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Fatigue of Materials

Written by a leading researcher in the field, this revised and updated second edition of a highly successful book provides an authoritative, comprehensive and unified treatment of the mechanics and micromechanisms of fatigue in metals, nonmetals and composites.

The author discusses the principles of cyclic deformation, crack initiation and crack growth by fatigue, covering both microscopic and continuum aspects. The book begins with discussions of cyclic deformation and fatigue crack initiation in monocrystalline and polycrystalline ductile alloys as well as in brittle, semi-crystalline and noncrystalline solids. Total-life and damage-tolerant approaches are then introduced in metals, nonmetals and composites along with such advanced topics as multiaxial fatigue, contact fatigue, variable amplitude fatigue, creep-fatigue, and environmentally assisted fatigue. Emphasis is placed upon scientific concepts and mechanisms and the basic concepts are extended to many practical cases wherever possible. The book includes an extensive bibliography and a problem set for each chapter, together with worked-out example problems and case studies.

The book will be an important reference for students, practicing engineers and researchers studying fracture and fatigue in materials science and engineering, mechanical, civil, nuclear and aerospace engineering, and biomechanics.

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Fatigue of Materials

SECOND EDITION

S. SURESH

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PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011–4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

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First published 1998
Reprinted 2001 (with corrections), 2003

Printed in the United Kingdom at the University Press, Cambridge

Typeset in 10/13pt Times Roman in 3B2 [KWS]

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

Library of Congress Cataloguing in Publication data
Suresh, S. (Subra)
Fatigue of materials / S. Suresh. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 57046 8 (hardcover). – ISBN 0 521 57847 7 (pbk.)
1. Materials – Fatigue. 2. Fracture mechanics. I. Title.
TA418.38.S87 1998
620.1'126–dc21 98-15181 CIP

ISBN 0 521 57046 8 hardback
ISBN 0 521 57847 7 paperback

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To
My wife Mary and our children,
Nina and Meera

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Preface to the second edition

The first edition of this book was written primarily as a research monograph for the Solid State Science Series of Cambridge University Press. Since its first publication, however, the book has found wide readership among students and practicing engineers as well as researchers. In view of this audience base which evolved to be much broader than what the book was originally intended for, it was felt that now would be an appropriate time for the preparation of an updated and revised second edition which includes newer material, example problems, case studies and exercises. In order to have the greatest flexibility in the incorporation of these new items in the book, it was also decided to publish the second edition as a 'stand-alone' book of Cambridge University Press, rather than as a research monograph of the Solid State Science Series.

In writing the second edition, I have adhered to the objectives which are stated in the preface to the first edition. In order to structure the expanded scope coherently, the book is organized in the following manner. The introduction to the subject of fatigue, the overall scope of the book and background information on some of the necessary fundamentals are provided in the first chapter. The book is then divided into four parts. Cyclic deformation and fatigue crack nucleation in ductile, brittle and semi-crystalline or noncrystalline solids are given extensive coverage in Part One. This is followed by discussions of stress-based and strain-based approaches to fatigue in Part Two. Principles of fracture mechanics and the characteristics of fatigue crack growth in ductile, brittle and semi-crystalline or noncrystalline solids are then taken up in separate chapters in Part Three. Part Four comprises advanced topics where, in addition to separate chapters on crack growth retardation under constant and variable amplitude fatigue, small cracks, and environmental interactions, a new chapter on contact fatigue is included. In each chapter, updated material and references, as well as case studies and worked-out and practice problems are included.

Since the publication of the first edition, numerous students, research colleagues and engineers from many countries have provided valuable feedback, constructive criticisms and suggestions. The first edition was translated into the Chinese language in 1993 under the sponsorship of the Chinese Academy of Sciences. Z. G. Wang and his colleagues of the State Key Laboratory for Fracture and Fatigue in Shenyang deserve special thanks for diligently going over the entire manuscript of the first edition and offering many helpful suggestions. Every attempt has been made to respond to these comments in the second edition, while trying to adhere to the main objectives of writing this book. The first edition as well as drafts of the second

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edition were also used by the author as text material for subjects taught for graduate students at the Massachusetts Institute of Technology, Harvard University and Brown University.

I am thankful to many individuals who supplied me with information and original micrographs for the second edition. They include H. Azimi, U. Essmann, W. Milligan, T. Nakamura, A. Pineau, R.O. Ritchie and D.F. Socie. A number of colleagues, especially J. Dominguez, T.C. Lindley, F.A. McClintock, T. Nicholas and L. Pruitt, kindly read drafts of some chapters and offered helpful suggestions. During the preparation of this second edition, I have had the good fortune to interact extensively with four colleagues, A.E. Giannakopoulos, L.P. Kubin, H. Mughrabi and C.F. Shih, who read many sections of the book, and provided helpful criticisms, suggestions on key references, solutions to some practice problems and advice on improvement of presentation. I am most grateful to them for their scholarly feedback and strong interest in this book.

I wish to thank S. Capelin of the Cambridge University Press for his strong and continued support of this book project and for giving me considerable flexibility in the preparation of the manuscript, and to M. Patterson for her efficient copy-editing of the manuscript. K. Greene, D. LaBonte, G. LaBonte, C.-T. Lin and L. Ward deserve special mention for their cheerful help with the preparation of figures and references.

