CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

This book addresses the issue of designing the microstructure of fiber composite materials in order to obtain optimum performance. Besides the systematic treatment of conventional continuous and discontinuous fiber composites, the book also presents the state-of-the-art of the development of textile structural composites as well as the nonlinear elastic finite deformation theory of flexible composites.

The author's experience during twenty years of research and teaching on composite materials is reflected in the broad spectrum of topics covered, including laminated composites, statistical strength theories of continuous fiber composites, short fiber composites, hybrid composites, two- and three-dimensional textile structural composites and flexible composites. This book provides the first comprehensive analysis and modeling of the thermomechanical behavior of fiber composites with these distinct microstructures. Overall, the inter-relationships among the processing, microstructures and properties of these materials are emphasized throughout the book.

The book is intended as a text for graduate or advanced undergraduate students, but will also be an excellent reference for all materials scientists and engineers who are researching or working with these materials.

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

Microstructural design of fiber composites

Cambridge Solid State Science Series

EDITORS:

Professor R. W. Cahn
Department of Materials Science and Metallurgy, University of Cambridge

Professor E. A. Davis
Department of Physics, University of Leicester

Professor I. M. Ward
Department of Physics, University of Leeds

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

Titles in print in this series

B. W. Cherry *Polymer surfaces*
D. Hull *An introduction to composite materials*
S. W. S. McKeever *Thermoluminescence of solids*
D. P. Woodruff and T. A. Delchar *Modern techniques of surface science*
C. N. R. Rao and J. Gopalakrishnan *New directions in solid state chemistry*
P. L. Rossiter *The electrical resistivity of metals and alloys*
D. I. Bower and W. F. Maddams *The vibrational spectroscopy of polymers*
S. Suresh *Fatigue of materials*
J. Zarzycki *Glasses and the vitreous state*
R. A. Street *Hydrogenated amorphous silicon*
A. M. Donald and A. H. Windle *Liquid crystalline polymers*
T.-W. Chou *Microstructural design of fiber composites*

© Cambridge University Press www.cambridge.org

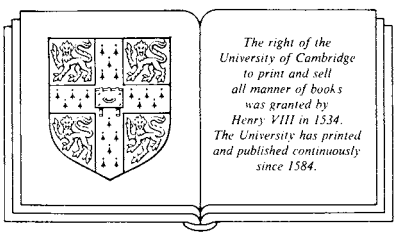
CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

TSU-WEI CHOU

Jerzy L. Nowinski Professor of Mechanical Engineering
University of Delaware

Microstructural design of fiber composites



CAMBRIDGE UNIVERSITY PRESS
Cambridge
New York *Port Chester*
Melbourne *Sydney*

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Victoria 3166, Australia

© Cambridge University Press 1992

First published 1992

British Library Cataloguing in Publication Data
Chou, Tsu-Wei *1940–*
Microstructural design of fiber composites.
1. Fibrous composite materials
I. Title
620.118

Library of Congress Cataloguing in Publication Data
Chou, Tsu-Wei
Microstructural design of fiber composites/Tsu-Wei Chou.
p. cm.—(Cambridge solid state science series)
ISBN 0-521-35482-X
1. Fibrous composites. 2. Microstructure. I. Title.
II. Series.
TA481.5.C48 1992
620.1′18—dc20 90-43347 CIP

ISBN 0 521 35482 X hardback

Transferred to digital printing 2004

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

To Mei-Sheng, Helen, Vivian and Evan

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

Contents

	Preface	**xvii**
1	**Introduction**	**1**
1.1	Evolution of engineering materials	1
1.2	Fiber composite materials	1
1.3	Why composites?	10
	1.3.1 Economic aspect	10
	1.3.2 Technological aspect	12
1.4	Trends and opportunities	17
1.5	Microstructure–performance relationships	19
	1.5.1 Versatility in performance	20
	1.5.2 Tailoring of performance	22
	1.5.3 Intelligent composites	24
1.6	Concluding remarks	26
2	**Thermoelastic behavior of laminated composites**	**29**
2.1	Introduction	29
2.2	Elastic behavior of a composite lamina	30
	2.2.1 Elastic constants	30
	2.2.2 Constitutive relations	33
2.3	Elastic behavior of a composite laminate	39
	2.3.1 Classical composite lamination theory	39
	2.3.2 Geometrical arrangements of laminae	44
2.4	Thick laminates	46
	2.4.1 Three-dimensional constitutive relations of a composite lamina	46
	2.4.2 Constitutive relations of thick laminated composites	48
2.5	Thermal and hygroscopic behavior	54
	2.5.1 Basic equations	55
	2.5.1.1 Constitutive relations	55
	2.5.1.2 Thermal and moisture diffusion equations	61
	2.5.2 Hygroscopic behavior	62
	2.5.2.1 Moisture concentration functions	62
	2.5.2.2 Hygroscopic stress field	65

