Mechanics of Biomaterials

Teaching mechanical and structural biomaterials concepts for successful medical implant design, this self-contained text provides a complete grounding for students and newcomers to the field. Divided into three sections – Materials, Mechanics, and Case Studies – it begins with a review of sterilization, biocompatibility, and foreign body response before presenting the fundamental structures of synthetic biomaterials and natural tissues. Mechanical behavior of materials is then discussed in depth, covering elastic deformation, viscoelasticity and time-dependent behavior, multiaxial loading and complex stress states, yielding and failure theories, and fracture mechanics. The final section on clinical aspects of medical devices provides crucial information on FDA regulatory issues and presents case studies in four key clinical areas: orthopedics, cardiovascular devices, dentistry, and soft tissue implants. Each chapter ends with a list of topical questions, making this an ideal course textbook for senior undergraduate and graduate students, and also a self-study tool for engineers, scientists, and clinicians.

Lisa A. Pruitt is the Lawrence Talbot Chair of Engineering at the University of California, Berkeley and also serves as an Adjunct Professor in the Department of Orthopedic Surgery at the University of California, San Francisco. She recently served as the Associate Dean of Lifelong Learning and Outreach Education in the College of Engineering and has received numerous awards including the Presidential Award for Excellence in Science, Mathematics, and Engineering Mentoring (2004) and the Graduate Student Instructor Mentor Award from UC Berkeley (2009).

Ayyana M. Chakravartula received her Ph.D. in Mechanical Engineering from the University of California, Berkeley in 2005. She currently works at Exponent, Inc. in Menlo Park, California in its Mechanics and Materials practice. She has worked as a research scientist at the Cambridge Polymer Group in Boston, MA, and has served as an Adjunct Lecturer at Boston University. She has mentored numerous students, interns, and research assistants in her graduate and post-graduate career.

CAMBRIDGE TEXTS IN BIOMEDICAL ENGINEERING

Cambridge Texts in Biomedical Engineering provides a forum for high-quality accessible textbooks targeted at undergraduate and graduate courses in biomedical engineering. It covers a broad range of biomedical engineering topics from introductory texts to advanced topics including, but not limited to, biomechanics, physiology, biomedical instrumentation, imaging, signals and systems, cell engineering, and bioinformatics. The series blends theory and practice, aimed primarily at biomedical engineering students. It also suits broader courses in engineering, the life sciences, and medicine.

Mechanics of Biomaterials is the textbook I have been waiting for. This comprehensive work synthesizes the science and engineering of biomaterials that has developed over the past three decades into a highly useful textbook for training students in two of the senior undergraduate/first-year graduate student courses I teach: Advanced Biomechanics, and Biomaterials and Medical Devices. In fact, as I reviewed this work it felt like I was reviewing my own lecture notes developed over 20 years. The work combines materials science, mechanics and medical device design and analysis in a seamless and thorough manner incorporating many critical studies from the literature into a clear and comprehensive work.

Pruitt and Chakravartula have succeeded in developing an outstanding text and reference book that should be required reading for all who aspire to design, develop and evaluate medical devices.

Jeremy L. Gilbert, *Syracuse University*

The authors have written a detailed yet easy-to-read book that can be used by materials scientists and biomedical engineers, from both the budding biomedical engineering student to the seasoned medical device designer. It combines the fundamentals of plastics, metals, and ceramics behavior with the required properties for the often challenging loading and environmental conditions found in the body. I particularly liked Pruitt and Chakravartula's technique of introducing a detailed discussion of the theoretical explanation of a particular material class's response to a loading environment, and then providing a real-life case study demonstrating how the theoretical response translates to clinical performance.

The book is rich in practical examples of biomaterials used in permanent implants currently on the market. Sufficient historical information is provided on implant successes and failures to appreciate the challenges for material and design selection in the areas of both hard and soft tissue replacement.