My research work on fatigue has been supported over the years by the U.S. Department of Energy, Office of Naval Research, Air Force Office of Scientific Research, and National Science Foundation. This support is gratefully acknowledged. I thank the Department of Materials Science and Engineering at the Massachusetts Institute of Technology for giving me the flexibility and the time for the preparation of this second edition through the award of the R.P. Simmons Endowed Professorship. In addition, I thank the Swedish Research Council for Engineering Sciences for awarding me the Swedish National Chair in Mechanical Engineering for the period 1996–98 at the Royal Institute of Technology (Kungl Tekniska Högskolan, KTH), Stockholm, where a significant portion of the new material for the second edition was written. I thank the colleagues in the Departments of Solid Mechanics and Materials Science and Engineering at KTH for their hospitality during my stay in Stockholm.

Finally, I express my deepest gratitude to my wife Mary and our daughters Nina and Meera for all their patience and support during the time I spent writing this book. Without their care, affection and tolerance, this project could not have been completed.

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Preface to the first edition

Fatigue of materials refers to the changes in properties resulting from the application of cyclic loads. Research into the deformation and fracture of materials by fatigue dates back to the nineteenth century. This branch of study has long been concerned with engineering approaches to design against fatigue cracks initiation and failure. However, along with the development of 'science of materials' and 'fracture mechanics' in recent decades, *fatigue of materials* has also emerged as a major area of scientific and applied research which encompasses such diverse disciplines as materials science (including the science of metals, ceramics, polymers, and composites), mechanical, civil and aerospace engineering, biomechanics, applied physics and applied mathematics. With the increasing emphasis on advanced materials, the scope of fatigue research continues to broaden at a rapid pace.

This book is written with the purpose of presenting the principles of cyclic deformation and fatigue fracture in materials. The main approach adopted here focuses attention on scientific concepts and mechanisms. Since fatigue of materials is a topic of utmost concern in many engineering applications, this book also includes discussions on the extension of basic concepts to practical situations, wherever appropriate. In writing this book, I have attempted to achieve the following objectives:

(i) To present an integrated treatment, in as quantitative terms as possible, of the mechanics, physics and micromechanisms of cyclic deformation, crack initiation and crack growth by fatigue.
(ii) To provide a unified scientific basis for understanding the fatigue behavior of metals, nonmetals and composites.
(iii) To develop a balanced perspective of the various approaches to fatigue, with a critical analysis of the significance and limitations of each approach.

The topics addressed in this book are developed to the extent that the presentation is sufficiently self-explanatory. The scope of the book is spelled out in Chapter 1. Some background information on the relevant topics is also provided in the first chapter to set the scene for later developments. This book could serve as a state-of-the-art reference guide to researchers interested in the fatigue behavior of materials and as a text for a graduate course on fatigue. Sections of the book could also be used for an introductory course on fatigue for practicing engineers. Senior undergraduate and graduate students taking courses on mechanical behavior of materials or fracture mechanics may find this monograph useful as a supplement to their textbooks.

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Cambridge University Press
978-0-521-57847-9 - Fatigue of Materials, Second Edition
S. Suresh
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Since there exists a vast amount of published information on fatigue of materials which spans a time period of well over a hundred years, it is not feasible to cover all the topics and results on this subject in a single monograph. This situation is further compounded by the fact that *fatigue* is a research area in which one encounters considerable empiricism and conflicting viewpoints. Therefore, I had to rely on my own judgement in the selection of topics and references in order to balance the aforementioned objectives of writing this book. My interpretations of this research area have been shaped over the past twelve years through collaborations, discussions and correspondence with numerous colleagues in the United States and abroad. Their contributions are cited throughout the text and in the bibliography.

In organizing various sections of this book, I have resisted the temptation to categorize materials systems in terms of their individual composition or microstructure, as commonly done in many books on materials. Instead, I have chosen to present a unified treatment of fatigue in different broad classes of materials while, at the same time, pinpointing the significant role of microstructure in influencing cyclic deformation and fracture. The mechanistic and mechanics aspects of fatigue are developed in the early chapters primarily in the context of ductile metals and alloys. These concepts are then extended to brittle solids (such as ceramics and ceramic composites) and to semi-crystalline and noncrystalline solids (such as polymers and organic composites) in later chapters of the book.

I am thankful to many colleagues who supplied me with information and original photographs. These individuals include R.W. Hertzberg, H. Kobayashi, T.C. Lindley, T. Nicholas, T. Ogawa, C.M. Rimnac, R.O. Ritchie and M.T. Takemori. I am indebted to J.R. Brockenbrough, C. Laird, M. Miller, H. Mughrabi, P. Neumann, R.M.N. Pelloux and A.K. Vasudevan for reviewing drafts of various chapters and for offering helpful comments. A special note of gratitude is extended to A.S. Argon who provided insightful suggestions on the presentation of fundamental concepts and to C.F. Shih who kindly read drafts of all the sections dealing with fracture mechanics.

My research work on fatigue has been sponsored over the years by U.S. Department of Energy, National Science Foundation and Office of Naval Research. This support is very much appreciated. My colleagues and students in the Solid Mechanics and Materials Science Groups in the Division of Engineering at Brown University have greatly contributed to my research by providing an intellectually stimulating and friendly environment.

This project was initiated with the encouragement and support of R.W. Cahn. His enthusiasm and interest in this work provided a strong motivation throughout the preparation of the manuscript. A special mention should also be made of R. Bentley, S. Capelin and I. Pizzie of Cambridge University Press for their efficient editorial work on the manuscript and for promptly responding to my queries and concerns. T. Judd skillfully helped with the preparation of figures.

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I express my profound gratitude to my wife Mary for her support, devotion and patience throughout this project. The company of our little daughters Nina and Meera provided joyful breaks from long hours of concentrated work.

Finally, I wish to dedicate this book to my mother Lakshmi on the occasion of her sixtieth birthday. Her countless sacrifices for the sake of my education are gratefully acknowledged.

S. Suresh

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