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

2.5.3 Transient interlaminar thermal stresses 67
2.5.3.1 Transient temperature field 67
2.5.3.2 Thermal stress field 68
2.5.4 Transient in-plane thermal stresses 73
2.5.4.1 Transient temperature field 74
2.5.4.2 Thermal stress field 77

3 Strength of continuous-fiber composites 80
3.1 Introduction 80
3.2 Rule-of-mixtures 81
3.3 Stress concentrations due to fiber breakages 85
3.3.1 Static case 85
3.3.1.1 Single filament failure 85
3.3.1.2 Multi-filament failure 88
3.3.2 Dynamic case 94
3.4 Statistical tensile strength theories 98
3.4.1 Preliminary 98
3.4.2 Strength of individual fibers 102
3.4.3 Strength of fiber bundles 104
3.4.4 Correlations between single fiber and fiber bundle strengths 106
3.4.4.1 Analysis 106
3.4.4.2 Single fiber strength distribution 108
3.4.5 Experimental measurements of Weibull shape parameter 109
3.4.5.1 Single fiber tests 110
3.4.5.2 Loose bundle tests 113
3.4.6 Strength of unidirectional fiber composites 115
3.4.6.1 Equal load sharing 115
3.4.6.2 Idealized local load sharing 118
3.4.6.3 Monte-Carlo simulation 132
3.4.7 Strength of cross-ply composites 134
3.4.7.1 Energy absorption during multiple fracture 134
3.4.7.2 Transverse cracking of cross-ply laminates 136
3.4.7.3 Statistical analysis 145
3.4.7.4 Transverse cracking and Monte-Carlo simulation 150
3.4.8 Delamination in laminates of multi-directional plies 157

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

3.4.8.1 Free-edge delamination 160
3.4.8.2 General delamination problems 165
3.4.9 Enhancement of composite strength through fiber prestressing 166

4 Short-fiber composites 169
4.1 Introduction 169
4.2 Load transfer 169
4.2.1 A single short fiber 170
4.2.2 Fiber–fiber interactions 171
4.3 Elastic properties 176
4.3.1 Unidirectionally aligned short-fiber composites 177
4.3.1.1 Shear-lag analysis 177
4.3.1.2 Self-consistent method 177
4.3.1.3 Bound approach 178
4.3.1.4 Halpin–Tsai equation 181
4.3.2 Partially aligned short-fiber composites 182
4.3.3 Random short-fiber composites 187
4.4 Physical properties 194
4.4.1 Thermal conductivity 194
4.4.2 Thermoelastic constants 198
4.5 Viscoelastic properties 200
4.6 Strength 201
4.6.1 Unidirectionally aligned short-fiber composites 202
4.6.1.1 Fiber length considerations 203
4.6.1.2 Probabilistic strength theory 205
4.6.2 Partially oriented short-fiber composites 216
4.6.3 Random short-fiber composites 224
4.7 Fracture behavior 227

5 Hybrid composites 231
5.1 Introduction 231
5.2 Stress concentrations 233
5.2.1 Static case 233
5.2.2 Dynamic case 243
5.3 Tensile stress–strain behavior 247
5.3.1 Elastic behavior 249
5.3.2 First cracking strain 251
5.3.3 Differential Poisson's effect 254
5.3.4 Differential thermal expansion 256

