The Mechanics and Reliability of Films, Multilayers and Coatings

A wide variety of applications ranging from microelectronics to turbines for propulsion and power generation rely on films, coatings and multilayers to improve performance. As such, the ability to predict coating failure – such as delamination (debonding), mud-cracking, blistering, crack kinking and the like – is critical to component design and development. This work compiles and organizes decades of research that established the theoretical foundation for predicting such failure mechanisms and clearly outlines the methodology needed to predict performance. Detailed coverage of cracking in multilayers is provided with an emphasis on the role of differences in thermoelastic properties between the layers. The comprehensive theoretical foundation of the book is complemented by easy-to-use analysis codes designed to empower novices with the tools needed to simulate cracking; these codes enable not only precise quantitative reproduction of results presented graphically in the literature, but also the generation of new results for more complex multilayered systems.

Professor Matthew R. Begley is broadly recognized for seminal contributions in the mechanics of multilayered systems with an emphasis on computational aspects of the required analysis. His codes are employed in some industries to design experiments, assess current designs and evaluate novel multilayer systems for improved performance. Both authors are widely sought after for consulting work on the mechanics of thin films, coatings and multilayers by companies such as General Electric, Pratt & Whitney, Intel, Sunpower, Raytheon, Areva etc.

Professor John W. Hutchinson is a member of the US National Academies of Engineering and Sciences and a Foreign Member of the Royal Society of London. He is one of the leading experts in the mechanics of thin film systems, with a number of highly cited, seminal journal papers on the subject. Hutchinson is broadly credited with generating many of the conceptual developments in this field, as well as illustrations of those concepts to applications ranging from microelectronics to thermal barrier coatings, microfluidic devices, hypersonics etc.

Cambridge University Press
978-1-107-13186-6 — The Mechanics and Reliability of Films, Multilayers and Coatings
Matthew R. Begley , John W. Hutchinson
Frontmatter
More Information

The Mechanics and Reliability of Films, Multilayers and Coatings

MATTHEW R. BEGLEY
University of California, Santa Barbara

JOHN W. HUTCHINSON
Harvard University

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/9781107131866

First published 2017

Printed in the United States of America by Sheridan Books, Inc.

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

Library of Congress Cataloging-in-Publication Data
Names: Begley, Matthew R., 1969– author. | Hutchinson, John W., author.
Title: The mechanics and reliability of films, multilayers and coatings / Matthew R. Begley (University of California, Santa Barbara), John W. Hutchinson (Harvard University).
Description: Cambridge, United Kingdom ; New York, NY : Cambridge University Press, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016036248 | ISBN 9781107131866 (hardback ; alk. paper) | ISBN 1107131863 (hardback ; alk. paper)
Subjects: LCSH: Thin films – Mechanical properties. | Protective coatings – Mechanical properties. | Fracture mechanics.
Classification: LCC TA418.9.T45 B44 2017 | DDC 667/.9–dc23 LC record available at https://lccn.loc.gov/2016036248

ISBN 978-1-107-13186-6 Hardback

Contents

Acknowledgements

This book would not have been possible without the extensive contributions of others, on many levels.

At the most fundamental level, Tony Evans and Zhigang Suo were responsible for much of the scientific foundation utilized in this book, not to mention countless inspirational applications, examples and key insights. Simply put, this book would not exist without their pioneering efforts.

Those pioneering efforts were made possible to a significant degree by the National Science Foundation and Office of Naval Research, who deserve special recognition for supporting the underlying research of the material in this book – not only the authors themselves, but also the entire community working on thin films and coatings.

Cedric and Lily Xia deserve special recognition for the ancestral codes that inspired those in this book; while their original codes have been supplanted, they played in important role in forming the vision for the codes accompanying this book.

R. Wesley Jackson was an early adopter of the codes and made significant contributions to their utility, as well many, many insightful analyses on thermal barrier coatings. It would be difficult to overestimate the practical contributions of Ryan Latture, whose edits sped up the codes by orders of magnitude, and Foucault de Franqueville, who did critical work in validating the codes by conducting an estimated 10^4 analyses. The authors are also deeply indebted to J. William Pro and Stephen Sehr for their help in data management and vetting the codes. Dr. Tyler Ray was a huge help with typesetting the book.

M. R. Begley would also like to acknowledge Carlos Levi, Bob McMeeking, Tresa Pollock and Frank Zok; my wonderful colleagues at UCSB provided encouragement at critical times and covered numerous obligations for me while I was ‘in the bunker’ writing the book. My appreciation for their direct and indirect support cannot be overstated.

Notation

The list below refers to the most common usage:

$\Lambda_U, \Lambda_B, \Lambda_o$	strain energy per unit area in thin strips
α	coefficient of thermal expansion
$\epsilon_{ij}, \sigma_{ij}$	strain and stress tensors, respectively
E, v	elastic modulus and Poisson's ratio
$\bar{E} = E/(1-v^2)$	plane strain modulus
E_*	effective interface modulus, eqn. (3.14)
$\eta_x, \eta_y, \eta_{xy}$	large strain definitions
α_D	first Dundurs' parameter, eqn. (3.9)
β_D	second Dundurs' parameter, eqn. (3.9)
ϵ	mismatch parameter when $\beta_D \neq 0$
θ	stress-free misfit strain, such as thermal expansion
$\bar{c}$	coefficient of misfit strain defined by geometry constraint
$u(x), w(x)$	axial and transverse displacements, respectively
κ	curvature (second derivative of transverse displacement)
ϵ_o	axial stretch of the reference axis
σ_o, σ_c	residual stress and critical stress for buckling
N, M	axial force and bending moment resultants, respectively
a_{ij}, b_j	coefficients in multilayer equations to find ϵ_o and κ
G	energy release rate
K_I, K_{II}	isotropic stress intensity factors
K_1, K_2	interface stress intensity factors
Γ_I, Γ_{II}	interface toughness in mode I and mode II
η	dimensionless stress parameter for kinking/deflection
λ	fitting parameter that dictates mode II toughness
ψ	phase angle that defines mode-mix
ω	phase factor used to compute mode-mix
ΔT	temperature change from stress-free reference state
q	heat flux
k	thermal conductivity