

Mechanical Behavior of Materials

A balanced mechanics–materials approach and coverage of the latest developments in biomaterials and electronic materials, the new edition of this popular text is the most thorough and modern book available for upper-level undergraduate courses on the mechanical behavior of materials. Kept mathematically simple and with no extensive background in materials assumed, this is an accessible introduction to the subject.

New to this edition:

Every chapter has been revised, reorganised and updated to incorporate modern materials whilst maintaining a logical flow of theory to follow in class.

Mechanical principles of biomaterials, including cellular materials, and electronic materials are emphasized throughout.

A new chapter on environmental effects is included, describing the key relationship between conditions, microstructure and behavior.

New homework problems included at the end of every chapter.

Providing a conceptual understanding by emphasizing the fundamental mechanisms that operate at micro- and nano-meter level across a wide-range of materials, reinforced through the extensive use of micrographs and illustrations, this is the perfect textbook for a course in mechanical behavior of materials, in mechanical engineering, and materials science.

Marc Meyers is a Professor in the Department of NanoEngineering and Mechanical and Aerospace Engineering at the University of California, San Diego. A Co-Founder and Co-Chair of the EXPLOMET Conferences, he has authored numerous texts and won international awards, including the Humboldt Senior Scientist Award (Germany), the TMS Distinguished Scientist/Engineer Awards (USA), and the Lee Hsun Award (China).

Krishan Chawla is a Professor in the Department of Materials Science and Engineering, University of Alabama at Birmingham. He is a Fellow of ASM International, Editor of *International Materials Reviews*, and has worked at various institutions in the Americas and Europe. He has authored several others texts and won numerous awards for his research and teaching.

Cambridge University Press
978-0-521-86675-0 - Mechanical Behavior of Materials
Marc Andre Meyers and Krishan Kumar Chawla
Frontmatter
[More information](#)

Mechanical Behavior of Materials

Marc André Meyers
University of California, San Diego

Krishan Kumar Chawla
University of Alabama at Birmingham



Cambridge University Press
978-0-521-86675-0 - Mechanical Behavior of Materials
Marc Andre Meyers and Krishan Kumar Chawla
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York
www.cambridge.org
Information on this title: www.cambridge.org/9780521866750

© Cambridge University Press 2009

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published in 1998 by Prentice-Hall
Second edition 2009 Cambridge University Press

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-86675-0 hardback

Cambridge University Press has no responsibility for the persistence or
accuracy of URLs for external or third-party Internet websites referred to
in this book and does not guarantee that any content on such
websites is, or will remain, accurate or appropriate.

Cambridge University Press
978-0-521-86675-0 - Mechanical Behavior of Materials
Marc Andre Meyers and Krishan Kumar Chawla
Frontmatter
[More information](#)

Lovingly dedicated to the memory of my parents,
Henri and Marie-Anne.

Marc André Meyers

Lovingly dedicated to the memory of my parents,
Manohar L. and Sumitra Chawla.

Krishan Kumar Chawla

Cambridge University Press
978-0-521-86675-0 - Mechanical Behavior of Materials
Marc Andre Meyers and Krishan Kumar Chawla
Frontmatter
[More information](#)

We dance round in a ring and suppose.
But the secret sits in the middle and knows.
Robert Frost