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

5.4	Strength theories	256
	5.4.1 Rule-of-mixtures	257
	5.4.2 Probabilistic initial failure strength	257
	5.4.3 Probabilistic ultimate failure strength	262
5.5	Softening strips	273
5.6	Mechanical properties	275
5.7	Property optimization analysis	279
	5.7.1 Constitutive relations	279
	5.7.2 Graphical illustration of performance optimization	282
6	**Two-dimensional textile structural composites**	**285**
6.1	Introduction	285
6.2	Textile preforms	287
	6.2.1 Wovens	288
	6.2.2 Knits	292
	6.2.3 Braids	294
6.3	Methodology of analysis	300
6.4	Mosaic model	302
6.5	Crimp (fiber undulation) model	308
6.6	Bridging model and experimental confirmation	314
6.7	Analysis of the knee behavior and summary of stiffness and strength modeling	319
6.8	In-plane thermal expansion and thermal bending coefficients	327
6.9	Hybrid fabric composites: mosaic model	335
	6.9.1 Definitions and idealizations	336
	6.9.2 Bounds of stiffness and compliance constants	340
	6.9.2.1 Iso-strain	341
	6.9.2.2 Iso-stress	343
	6.9.3 One-dimensional approximation	344
	6.9.4 Numerical results	345
6.10	Hybrid fabric composites: crimp and bridging models	348
	6.10.1 Crimp model	349
	6.10.2 Bridging model	352
	6.10.3 Numerical results and summary of thermoelastic properties	354
6.11	Triaxial woven fabric composites	356
	6.11.1 Geometrical characteristics	356
	6.11.2 Analysis of thermoelastic behavior	358
	6.11.3 Biaxial non-orthogonal woven fabric composites	365

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

6.12	Nonlinear stress–strain behavior	366
6.13	Mechanical properties	368
	6.13.1 Friction and wear behavior	368
	6.13.2 Notched strength	371
7	**Three-dimensional textile structural composites**	**374**
7.1	Introduction	374
7.2	Processing of textile preforms	376
	7.2.1 Braiding	377
	7.2.1.1 2-step braiding	377
	7.2.1.2 4-step braiding	379
	7.2.1.3 Solid braiding	382
	7.2.2 Weaving	382
	7.2.2.1 Angle-interlock multi-layer weaving	383
	7.2.2.2 Orthogonal weaving	387
	7.2.3 Stitching	387
	7.2.4 Knitting	389
7.3	Processing windows for 2-step braids	389
	7.3.1 Packing of fibers and yarn cross-sections	390
	7.3.2 Unit cell of the preform	395
	7.3.3 Criterion for yarn jamming	398
7.4	Yarn packing in 4-step braids	402
	7.4.1 Unit cell of the preform	402
	7.4.2 Criterion for yarn jamming	403
7.5	Analysis of thermoelastic behavior of composites	405
	7.5.1 Elastic strain-energy approach	406
	7.5.2 Fiber inclination model	407
	7.5.3 Macro-cell approach	414
	7.5.3.1 Geometric relations	414
	7.5.3.2 Elastic constants	416
7.6	Structure–performance maps of composites	419
7.7	Mechanical properties of composites	428
	7.7.1 Tensile and compressive behavior	428
	7.7.2 Shear behavior	431
	7.7.3 Fracture behavior	432
	7.7.3.1 In-plane fracture	432
	7.7.3.2 Interlaminar fracture	435
	7.7.4 Impact	440
8	**Flexible composites**	**443**
8.1	Introduction	443
8.2	Cord/rubber composites	445

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

8.2.1 Rubber and cord properties 446
8.2.2 Unidirectional composites 447
8.2.3 Laminated composites 449
8.2.4 Cord loads in tires 453
8.3 Coated fabrics 456
8.4 Nonlinear elastic behavior – incremental analysis 459
8.4.1 Geometry of wavy fibers 460
8.4.2 Axial tensile behavior 462
8.4.2.1 Iso-phase model 462
8.4.2.2 Random-phase model 465
8.4.2.3 Nonlinear tensile stress–strain behavior 467
8.4.3 Transverse tensile behavior 471
8.4.3.1 Iso-phase model 471
8.4.3.2 Random-phase model 472

