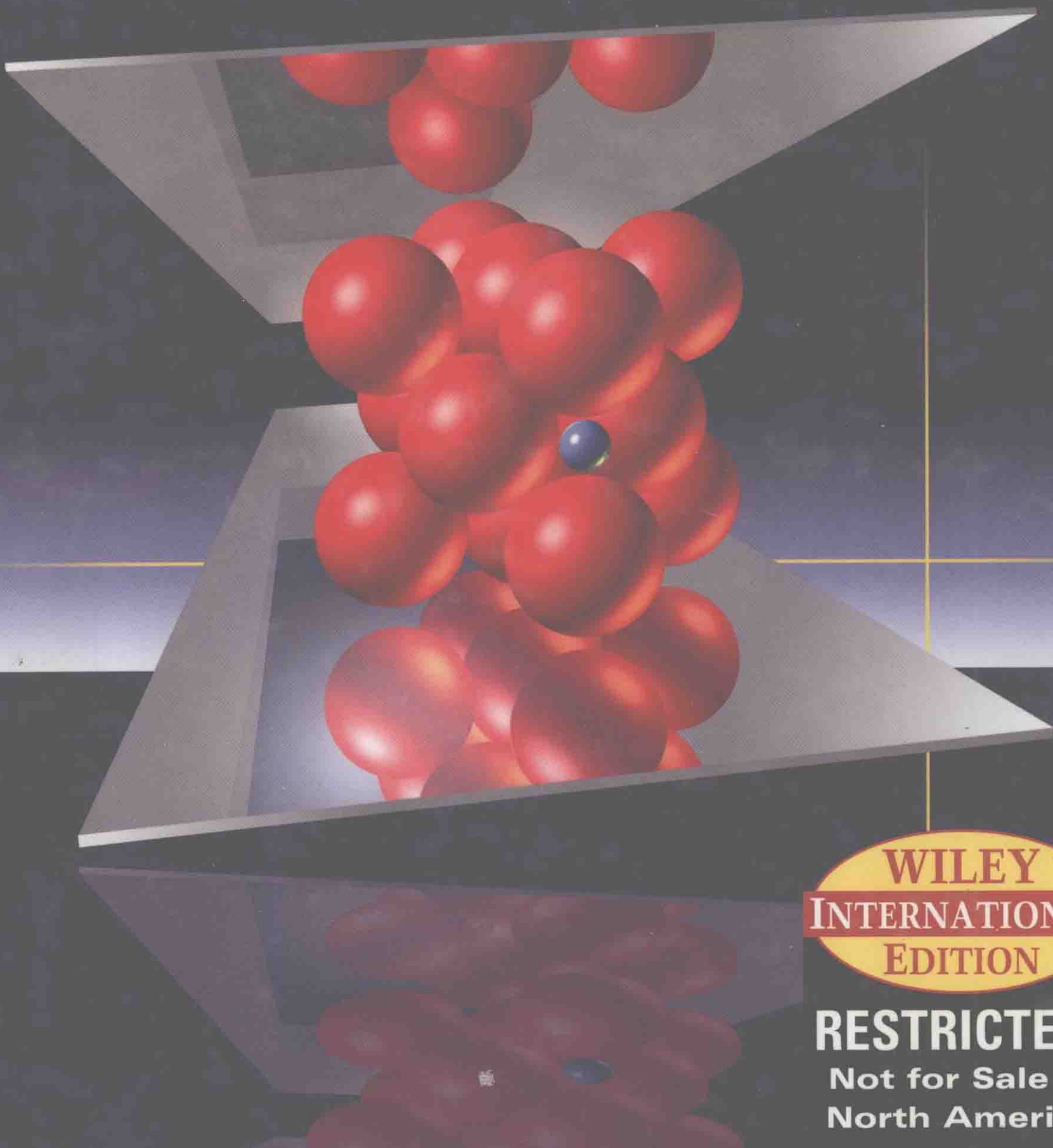
# MATERIALS SCIENCE AND ENGINEERING AN INTRODUCTION

William D. Callister, Jr.