Contents

<i>Preface to the First Edition</i>	<i>page xvii</i>
<i>Preface to the Second Edition</i>	<i>xxi</i>
<i>A Note to the Reader</i>	<i>xxiii</i>
Chapter 1 Materials: Structure, Properties, and Performance	1
1.1 Introduction	1
1.2 Monolithic, Composite, and Hierarchical Materials	3
1.3 Structure of Materials	15
1.3.1 Crystal Structures	16
1.3.2 Metals	19
1.3.3 Ceramics	25
1.3.4 Glasses	30
1.3.5 Polymers	31
1.3.6 Liquid Crystals	39
1.3.7 Biological Materials and Biomaterials	40
1.3.8 Porous and Cellular Materials	44
1.3.9 Nano- and Microstructure of Biological Materials	45
1.3.10 The Sponge Spicule: An Example of a Biological Material	56
1.3.11 Active (or Smart) Materials	57
1.3.12 Electronic Materials	58
1.3.13 Nanotechnology	60
1.4 Strength of Real Materials	61
Suggested Reading	64
Exercises	65
Chapter 2 Elasticity and Viscoelasticity	71
2.1 Introduction	71
2.2 Longitudinal Stress and Strain	72
2.3 Strain Energy (or Deformation Energy) Density	77
2.4 Shear Stress and Strain	80
2.5 Poisson’s Ratio	83
2.6 More Complex States of Stress	85
2.7 Graphical Solution of a Biaxial State of Stress: the Mohr Circle	89
2.8 Pure Shear: Relationship between G and E	95
2.9 Anisotropic Effects	96
2.10 Elastic Properties of Polycrystals	107
2.11 Elastic Properties of Materials	110
2.11.1 Elastic Properties of Metals	111
2.11.2 Elastic Properties of Ceramics	111
2.11.3 Elastic Properties of Polymers	116
2.11.4 Elastic Constants of Unidirectional Fiber Reinforced Composite	117

2.12	Viscoelasticity	120
2.12.1	Storage and Loss Moduli	124
2.13	Rubber Elasticity	126
2.14	Mooney–Rivlin Equation	131
2.15	Elastic Properties of Biological Materials	134
2.15.1	Blood Vessels	134
2.15.2	Articular Cartilage	137
2.15.3	Mechanical Properties at the Nanometer Level	140
2.16	Elastic Properties of Electronic Materials	143
2.17	Elastic Constants and Bonding	145
	Suggested Reading	155
	Exercises	155
Chapter 3 Plasticity		161
3.1	Introduction	161
3.2	Plastic Deformation in Tension	163
3.2.1	Tensile Curve Parameters	171
3.2.2	Necking	172
3.2.3	Strain Rate Effects	176
3.3	Plastic Deformation in Compression Testing	183
3.4	The Bauschinger Effect	187
3.5	Plastic Deformation of Polymers	188
3.5.1	Stress–Strain Curves	188
3.5.2	Glassy Polymers	189
3.5.3	Semicrystalline Polymers	190
3.5.4	Viscous Flow	191
3.5.5	Adiabatic Heating	192
3.6	Plastic Deformation of Glasses	193
3.6.1	Microscopic Deformation Mechanism	195
3.6.2	Temperature Dependence and Viscosity	197
3.7	Flow, Yield, and Failure Criteria	199
3.7.1	Maximum-Stress Criterion (Rankine)	200
3.7.2	Maximum-Shear-Stress Criterion (Tresca)	200
3.7.3	Maximum-Distortion-Energy Criterion (von Mises)	201
3.7.4	Graphical Representation and Experimental Verification of Rankine, Tresca, and von Mises Criteria	201
3.7.5	Failure Criteria for Brittle Materials	205
3.7.6	Yield Criteria for Ductile Polymers	209
3.7.7	Failure Criteria for Composite Materials	211
3.7.8	Yield and Failure Criteria for Other Anisotropic Materials	213
3.8	Hardness	214
3.8.1	Macroindentation Tests	216
3.8.2	Microindentation Tests	221
3.8.3	Nanoindentation	225
3.9	Formability: Important Parameters	229
3.9.1	Plastic Anisotropy	231