9 Nonlinear elastic finite deformation of flexible composites 474
9.1 Introduction 474
9.2 Background 478
9.2.1 Tensor notation 478
9.2.2 Lagrangian and Eulerian descriptions 480
9.3 Constitutive relations based on the Lagrangian description 485
9.3.1 Finite deformation of a composite lamina 485
9.3.2 Constitutive equations for a composite lamina 487
9.3.2.1 Strain-energy function 487
9.3.2.2 General constitutive equations for a unidirectional lamina 488
9.3.2.3 Pure homogeneous deformation 490
9.3.2.4 Simple shear 492
9.3.2.5 Simple shear superposed on simple extension 495
9.3.3 Constitutive equations of flexible composite laminates 499
9.3.3.1 Constitutive equations 499
9.3.3.2 Homogeneous deformation 500
9.3.3.3 Simple extension of a symmetric composite laminate 502
9.3.4 Determination of elastic constants 505
9.3.4.1 Tensile properties 505
9.3.4.2 Shear properties 506

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

9.4 Constitutive relations based on the Eulerian description 508
9.4.1 Stress-energy function 509
9.4.2 General constitutive equations 511
9.4.3 Pure homogeneous deformation 514
9.4.4 Simple shear superposed on simple extension 515
9.4.5 Determination of elastic compliance constants 517
9.5 Elastic behavior of flexible composites reinforced with wavy fibers 519
9.5.1 Introduction 519
9.5.2 Longitudinal elastic behavior based on the Lagrangian approach 520
9.5.3 Longitudinal elastic behavior based on the Eulerian approach 522

References **526**

Author index **556**
Subject index **563**

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

Preface

The science and technology of composite materials are based on a design concept which is fundamentally different from that of conventional structural materials. Metallic alloys, for instance, generally exhibit a uniform field of material properties; hence, they can be treated as homogeneous and isotropic. Fiber composites, on the other hand, show a high degree of spacial variation in their microstructures, resulting in non-uniform and anisotropic properties. Furthermore, metallic materials can be shaped into desired geometries through secondary work (e.g. rolling, extrusion, etc.); the macroscopic configuration and the microscopic structure of a metallic component are related through the processing route it undergoes. With fiber composites, the co-relationship between microstructure and macroscopic configuration and their dependence on processing technique are even stronger. As a result, composites technology offers tremendous potential to design materials for specific end uses at various levels of scale.

First, at the microscopic level, the internal structure of a component can be controlled through processing. A classical example is the molding of short-fiber composites, where fiber orientation, fiber length and fiber distribution may be controlled to yield the desired local properties. Other examples can be found in the filament winding of continuous fibers, hybridization of fibers, and textile structural forms based upon weaving, braiding, knitting, etc. In all these cases, the desired local stiffness, strength, toughness and other prespecified properties may be achieved by controlling the fiber type, orientation, and volume fraction throughout the structural component.

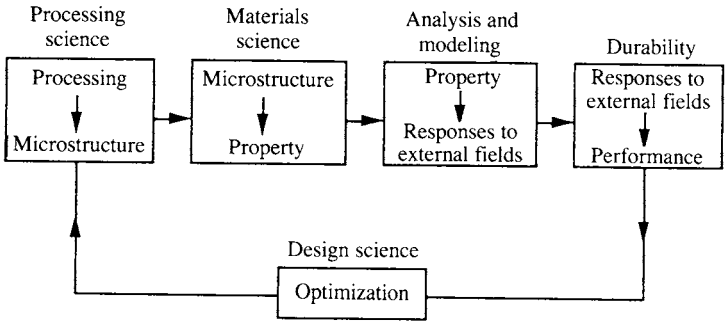
Second, the external geometrical shape of a structural component can also be designed. Advances in the technology of filament winding enable the automated production of components with complex contours. It is now also feasible to fabricate three-dimensional fiber preforms using advanced textile technology. As the ability to fabricate larger and more integrated structural components of net shape is further enhanced, the need to handle and join a large number of small parts, as is currently done with metallic materials, diminishes.

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

The integrated and system approach, ranging from microstructure to component net shape, offers almost unlimited opportunity in composites processing and manufacturing. The figure below depicts the interdependence of processing, microstructure, properties, responses to external fields (physical, chemical and mechanical), and performance of composites.



