Cambridge University Press
978-0-521-86675-0 - Mechanical Behavior of Materials
Marc Andre Meyers and Krishan Kumar Chawla
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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.

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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

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

Robert Frost

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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. Ilschner at the École Polytechnique Fédérale de Lausanne, Switzerland during the last part of the preparation of the book.

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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 Voorhees[1] 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.

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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!