3.9.2	Punch–Stretch Tests and Forming-Limit Curves (or Keeler–Goodwin Diagrams)	232
3.10	Muscle Force	237
3.11	Mechanical Properties of Some Biological Materials	241
	Suggested Reading	245
	Exercises	246
Chapter 4 Imperfections: Point and Line Defects		251
4.1	Introduction	251
4.2	Theoretical Shear Strength	252
4.3	Atomic or Electronic Point Defects	254
4.3.1	Equilibrium Concentration of Point Defects	256
4.3.2	Production of Point Defects	259
4.3.3	Effect of Point Defects on Mechanical Properties	260
4.3.4	Radiation Damage	261
4.3.5	Ion Implantation	265
4.4	Line Defects	266
4.4.1	Experimental Observation of Dislocations	270
4.4.2	Behavior of Dislocations	273
4.4.3	Stress Field Around Dislocations	275
4.4.4	Energy of Dislocations	278
4.4.5	Force Required to Bow a Dislocation	282
4.4.6	Dislocations in Various Structures	284
4.4.7	Dislocations in Ceramics	293
4.4.8	Sources of Dislocations	298
4.4.9	Dislocation Pileups	302
4.4.10	Intersection of Dislocations	304
4.4.11	Deformation Produced by Motion of Dislocations (Orowan’s Equation)	306
4.4.12	The Peierls–Nabarro Stress	309
4.4.13	The Movement of Dislocations: Temperature and Strain Rate Effects	310
4.4.14	Dislocations in Electronic Materials	313
	Suggested Reading	316
	Exercises	317
Chapter 5 Imperfections: Interfacial and Volumetric Defects		321
5.1	Introduction	321
5.2	Grain Boundaries	321
5.2.1	Tilt and Twist Boundaries	326
5.2.2	Energy of a Grain Boundary	328
5.2.3	Variation of Grain-Boundary Energy with Misorientation	330
5.2.4	Coincidence Site Lattice (CSL) Boundaries	332
5.2.5	Grain-Boundary Triple Junctions	334

5.2.6	Grain-Boundary Dislocations and Ledges	334
5.2.7	Grain Boundaries as a Packing of Polyhedral Units	336
5.3	Twinning and Twin Boundaries	336
5.3.1	Crystallography and Morphology	337
5.3.2	Mechanical Effects	341
5.4	Grain Boundaries in Plastic Deformation (Grain-size Strengthening)	345
5.4.1	Hall-Petch Theory	348
5.4.2	Cottrell's Theory	349
5.4.3	Li's Theory	350
5.4.4	Meyers-Ashworth Theory	351
5.5	Other Internal Obstacles	353
5.6	Nanocrystalline Materials	355
5.7	Volumetric or Tridimensional Defects	358
5.8	Imperfections in Polymers	361
	Suggested Reading	364
	Exercises	364
Chapter 6 Geometry of Deformation and Work-Hardening		369
6.1	Introduction	369
6.2	Geometry of Deformation	373
6.2.1	Stereographic Projections	373
6.2.2	Stress Required for Slip	374
6.2.3	Shear Deformation	380
6.2.4	Slip in Systems and Work-Hardening	381
6.2.5	Independent Slip Systems in Polycrystals	384
6.3	Work-Hardening in Polycrystals	384
6.3.1	Taylor's Theory	386
6.3.2	Seeger's Theory	388
6.3.3	Kuhlmann-Wilsdorf's Theory	388
6.4	Softening Mechanisms	392
6.5	Texture Strengthening	395
	Suggested Reading	399
	Exercises	399
Chapter 7 Fracture: Macroscopic Aspects		404
7.1	Introduction	404
7.2	Theoretical Tensile Strength	406
7.3	Stress Concentration and Griffith Criterion of Fracture	409
7.3.1	Stress Concentrations	409
7.3.2	Stress Concentration Factor	409
7.4	Griffith Criterion	416
7.5	Crack Propagation with Plasticity	419
7.6	Linear Elastic Fracture Mechanics	421
7.6.1	Fracture Toughness	422