Stephen Spiegelberg, *Cambridge Polymer Group, Inc., MA, USA*

Mechanics of Biomaterials: Fundamental Principles for Implant Design provides a much needed comprehensive resource for engineers, physicians, and implant designers at every level of training and practice. The book includes a historical background which outlines the engineering basis of traditional implant designs, and interactions of materials, biology, and mechanics resulting in clinical success or failure of these devices. Each chapter contains a detailed description of the engineering principles which are critical to understand the mechanical behavior of biomaterials and implants in vivo. The scope of the text covers orthopaedics, cardiovascular devices, dental, and soft tissue implants, and should help considerably in our efforts to improve the function and durability of biomaterials and implants used in clinical practice.

Michael Ries, *University of California, San Francisco*

Mechanics of Biomaterials

Fundamental Principles for Implant Design

Lisa A. Pruitt
University of California, Berkeley
Ayyana M. Chakravartula
Exponent, Inc., Menlo Park, California

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi - 110002, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521762212

First published 2011

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

Library of Congress Cataloging in Publication data
Pruitt, Lisa A.
Mechanics of biomaterials : fundamental principles for implant design / Lisa A. Pruitt, Ayyana M. Chakravartula.
p. cm. – (Cambridge texts in biomedical engineering)
Includes bibliographical references and index.
ISBN 978-0-521-76221-2
1. Biomedical materials. 2. Prosthesis – Design and construction. I. Chakravartula, Ayyana M. II. Title. III. Series.
R857.M3P78 2011
610.284 – dc23 2011019855

ISBN 978-0-521-76221-2 Hardback

Cambridge University Press
978-0-521-76221-2 — Mechanics of Biomaterials
Lisa A. Pruitt , Ayyana M. Chakravartula
Frontmatter
More Information

Contents

Cambridge University Press
978-0-521-76221-2 — Mechanics of Biomaterials
Lisa A. Pruitt , Ayyana M. Chakravartula
Frontmatter
More Information

Symbols

Roman letters

a	crack length
a, b, c	characteristic lengths in crystal system
a_T	shift factor for time-temperature superposition
A	area
A, B, C	reciprocal of Miller indices
b	Burgers vector, Basquin exponent
B	thickness
c	maximum distance from neutral axis in beam theory
C	degrees Celsius, Marin factor, material constant in Paris Equation
d	atomic diameter, grain diameter, diameter, incremental fatigue damage
D	total fatigue damage
D_e	Deborah number
E	elastic modulus, energy
F	force, function of, degrees Fahrenheit
g	weight coefficient for generalized Maxwell model
G	shear modulus, energy release rate
h	height, lubricant film thickness, weight coefficient for generalized Kelvin model
h, k, l	Miller indices
H	enthalpy
i	imaginary number defined as $i^2 = -1$
I	area moment of inertia
J	stress invariants, energy release rate
k	stiffness, Archard's coefficient
K	stress intensity factor, degrees Kelvin
l	lamellar thickness, object length
L	load
m	material constant in Paris Equation
M	molecular weight, moment

n	vector normal to plane, number of polymer chains, number of cycles
N	number of fatigue cycles, total number of polymer chains
p	pressure, hydrostatic pressure
P	force
r	interatomic separation, distance from crack tip, radius
R	crystallographic direction vector, radius, resistance to crack growth, roughness
s	deviatoric part of stress tensor
S	stiffness, strength, compliance, stress
t	time, direction of dislocation line, thickness
T	temperature, force
u, v, w	directional vector components
U	energy, bond energy, strain energy
v	viscosity
V	volume, wear volume
w	strain energy density
W	width, work
x	separation distance, degree of crystallinity, distance traveled
x, y, z	spatial coordinates
Y	geometric flaw factor

Greek letters

α	thermal expansion coefficient
α, β, γ	characteristic angles in crystal system
γ	surface energy, shear strain
δ	crack opening displacement, phase shift
ε	strain
η	viscosity
θ	angle
κ	curvature, bulk modulus
λ	mean free spacing of particles
μ	pressure sensitivity coefficient, coefficient of friction
ν	Poisson's ratio, frequency
π	pi
ρ	bond density, atomic packing density, dislocation density, mass density, radius of curvature, length of plastic zone
σ	stress
τ	shear stress, shear strength, relaxation time
ω	rotational velocity, frequency

Cambridge University Press
978-0-521-76221-2 — Mechanics of Biomaterials
Lisa A. Pruitt , Ayyana M. Chakravartula
Frontmatter
More Information