WILEY INTERNATIONAL EDITION

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Sixth Edition

# Materials Science and Engineering

## An Introduction

**William D. Callister, Jr.**

*Department of Metallurgical Engineering*
*The University of Utah*

John Wiley & Sons, Inc.

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# Preface

In this Sixth 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 eleven 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 10, which treat atomic bonding, crystal structures, imperfections, diffusion, mechanical properties, dislocations, failure, phase diagrams, and phase transformations, 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, answers to selected problems, and complete solutions to approximately half of these 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/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

Several important changes have been made with this Sixth Edition. One of the most significant is the incorporation of a number of new sections. Some of these are updates; others involve discussions of topics that have been suggested by adopters of previous editions. These new sections are as follows:

- Materials of the Future (Section 1.6)
- Point Coordinates (Section 3.8)
- Failure of an Automobile Rear Axle (a case study, Section 8.18)
- The Kinetics of Phase Transformations (Section 10.3W)
- Carbon Nanotubes (in Section 12.4, "Carbon")
- Diffusion in Ionic Materials (Section 12.6)
- Defects in Polymers (Section 14.13)
- Diffusion in Polymeric Materials (Section 14.14)

Furthermore, several sections have been revised, to include: "Linear and Planar Densities" (Section 3.11); "Advanced Ceramics" [Section 13.7, which now discusses piezoelectric ceramics, microelectromechanical systems (MEMS), and ceramic ball bearings]; and Sections 18.12 ("Temperature Dependence of Carrier Concentration") and 18.13 ("Factors That Affect Carrier Mobility") which replace Section 19.12 ("The Temperature Variation of Conductivity and Carrier Concentration") of the Fifth Edition.

A number of reorganizational changes have been made with this Sixth Edition. Each of the case studies that appeared in Chapter 23 ("Materials Selection and Design Considerations") of the Fifth Edition has been relocated to that chapter for which the topical coverage is most relevant (e.g., the automobile valve spring case study now appears in Chapter 8, "Failure"). In addition, Chapter 11 ("Thermal Processing of Metal Alloys") and Chapter 12 ("Metal Alloys") of the Fifth Edition have been consolidated into a single chapter, Chapter 11 ("Applications and Processing of Metal Alloys"). There has also been some reordering of the material: metal alloy types (ferrous and nonferrous) are presented first followed by a discussion on the fabrication of metals; then, the thermal processing of metals is treated. Chapter 13 ("Applications and Processing of Ceramics") and Chapter 15 ("Characteristics, Applications, and Processing of Polymers") were reorganized similarly.

The most frequently encountered criticism of this textbook is that it is too long, and with each new edition, the number of pages increases. After struggling with this concern for quite some time, it was decided to decrease the length of this Sixth Edition by transferring several sections involving topics that are covered less frequently to our web site and also to the accompanying *Student Learning Resources* CD, under the title "Additional Coverage of Selected Topics." Decisions as to which topics to exclude from the print component were based on the results of a recent survey of instructors and confirmed by developmental reviews. A list of these non-print sections are as follows:

- X-ray Diffraction: Determination of Crystal Structures—Section 3.16W
- Deformation by Twinning—Section 7.7W
- Crack Propagation Rate (fatigue)—Section 8.10W
- Automobile Valve Spring (case study)—Section 8.13W

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- Extrapolation Methods (creep)—Section 8.16W
- The Gibbs Phase Rule—Section 9.16W
- The Kinetics of Phase Transformations—Section 10.3W
- Prediction of Corrosion Rates—Section 17.4W
- The Hall Effect—Section 18.14W
- Capacitance (under "Dielectric Behavior")—Section 18.18W
- Field Vectors and Polarization—Section 18.19W
- Types of Polarization—Section 18.20W
- Frequency Dependence of the Dielectric Constant—Section 18.21W
- Dielectric Strength—Section 18.22W
- Dielectric Materials—Section 18.23W
- Thermal Protection System on the Space Shuttle Orbiter (case study)—Section 19.6W

Also relocated to the *Student Learning Resources* CD is Chapter 22W, "Economic, Environmental, and Societal Issues in Materials Science and Engineering", which most instructors never covered in class.