7.6.2	Hypotheses of LEFM	423
7.6.3	Crack-Tip Separation Modes	423
7.6.4	Stress Field in an Isotropic Material in the Vicinity of a Crack Tip	424
7.6.5	Details of the Crack-Tip Stress Field in Mode I	425
7.6.6	Plastic-Zone Size Correction	428
7.6.7	Variation in Fracture Toughness with Thickness	431
7.7	Fracture Toughness Parameters	434
7.7.1	Crack Extension Force G	434
7.7.2	Crack Opening Displacement	437
7.7.3	J Integral	440
7.7.4	R Curve	443
7.7.5	Relationships among Different Fracture Toughness Parameters	444
7.8	Importance of K_{Ic} in Practice	445
7.9	Post-Yield Fracture Mechanics	448
7.10	Statistical Analysis of Failure Strength	449
	Appendix: Stress Singularity at Crack Tip	458
	Suggested Reading	460
	Exercises	460
Chapter 8 Fracture: Microscopic Aspects		466
8.1	Introduction	466
8.2	Fracture in Metals	468
8.2.1	Crack Nucleation	468
8.2.2	Ductile Fracture	469
8.2.3	Brittle, or Cleavage, Fracture	480
8.3	Fracture in Ceramics	487
8.3.1	Microstructural Aspects	487
8.3.2	Effect of Grain Size on Strength of Ceramics	494
8.3.3	Fracture of Ceramics in Tension	496
8.3.4	Fracture in Ceramics Under Compression	499
8.3.5	Thermally Induced Fracture in Ceramics	504
8.4	Fracture in Polymers	507
8.4.1	Brittle Fracture	507
8.4.2	Crazing and Shear Yielding	508
8.4.3	Fracture in Semicrystalline and Crystalline Polymers	512
8.4.4	Toughness of Polymers	513
8.5	Fracture and Toughness of Biological Materials	517
8.6	Fracture Mechanism Maps	521
	Suggested Reading	521
	Exercises	521
Chapter 9 Fracture Testing		525
9.1	Introduction	525
9.2	Impact Testing	525
9.2.1	Charpy Impact Test	526

9.2.2	Drop-Weight Test	529
9.2.3	Instrumented Charpy Impact Test	531
9.3	Plane-Strain Fracture Toughness Test	532
9.4	Crack Opening Displacement Testing	537
9.5	J-Integral Testing	538
9.6	Flexure Test	540
9.6.1	Three-Point Bend Test	541
9.6.2	Four-Point Bending	542
9.6.3	Interlaminar Shear Strength Test	543
9.7	Fracture Toughness Testing of Brittle Materials	545
9.7.1	Chevron Notch Test	547
9.7.2	Indentation Methods for Determining Toughness	549
9.8	Adhesion of Thin Films to Substrates	552
	Suggested Reading	553
	Exercises	553
Chapter 10 Solid Solution, Precipitation, and Dispersion Strengthening		558
10.1	Introduction	558
10.2	Solid-Solution Strengthening	559
10.2.1	Elastic Interaction	560
10.2.2	Other Interactions	564
10.3	Mechanical Effects Associated with Solid Solutions	564
10.3.1	Well-Defined Yield Point in the Stress–Strain Curves	565
10.3.2	Plateau in the Stress–Strain Curve and Lüders Band	566
10.3.3	Strain Aging	567
10.3.4	Serrated Stress–Strain Curve	568
10.3.5	Snoek Effect	569
10.3.6	Blue Brittleness	570
10.4	Precipitation- and Dispersion-Hardening	571
10.5	Dislocation–Precipitate Interaction	579
10.6	Precipitation in Microalloyed Steels	585
10.7	Dual-Phase Steels	590
	Suggested Reading	590
	Exercises	591
Chapter 11 Martensitic Transformation		594
11.1	Introduction	594
11.2	Structures and Morphologies of Martensite	594
11.3	Strength of Martensite	600
11.4	Mechanical Effects	603
11.5	Shape-Memory Effect	608
11.5.1	Shape-Memory Effect in Polymers	614
11.6	Martensitic Transformation in Ceramics	614
	Suggested Reading	618
	Exercises	619