Subscripts

0	equilibrium separation (r_0)
a	amorphous (ρ_a), average (R_a)
c	critical (K_{IC}), crystalline (ρ_c)
f	fracture (σ_f), failure (S_y)
f	final (l_f)
g	glass transition (T_g)
i	initial (l_i)
I, *II*, *III*	fracture mode (K_I)
K	relating to the Kelvin model (ε_K)
m	melt (T_m), mean (σ_m)
max	maximum ($\sigma_{\max}$)
min	minimum ($\sigma_{\min}$)
M	relating to the Maxwell model (ε_M)
n	number average (M_n)
N	normal (F_N)
o	yield (σ_o)
p	plastic zone (r_p)
S	shear (F_S)
SCC	stress corrosion cracking (K_{ISCC})
SLS	relating to the Standard Linear Solid model (ε_{SLS})
th	theoretical (σ_{th})
w	weight average (M_w)
y	yield (σ_y)

Prologue

Mechanics of Biomaterials: Fundamental Principles for Implant Design provides the requisite engineering principles needed for the design of load-bearing medical implants with the intention of successfully employing synthetic materials to restore structural function in biological systems. This textbook makes available a collection of relevant case studies in the areas of orthopedics, cardiology, dentistry, and soft tissue reconstruction and elucidates the functional requirements of medical implants in the context of the specific restorative nature of the device. Each chapter opens with an exploratory question related to the chapter content in order to facilitate inquiry-based learning. Subsequently, a general overview, learning objectives, worked examples, clinical case studies, and problems for consideration are provided for each topic.

The organization of the book is designed to be self-contained, such that a student can be trained to competently engineer and design with biomaterials using the book as a standalone text, while practicing engineers or clinicians working with medical devices may use its content frequently in their careers as a guide and reference. The book comprises three basic sections: (i) overview of the materials science of biological materials and their engineered replacements; (ii) mechanical behavior of materials and structural properties requisite for implants; and (iii) clinical aspects of medical device design.

The first section of this book begins with a synopsis of medical devices and the fundamental issues pertaining to biocompatibility, sterilization, and design of medical implants. Engineered biomaterials including metals, ceramics, polymers, and composites are examined. The first segment of the book concludes with a description of structural tissues. In these chapters, the mechanical properties of common synthetic and natural materials are discussed within the context of their structure-property relationships.

The second portion of the book addresses mechanical behavior of materials and provides the framework for how these properties are important in load-bearing medical implants. This section commences with a review of elastic deformation, constitutive behavior of biomaterials, multiaxial loading, and complex stress states in the body. Elastic behavior is followed by time-dependent behavior and failure theories. The topics of fracture mechanics, fatigue, and tribology and the concomitant design concerns round out this section of the text. Key example problems are carried through successive chapters in this section in order to demonstrate the layered critical thinking that accompanies engineering design decisions.

The final part of the textbook is concerned with the clinical applications of medical devices. This section opens with a broad overview of the FDA, medical device classifications, and regulatory information for implants. Chapters devoted to orthopedics, cardiology, dentistry, and soft tissue repair that include embedded case studies as well as the current challenges associated with implant design in these specialized fields complete the third section of the book.

Appendices that provide the ASTM testing protocols used for medical devices in the FDA regulatory process, structural equations, and teaching strategies that may be employed in the classroom for this multidisciplinary topic appear at the end of the textbook to serve as references for engineers, researchers, clinicians, and faculty working in this field.

The compilation of this textbook is the result of the synergistic efforts of many people. The fundamental technical content has been developed over the past decade through a mezzanine undergraduate-graduate course entitled *Structural Aspects of Biomaterials*. This is a technical elective course designed for students in the fields of bioengineering, materials science, and mechanical engineering and has been evolving since its inception at UC Berkeley in 1998.

This book would not have been possible without the hundreds of dedicated undergraduates and graduate students who enrolled in this course over the past decade. Their continued feedback in course content and format has been invaluable to its development. Doctoral research students in the Medical Polymer Group at UC Berkeley have served as the graduate instructors for this course. They have relentlessly offered their time, pedagogy, and expertise in the implementation of this highly successful course. Specifically, we thank Sara Atwood, Dezba Coughlin, Donna Ebenstein, Jevan Furmanski, Jove Graham, Shikha Gupta, Sheryl Kane, Catherine Klapperich, Cheng Li, and Eli Patten.