Numbers of these sections that appear on the web site and CD are followed by the letter "W", as noted in the above list. Similarly, a "W" suffix is included in all figure, table, and equation numbers for these sections; in addition, in the print component, any text that relates to non-print material is enclosed within braces, { }. And, end-of-chapter questions and problems that can be answered/solved only by consultation of topics found on the web site/CD also have a "W" suffix associated with their numbers.

Furthermore, we have compiled two versions of several sections—a concise (and revised) version, which appears in print, and a detailed version (as in the Fifth Edition), which is allocated to the CD and the web site (also found in "Additional Coverage of Selected Topics"). These two-version sections are as follows: "Principles of Fracture Mechanics" (Section 8.5); "Crack Initiation and Propagation" (Section 8.9); "The Kinetics of Phase Transformations" ("The Kinetics of Solid State Reactions") (Section 10.3); "Isothermal Transformation Diagrams" for discussions of the microstructures of bainite and martensite (Section 10.5); and "Passivity" (Section 17.5).

## Student Learning Resources on CD

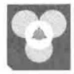
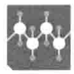
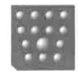
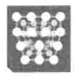
Included as a part of this text package is a CD, entitled *Student Learning Resources to accompany Materials Science and Engineering: An Introduction, Sixth Edition*. It contains several important instructional elements for the student that complement the text; these include the following:

(1) "Additional Coverage of Selected Topics" as detailed above.

(2) *IMSE: Interactive Materials Science and Engineering*. This is the same software program that accompanied the Fifth Edition, and consists of

- Interactive simulations and animations that enhance the learning of key concepts in materials science and engineering.
- A materials properties/cost database.
- *E-Z Solve: The Engineer's Equation Solving and Analysis Tool.*

Throughout the book, whenever there is some text or a problem that is supplemented by *IMSE*, a small "icon" that denotes the associated module is included in the margin. 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 |  |

(3) *Complete Solutions to Selected Problems.* This resource component (available in print in prior editions) contains detailed solutions to approximately half of the end-of-chapter problems which have answers included in the "Answers to Selected Problems" section at the back of the book. A student may use this component for assistance in solving problems, in preparation for examinations, and for further exploration of specific topics.

(4) Direct access to online self-assessment exercises. Clicking on the icon on the CD links the user to *eGrade*, a web-based assessment program that contains a large number of 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) Direct access to additional web resources. These resources include the following:

- *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.
- *Extended Learning Objectives.* A more extensive list of learning objectives than is provided at the beginning of each chapter.
- *Links to Other Web Resources*. These links are categorized according to general, internet, software, teaching, specific course content/activities, and materials databases.

(6) A *User's Guide* to the learning resources on the CD. The guide contains instructions on how to access and utilize the modules in *IMSE* and the other components on the CD.

## Instructors' Resources

An *Instructor's Resource CD* (or *IRCD*) is available for instructors who have adopted this text. It includes the following components:

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

2) Photographs, illustrations, and tables that appear in the book (in PDF and JPEG formats); an instructor can print them for handouts or prepare transparencies in his/her desired format.

3) A set of PowerPoint® lecture slides developed by Peter M. Anderson at The Ohio State University. These slides follow the flow of topics presented in the Sixth Edition and include materials from the text and other sources as well as illustrations and animations developed by Professor Anderson for use in his materials science course. Instructors may use the slides as is or edit them to fit their teaching needs.

4) A list of classroom demonstrations and laboratory experiments 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.

5) Suggested course syllabi for the various engineering disciplines.

In addition to the *IRCD*, instructors who have adopted this text have available to them the instructor's version of *eGrade*. This online assessment program is browser-based and contains a large bank of materials science/engineering problems/questions and their solutions. Instructors have the ability to add their own questions to the database, 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 identifies the student's learning needs. To learn more about this instructor resource go to *www.wiley.com/college/callister*.