Chapter 12	Special Materials: Intermetallics and Foams	621
12.1	Introduction	621
12.2	Silicides	621
12.3	Ordered Intermetallics	622
12.3.1	Dislocation Structures in Ordered Intermetallics	624
12.3.2	Effect of Ordering on Mechanical Properties	628
12.3.3	Ductility of Intermetallics	634
12.4	Cellular Materials	639
12.4.1	Structure	639
12.4.2	Modeling of the Mechanical Response	639
12.4.3	Comparison of Predictions and Experimental Results	645
12.4.4	Syntactic Foam	645
12.4.5	Plastic Behavior of Porous Materials	646
	Suggested Reading	650
	Exercises	650
Chapter 13	Creep and Superplasticity	653
13.1	Introduction	653
13.2	Correlation and Extrapolation Methods	659
13.3	Fundamental Mechanisms Responsible for Creep	665
13.4	Diffusion Creep	666
13.5	Dislocation (or Power Law) Creep	670
13.6	Dislocation Glide	673
13.7	Grain-Boundary Sliding	675
13.8	Deformation-Mechanism (Weertman–Ashby) Maps	676
13.9	Creep-Induced Fracture	678
13.10	Heat-Resistant Materials	681
13.11	Creep in Polymers	688
13.12	Diffusion-Related Phenomena in Electronic Materials	695
13.13	Superplasticity	697
	Suggested Reading	705
	Exercises	705
Chapter 14	Fatigue	713
14.1	Introduction	713
14.2	Fatigue Parameters and <i>S–N</i> (Wöhler) Curves	714
14.3	Fatigue Strength or Fatigue Life	716
14.4	Effect of Mean Stress on Fatigue Life	719
14.5	Effect of Frequency	721
14.6	Cumulative Damage and Life Exhaustion	721
14.7	Mechanisms of Fatigue	725

14.7.1	Fatigue Crack Nucleation	725
14.7.2	Fatigue Crack Propagation	730
14.8	Linear Elastic Fracture Mechanics Applied to Fatigue	735
14.8.1	Fatigue of Biomaterials	744
14.9	Hysteretic Heating in Fatigue	746
14.10	Environmental Effects in Fatigue	748
14.11	Fatigue Crack Closure	748
14.12	The Two-Parameter Approach	749
14.13	The Short-Crack Problem in Fatigue	750
14.14	Fatigue Testing	751
14.14.1	Conventional Fatigue Tests	751
14.14.2	Rotating Bending Machine	751
14.14.3	Statistical Analysis of S-N Curves	753
14.14.4	Nonconventional Fatigue Testing	753
14.14.5	Servohydraulic Machines	755
14.14.6	Low-Cycle Fatigue Tests	756
14.14.7	Fatigue Crack Propagation Testing	757
	Suggested Reading	758
	Exercises	759
Chapter 15 Composite Materials		765
15.1	Introduction	765
15.2	Types of Composites	765
15.3	Important Reinforcements and Matrix Materials	767
15.3.1	Microstructural Aspects and Importance of the Matrix	769
15.4	Interfaces in Composites	770
15.4.1	Crystallographic Nature of the Fiber-Matrix Interface	771
15.4.2	Interfacial Bonding in Composites	772
15.4.3	Interfacial Interactions	773
15.5	Properties of Composites	774
15.5.1	Density and Heat Capacity	775
15.5.2	Elastic Moduli	775
15.5.3	Strength	780
15.5.4	Anisotropic Nature of Fiber Reinforced Composites	783
15.5.5	Aging Response of Matrix in MMCs	785
15.5.6	Toughness	785
15.6	Load Transfer from Matrix to Fiber	788
15.6.1	Fiber and Matrix Elastic	789
15.6.2	Fiber Elastic and Matrix Plastic	792
15.7	Fracture in Composites	794
15.7.1	Single and Multiple Fracture	795
15.7.2	Failure Modes in Composites	796
15.8	Some Fundamental Characteristics of Composites	799
15.8.1	Heterogeneity	799