For more than a decade we have collaborated with the Lawrence Hall of Science in the development of an annual course project entitled *Body by Design* that has focused on teaching mechanical behavior and medical device technology to elementary school and middle school children in the surrounding communities. We are most grateful to Barbara Ando, Craig Hansen, JohnMichael Selzer, Brooke Smith, and Gretchen Walker for their inspiring commitment to k-12 engineering education. Elements of our outreach teaching and active learning strategies are provided in the Appendix of the textbook. In the educational domain we would also like to acknowledge Rebecca Brent and Richard Felder (National Effective Teaching Institute) for sharing many great practices in pedagogy including methods for teaching to audiences with diverse learning styles, activities for active learning, and formats for inquiry-based learning.

The clinical content of this book has been facilitated by a number of ongoing collaborations in the field of biomaterials science and the medical device research industry. We are most appreciative to Tamara Alliston (University of California, San Francisco), Paul Ashby (Lawrence Berkeley National Labs), Mehdi Balooch (Lawrence Livermore National Labs), Anuj Bellare (Brigham and Women's Hospital), Alessandro Bistolfi (Centro Traumatologico Ortopedico, Torino), Luigi Costa (University of Torino), Avram Ediden (Kyphon), Alistair Elfick (University of Edinburgh), Seth Greenwald (Cleveland

Clinic), Steve Gunther (private practice), Bob Hastings (DePuy Orthopaedics, Inc.), Paul Hansma (University of California, Santa Barbara), Tony Keaveny (University of California, Berkeley), Karen King (University of California, San Francisco), Steve Kurtz (Exponent, Inc.), Steve Kaplan (4th State, Inc.), Kyriakos Komvopoulos (University of California, Berkeley), Jeff Lotz (University of California, San Francisco), Sally Marshall (University of California, San Francisco), Corey Maas (University of California, San Francisco), Tom Norris (San Francisco Shoulders and Elbows), Alan Pelton (Nitinol Devices & Components), Christian Puttlitz (Colorado State University), Michael Ries (University of California, San Francisco), Clare Rimnac (Case Western Reserve University), Robert Ritchie (University of California, Berkeley), David Saloner (University of California, San Francisco), Stephen Spiegelberg (Cambridge Polymer Group, Inc.), Subra Suresh (Massachusetts Institute of Technology), Linda Wang (private practice), Tim Wright (Hospital for Special Surgery), and Thomas Wyrobek (Hysitron, Inc.).

We would like to express gratitude to Dr. Jevan Furmanski for his technical input and contributions to this textbook, especially on the topics of tissues, viscoelasticity, and fracture mechanics. Additionally we thank Dr. Shikha Gupta for her contribution on dental materials. We are indebted to the numerous students who provided the high-quality technical illustrations for this book. We are most thankful to AJ Almaguer, Perry Johnson, Matt Kury, Mimi Lan, David Lari, Amir Mehdizadeh, Helen Wu, as well as Kayla and Eli Patten. We are most grateful for the funding from the Lawrence Talbot Chaired Professorship in Engineering that provided financial support for the technical illustration of this book.

We are deeply indebted to our friends and colleagues who served as our technical editors. In particular we thank Sara Atwood (Elizabethtown College), Bhaskararao Chakravartula, Neela Chakravartula (32BJ Benefit Fund), Dezba Coughlin (University of California, San Francisco), Donna Ebenstein (Bucknell University), Jove Graham (Geisinger Center for Health Research), Shikha Gupta (Food and Drug Administration), Cheng Li (Trivascular, Inc), Elise Morgan (Boston University), Gerry Pruitt (Northrop Grummen), Greg Supple (Hospital of the University of Pennsylvania), and Jingli Wang (PRD USA).

Finally and most important, we thank our families for their unwavering support. This book is dedicated to our families. We are most grateful to Raiden and Will, Savanna and Ric, and Juan and JJ for their relentless support in this process. Thank you.