The purpose of this book is to address the issue of designing the microstructure of composites for optimum performance. This is achieved through the selection of fiber and matrix materials as well as the placement of both continuous and discontinuous fibers in matrix materials. Continuous fibers can assume straight or wavy shapes; they can also be hybridized or woven into textile preforms. The wide range of microstructures available offers tremendous versatility in the performance of composites; the ability to design microstructures enables performance to be optimized.

The book is intended as an intermediate-level textbook for students and a reference for research scientists and engineers. Readers need some background and preparation in materials science and applied mechanics. The first chapter examines the driving forces for advances in fiber composites, as well as the trends and opportunities of this rapidly developing field. Besides providing a concise summary of the linear elastic laminate theory, Chapter 2 examines some of the recent developments in the mechanics of laminated composites. Particular emphasis is given to thick laminates, hygrothermal effects and thermal transient effects. Chapter 3 treats the strength of continuous-fiber composites. Analyses of the local load redistribution due to fiber breakages are presented first. They are followed by a fairly comprehensive treatment of the statistical tensile strength theories which encompasses the behavior of individual fibers, fiber bundles, unidirectional fiber composites,

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

cross-ply composites and laminates of multi-directional plies. Various modes of failure of laminated composites are examined. Section 3.4.6.2 is contributed by S. L. Phoenix, and Sections 3.4.7.4 and 3.4.8 are contributed by A. S. D. Wang. Chapter 4 deals with the elastic, physical and viscoelastic properties as well as the strength and fracture behavior of short-fiber composites. The effects of variations in fiber length and orientation are examined using a probabilistic approach. In Chapter 5, fiber hybridization serves as a vivid example of how the performance of composites can be controlled through the selection of material systems and their geometric distributions. The synergistic effects between the component phases with low elongation and high elongation fibers are of particular interest. Chapter 6 is devoted to two-dimensional textile structural composites based on woven, knitted and braided preforms. A comprehensive treatment of the techniques for analyzing and modeling the thermomechanical behavior of two-dimensional textile composites is presented. Chaper 7 introduces recent developments in the processing of three-dimensional textile preforms based on braiding, weaving, stitching and knitting. The processing–microstructure relationship is demonstrated by the establishment of 'processing windows' for a specific forming technique. Then the microstructure–property relationship is exemplified through the construction of 'performance maps'. Mechanical properties of polymer- and metal-based composites using three-dimensional textile preforms are reviewed. Chapters 8 and 9, in contrast to the earlier chapters, treat the topic of finite elastic deformation of flexible composites. The fundamental characteristics of flexible composites and the technique for analyzing them are presented in Chapter 8. A rigorous treatment of the constitutive relations of flexible composites is developed in Chapter 9 based upon both the Lagrangian and Eulerian descriptions of finite elastic deformation. Overall, the inter-relationship among processing, microstructure, property, responses to external fields, and performance of composites is emphasized throughout this text.

The contents of this book have evolved from my experience during two decades of teaching and research of composite materials at the University of Delaware. Stimulation from students and co-workers was indispensable to the preparation of this book. The contributions of the individuals with whom I had the privilege and pleasure to interact are too numerous to cite here. However, this book serves as a tribute to the intellectual achievements of them all. The generous support provided by the National Science Founda-

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052135482X - Microstructural Design of Fiber Composites
Tsu-Wei Chou
Frontmatter
More information

tion, Department of Energy, Department of Transportation, Army Research Office, Office of Naval Research, Naval Research Laboratory, Air Force Office of Scientific Research, NASA, industrial companies and the Center for Composite Materials of the University of Delaware for conducting the research reported in this book is greatly appreciated. Ding-Guey Hwang, Shen-Yi Luo, Joon-Hyung Byun and Wen-Shyong Kuo read the manuscript and gave critical comments. Te-Pei Niu, Yih-Cherng Chiang, Mark Deshon and Alison Gier provided valuable assistance in the preparation of the manuscript.

Lastly, I should like to express my deep appreciation to the following persons. The late Prof. Alan S. Tetelman of Stanford University first pointed out to me the technological potential of fiber composites. As a colleague of mine at Delaware, Prof. R. Byron Pipes has greatly enriched my perspective on the subject matter. The scholarship and guidance of Prof. Anthony Kelly have always been a source of inspiration to me. Prof. Jerzy L. Nowinski encouraged me throughout the course of this endeavor.

© Cambridge University Press www.cambridge.org