15.8.2	Anisotropy	799
15.8.3	Shear Coupling	801
15.8.4	Statistical Variation in Strength	802
15.9	Functionally Graded Materials	803
15.10	Applications	803
15.10.1	Aerospace Applications	803
15.10.2	Nonaerospace Applications	804
15.11	Laminated Composites	806
	Suggested Reading	809
	Exercises	810
Chapter 16 Environmental Effects		815
16.1	Introduction	815
16.2	Electrochemical Nature of Corrosion in Metals	815
16.2.1	Galvanic Corrosion	816
16.2.2	Uniform Corrosion	817
16.2.3	Crevice corrosion	817
16.2.4	Pitting Corrosion	818
16.2.5	Intergranular Corrosion	818
16.2.6	Selective leaching	819
16.2.7	Erosion-Corrosion	819
16.2.8	Radiation Damage	819
16.2.9	Stress Corrosion	819
16.3	Oxidation of metals	819
16.4	Environmentally Assisted Fracture in Metals	820
16.4.1	Stress Corrosion Cracking (SCC)	820
16.4.2	Hydrogen Damage in Metals	824
16.4.3	Liquid and Solid Metal Embrittlement	830
16.5	Environmental Effects in Polymers	831
16.5.1	Chemical or Solvent Attack	832
16.5.2	Swelling	832
16.5.3	Oxidation	833
16.5.4	Radiation Damage	834
16.5.5	Environmental Crazing	835
16.5.6	Alleviating the Environmental Damage in Polymers	836
16.6	Environmental Effects in Ceramics	836
16.6.1	Oxidation of Ceramics	839
	Suggested Reading	840
	Exercises	840
<i>Appendixes</i>		843
<i>Index</i>		851

Preface to the First Edition

Courses in the mechanical behavior of materials are standard in both mechanical engineering and materials science/engineering curricula. These courses are taught, usually, at the junior or senior level. This book provides an introductory treatment of the mechanical behavior of materials with a balanced mechanics–materials approach, which makes it suitable for both mechanical and materials engineering students. The book covers metals, polymers, ceramics, and composites and contains more than sufficient information for a one-semester course. It therefore enables the instructor to choose the path most appropriate to the class level (junior- or senior-level undergraduate) and background (mechanical or materials engineering). The book is organized into 15 chapters, each corresponding, approximately, to one week of lectures. It is often the case that several theories have been developed to explain specific effects; this book presents only the principal ideas. At the undergraduate level the simple aspects should be emphasized, whereas graduate courses should introduce the different viewpoints to the students. Thus, we have often ignored active and important areas of research. Chapter 1 contains introductory information on materials that students with a previous course in the properties of materials should be familiar with. In addition, it enables those students unfamiliar with materials to “get up to speed.” The section on the theoretical strength of a crystal should be covered by all students. Chapter 2, on elasticity and viscoelasticity, contains an elementary treatment, tailored to the needs of undergraduate students. Most metals and ceramics are linearly elastic, whereas polymers often exhibit nonlinear elasticity with a strong viscous component. In Chapter 3, a broad treatment of plastic deformation and flow and fracture criteria is presented. Whereas mechanical engineering students should be fairly familiar with these concepts, (Section 3.2 can therefore be skipped), materials engineering students should be exposed to them. Two very common tests applied to materials, the uniaxial tension and compression tests, are also described. Chapters 4 through 9, on imperfections, fracture, and fracture toughness, are essential to the understanding of the mechanical behavior of materials and therefore constitute the core of the course. Point, line (Chapter 4), interfacial, and volumetric (Chapter 5) defects are discussed. The treatment is introductory and primarily descriptive. The mathematical treatment of defects is very complex and is not really essential to the understanding of the mechanical behavior of materials at an engineering level. In Chapter 6, we use the concept of dislocations to explain work-hardening; our understanding of this phenomenon, which dates from the 1930s, followed by contemporary developments, is presented. Chapters 7 and 8 deal with fracture from a macroscopic (primarily mechanical) and a microstructural viewpoint, respectively. In brittle materials, the fracture strength under