## Acknowledgments

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Since I undertook the task of writing my first text on this subject in the early-80'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*
*June 2002*

# 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 (4.4)
$B$ = 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 (18.18W)
$C_i$ = 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 (18.19W)
$d$ = diameter
$d$ = average grain diameter (7.8)
$d_{hkl}$ = interplanar spacing for planes of Miller indices $h$, $k$, and $l$ (3.16W)
$E$ = 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 (17.4W)

$J$ = diffusion flux (5.3)

$J$ = electric current density (18.3)

$K$ = stress intensity factor (8.5W)

$K_c$ = fracture toughness (8.5, 8.5W)

$K_{Ic}$ = plane strain fracture toughness for mode I crack surface displacement (8.5, 8.5W)

$k$ = 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)

$n_n$ = number-average degree of polymerization (14.5)

$n_w$ = weight-average degree of polymerization (14.5)

$P$ = dielectric polarization (18.19W)

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 (18.18W)

$R$ = atomic radius (3.4)

$R$ = gas constant

$r$ = interatomic distance (2.5)

$r$ = reaction rate (10.3, 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 (20.11)

$T_g$ = glass transition temperature (13.8)

$T_m$ = melting temperature

TEM = transmission electron microscopy or microscope

$TS$ = tensile strength (6.6)

$t$ = time

$t_r$ = rupture lifetime (8.14)

$U_r$ = modulus of resilience (6.6)

$[uvw]$ = indices for a crystallographic direction (3.9)

$V$ = electrical potential difference (voltage) (17.2)
$V_C$ = unit cell volume (3.4)
$V_C$ = corrosion potential (17.4W)
$V_H$ = Hall voltage (18.14W)
$V_i$ = volume fraction of phase $i$ (9.7)
$v$ = velocity
vol% = volume percent
$W_i$ = mass fraction of phase $i$ (9.7)
wt% = weight percent (4.4)
$x$ = length
$x$ = space coordinate
$Y$ = dimensionless parameter or function in fracture toughness expression (8.5, 8.5W)
$y$ = 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 (19.3)
$\beta$ = 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)
$\Delta$ = precedes the symbol of a parameter to denote finite change
$\epsilon$ = engineering strain (6.2)
$\epsilon$ = dielectric permittivity (18.18W)
$\epsilon_r$ = dielectric constant or relative permittivity (18.18W)
$\dot{\epsilon}_s$ = steady-state creep rate (8.14)
$\epsilon_T$ = true strain (6.7)
$\eta$ = viscosity (12.10)
$\eta$ = overvoltage (17.4W)
$\theta$ = Bragg diffraction angle (3.16W)
$\theta_D$ = Debye temperature (19.2)
$\lambda$ = wavelength of electromagnetic radiation (3.16W)
$\mu$ = magnetic permeability (20.2)
$\mu_B$ = Bohr magneton (20.2)
$\mu_r$ = relative magnetic permeability (20.2)
$\mu_e$ = electron mobility (18.7)
$\mu_h$ = hole mobility (18.10)
$\nu$ = Poisson's ratio (6.5)
$\nu$ = frequency of electromagnetic radiation (21.2)
$\rho$ = density (3.5)
$\rho$ = electrical resistivity (18.2)
$\rho_t$ = radius of curvature at the tip of a crack (8.5, 8.5W)
$\sigma$ = engineering stress, tensile or compressive (6.2)
$\sigma$ = electrical conductivity (18.3)
$\sigma^*$ = longitudinal strength (composite) (16.5)
$\sigma_c$ = critical stress for crack propagation (8.5, 8.5W)
$\sigma_{fs}$ = flexural strength (12.9)
$\sigma_m$ = maximum stress (8.5, 8.5W)
$\sigma_m$ = mean stress (8.7)
$\sigma'_m$ = stress in matrix at composite failure (16.5)
$\sigma_T$ = 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 (16.4)
$\tau_{crss}$ = critical resolved shear stress (7.5)
$\chi_m$ = 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

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# Contents

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