tension and compression can differ by a factor of 10, and this difference is discussed. The variation in strength from specimen to specimen is also significant and is analyzed in terms of Weibull statistics. In Chapter 9, the different ways in which the fracture resistance of materials can be tested is described. In Chapter 10, solid solution, precipitation, and dispersion strengthening, three very important mechanisms for strengthening metals, are presented. Martensitic transformation and toughening (Chapter 11) are very effective in metals and ceramics, respectively. Although this effect has been exploited for over 4,000 years, it is only in the second half of the 20th century that a true scientific understanding has been gained; as a result, numerous new applications have appeared, ranging from shape-memory alloys to maraging steels, that exhibit strengths higher than 2 GPa. Among novel materials with unique properties that have been developed for advanced applications are intermetallics, which often contain ordered structures. These are presented in Chapter 12. In Chapters 13 and 14, a detailed treatment of the fundamental mechanisms responsible for creep and fatigue, respectively, is presented. This is supplemented by a description of the principal testing and data analysis methods for these two phenomena. The last chapter of the book deals with composite materials. This important topic is, in some schools, the subject of a separate course. If this is the case, the chapter can be omitted.

This book is a spinoff of a volume titled *Mechanical Metallurgy* written by these authors and published in 1984 by Prentice-Hall. That book had considerable success in the United States and overseas, and was translated into Chinese. For the current volume, major changes and additions were made, in line with the rapid development of the field of materials in the 1980s and 1990s. Ceramics, polymers, composites, and intermetallics are nowadays important structural materials for advanced applications and are comprehensively covered in this book. Each chapter contains, at the end, a list of suggested reading; readers should consult these sources if they need to expand a specific point or if they want to broaden their knowledge in an area. Full acknowledgment is given in the text to all sources of tables and illustrations. We might have inadvertently forgotten to cite some of the sources in the final text; we sincerely apologize if we have failed to do so. All chapters contain solved examples and extensive lists of homework problems. These should be valuable tools in helping the student to grasp the concepts presented.

By their intelligent questions and valuable criticisms, our students provided the most important input to the book; we are very grateful for their contributions. We would like to thank our colleagues and fellow scientists who have, through painstaking effort and unselfish devotion, proposed the concepts, performed the critical experiments, and developed the theories that form the framework of an emerging quantitative understanding of the mechanical behavior of materials. In order to make the book easier to read, we have opted to minimize the use of references. In a few places, we have placed them

in the text. The patient and competent typing of the manuscript by Jennifer Natelli, drafting by Jessica McKinnis, and editorial help with text and problems by H. C. (Bryan) Chen and Elizabeth Kristofetz are gratefully acknowledged. Krishan Chawla would like to acknowledge research support, over the years, from the US Office of Naval Research, Oak Ridge National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories. He is also very thankful to his wife, Nivedita; son, Nikhilesh; and daughter, Kanika, for making it all worthwhile! Kanika's help in word processing is gratefully acknowledged. Marc Meyers acknowledges the continued support of the National Science Foundation (especially R. J. Reynik and B. MacDonald), the US Army Research Office (especially G. Mayer, A. Crowson, K. Iyer, and E. Chen), and the Office of Naval Research. The inspiration provided by his grandfather, Jean-Pierre Meyers, and father, Henri Meyers, both metallurgists who devoted their lives to the profession, has inspired Marc Meyers. The Institute for Mechanics and Materials of the University of California at San Diego generously supported the writing of the book during the 1993–96 period. The help provided by Professor R. Skalak, director of the institute, is greatly appreciated. The Institute for Mechanics and Materials is supported by the National Science Foundation. The authors are grateful for the hospitality of Professor B. Ilshner at the École Polytechnique Fédérale de Lausanne, Switzerland during the last part of the preparation of the book.

Marc André Meyers
La Jolla, California

Krishan Kumar Chawla
Birmingham, Alabama

Preface to the Second Edition

The second edition of *Mechanical Behavior of Materials* has revised and updated material in every chapter to reflect the changes occurring in the field. In view of the increasing importance of bioengineering, a special emphasis is given to the mechanical behavior of biological materials and biomaterials throughout this second edition. A new chapter on environmental effects has been added. Professors Fine and Voorhees¹ make a cogent case for integrating biological materials into materials science and engineering curricula. This trend is already in progress at many US and European universities. Our second edition takes due recognition of this important trend. We have resisted the temptation to make a separate chapter on biological and biomaterials. Instead, we treat these materials together with traditional materials, viz., metals, ceramics, polymers, etc. In addition, taking due cognizance of the importance of electronic materials, we have emphasized the distinctive features of these materials from a mechanical behavior point of view.

The underlying theme in the second edition is the same as in the first edition. The text connects the fundamental mechanisms to the wide range of mechanical properties of different materials under a variety of environments. This book is unique in that it presents, in a unified manner, important principles involved in the mechanical behavior of different materials: metals, polymers, ceramics, composites, electronic materials, and biomaterials. The unifying thread running throughout is that the nano/microstructure of a material controls its mechanical behavior. A wealth of micrographs and line diagrams are provided to clarify the concepts. Solved examples and chapter-end exercise problems are provided throughout the text.

This text is designed for use in mechanical engineering and materials science and engineering courses by upper division and graduate students. It is also a useful reference tool for the practicing engineers involved with mechanical behavior of materials. The book does not presuppose any extensive knowledge of materials and is mathematically simple. Indeed, Chapter 1 provides the background necessary. We invite the reader to consult this chapter off and on because it contains very general material.

In addition to the major changes discussed above, the mechanical behavior of cellular and electronic materials was incorporated. Major reorganization of material has been made in the following parts: elasticity; Mohr circle treatment; elastic constants of fiber reinforced composites; elastic properties of biological and of biomaterials; failure criteria of composite materials; nanoindentation technique and its use in extracting material properties; etc. New solved and

¹ M. E. Fine and P. Voorhees, "On the evolving curriculum in materials science & engineering," *Daedalus*, Spring 2005, 134.

chapter-end exercises are added. New micrographs and line diagrams are provided to clarify the concepts.

We are grateful to many faculty members who adopted the first edition for classroom use and were kind enough to provide us with very useful feedback. We also appreciate the feedback we received from a number of students. MAM would like to thank Kanika Chawla and Jennifer Ko for help in the biomaterials area. The help provided by Marc H. Meyers and M. Cristina Meyers in teaching him the rudiments of biology has been invaluable. KKC would like thank K. B. Carlisle, N. Chawla, A. Goel, M. Koopman, R. Kulkarni, and B. R. Patterson for their help. KKC acknowledges the hospitality of Dr. P. D. Portella at Federal Institute for Materials Research and Testing (BAM), Berlin, Germany, where he spent a part of his sabbatical. As always, he is grateful to his family members, Anita, Kanika, Nikhil, and Nivi for their patience and understanding.

Marc André Meyers
University of California, San Diego

Krishan Kumar Chawla
University of Alabama at Birmingham

A Note to the Reader

Our goal in writing *Mechanical Behavior of Materials* has been to produce a book that will be the pre-eminent source of fundamental knowledge about the subject. We expect this to be a guide to the student beyond his or her college years. There is, of course, a lot more material than can be covered in a normal semester-long course. We make no apologies for that in addition to being a classroom text, we want this volume to act as a useful reference work on the subject for the practicing scientist, researcher, and engineer.

Specifically, we have an introductory chapter dwelling on the themes of the book: structure, mechanical properties, and performance. This section introduces some key terms and concepts that are covered in detail in later chapters. We advise the reader to use this chapter as a handy reference tool, and consult it as and when required. We strongly suggest that the instructor use this first chapter as a self-study resource. Of course, individual sections, examples, and exercises can be added to the subsequent material as and when desired.

Enjoy!