ADVANCED COMPOSITES MANUFACTURING

Edited by
TIMOTHY G. GUTOWSKI

ADVANCED COMPOSITES MANUFACTURING

Edited by

Timothy G. Gutowski
Massachusetts Institute of Technology
Cambridge, MA

A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS, INC.

New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

This text is printed on acid-free paper.

Library of Congress Cataloging in Publication Data:

Advanced composites manufacturing/edited by T. G. Gutowski.
p. cm.
Includes index.
ISBN 0-471-15301-X (alk. paper)
1. Plastics. 2. Composite materials. I. Gutowski, Timothy George Peter.
TP1105.A38 1997
668.4'94–dc20 96-21059

Printed in the United States of America

10 9 8 7 6 5 4 3 2

DEDICATED TO Dr. ZHONG CAI

This book is dedicated to Zhong Cai, a former student of mine, colleague and friend. Zhong Cai was a major contributor to many of the basic principles developed in this book. In particular he made significant contributions to our understanding in such fundamental areas as composites consolidation, fiber deformation behavior and fiber bundle permeability. Many of the chapters in this book are filled with references to his work. In Zhong's short life he accomplished much, and in this dedication we would like to acknowledge his fine work and many accomplishments.

Zhong was born in Shanghai, China in 1951. He missed high school because of the "Cultural Revolution" of Mao Tse-Tung. On his own he studied high school and college courses while working in industry and passed the national college entry exam in the top 100 out of 100,000. He attended the East China Institute of Textile and Technology and graduated in 1982 with honors. At that time, he won the highly competitive Chinese National Scholarship Award, ranking first out of 400. This allowed him to come to the United States and attend MIT, where he obtained his M.S. and Sc.D. degrees in mechanical engineering. While there, he helped develop some of the basic ideas and theories that we use today to understand the processing of composites. After MIT, Zhong held several posts, both industrial (Lord Corporation) and academic (Drexel University), where he expanded his interests into such areas as resin transfer molding and textile processes, made significant contributions, and continued his work on the fundamental nature of fiber bundle permeability. At the time of his unexpected death, he had just started a new faculty position at the Institute of Paper Science and Technology/Georgia Tech in Atlanta, Georgia. Here, his bright and ambitious career was, unfortunately, cut short. For those of us who have worked with him, we will remember those occasions with pleasure, for Zhong was not only extremely bright and hard-working, but also a very sincere and friendly individual. Now, in some small way, we try to honor him by the dedication of this book.

CONTRIBUTORS

Avraham Benatar, Department of Industrial, Welding, and Systems Engineering, The Ohio State University, 190 West 19th Avenue, Columbus, OH 43210-1182

Jonathan S. Colton, Composites Manufacturing Research Program, School of Chemical and Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405

Greg Dillon, Northrop Grumman, Bethpage, NY 11714

Guang-Wu Du, Department of Materials Engineering, Fibrous Materials Research Laboratory, Drexel University, 31 Market St., Philadelphia, PA 19104

Jerome Paul Fanucci, KaZaK Composites, Inc., 423 Bunker Hill St., Burlington, MA 02129

John Gillespie, Jr., Center for Composite Materials and Materials Science Program, University of Delaware, 207 Spencer Laboratory, Newark, DE 19716

Timothy G. Gutowski, Department of Mechanical Engineering, Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology, 77 Massachusetts Ave., Building 35-235, Cambridge, MA 02139

David E. Hardt, Department of Mechanical Engineering, Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology, 77 Massachusetts Ave., Building 35-132, Cambridge, MA 02139

John L. Kardos, Department of Chemical Engineering, Materials Research Laboratory, Washington University, Campus Box 1198, One Brookings Dr., Saint Louis, MO 63130-4899

Keith Kedward, Department of Mechanical Engineering, University of California at Santa Barbara, Santa Barbara, CA 93106

Frank K. Ko, Department of Materials Engineering, Fibrous Materials Research Laboratory, 31 Market St., Drexel University, Philadelphia, PA 19104

L. James Lee, Department of Chemical Engineering, The Ohio State University, 140 West 19th Ave., Columbus, OH 43210-1182

Pat Mallon, Department of Mechanical and Aeronautical Engineering, University of Limerick, Plassey Technological Park, Castletroy, Limerick, Ireland

Stephen McCarthy, Plastics Engineering Department, University of Lowell, 1 University Ave., Lowell, MA 01854

Martin Monaghan, Baxter Laboratories, Chicago, IL 60073

John D. Muzzy, Composites Manufacturing Research Program, School of Chemical and Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

Stephen Nolet, Fiberspar, Inc., 2380 Cranberry Highway, West Wareham, MA 02576

George S. Springer, Department of Aeronautics and Astronautics, Stanford University, Stanford, CA 94305

Charles L. Tucker III, Department of Mechanical and Industrial Engineering, University of Illinois, 144 Mechanical Engineering Bldg., Rm. 332C, 1206 West Green St., Urbana, IL 61801

PREFACE

During my 15 or so years in the field of advanced composites processing, I have watched, with interest, the transition from manufacturing practice based primarily on "descriptive art" to one based on scientific and engineering principles. In the "old days" it seemed that there were only a few of us working in this field. And, of course, the pioneer was George Springer. Now, there are many new (and old) industrious researchers in this field. During this time, we have not only greatly increased our understanding of the basic physical and chemical phenomena that control composites processes but also witnessed the introduction of many new and exciting processes. For example, in an earlier collection on our scientific knowledge in 1988, which I edited (*The Manufacturing Science of Composites*, ASME proceedings MI'88), new processes such as advanced tow placement, the integration of textile processing with resin transfer molding, and forming processes for thermoplastics and thermosets, hardly appeared. Now we have included quite extensive treatments in these areas. These new processes point the direction for the development of new principles and basic problems that need to be solved. To be sure there is much that needs to be done, but our collective advancement over the "descriptive art" days has been significant.

The intention of this volume is to document our progress in this understanding and to present the basic principles of composites processing. In addition, this book includes an overview of the manufacturing processes for advanced composites, and a special chapter at the end that provides an economic perspective for those pondering the future of advanced composites.

In the development of this book, I have had the enormous pleasure of working with many talented authors. To my mind these are the people who have developed many of the scientific and engineering principles on which we construct our new knowledge. In addition, many colleagues and friends have helped by reviewing chapters and providing me with insight into this challenging and exciting field. In particular, I would like to thank Branko Sarh, Hank Fenbert, Ed Bernardon, Sue Mantell, Sang Beom Shim, Haorong Li, and Conchur O'Bradaigh for reviewing chapters in this book. In addition, I would like to thank some of the many others who have contributed in one way or another to this effort including, Stan Wilcox, Archie Bice, Richard Okine, Duncan Laurie, Herb Lause, Gil Gilliland, Bob Allison, Jordan Olson, Gerry Mabson, Steve Metchan, Larry Ilcewicz, Nam Suh, Dave Hoult, Paul Lagace, and Tom Freeman.

Through the years much of my work has come about through the hard work and intelligence of my current and former students. And although I have not listed every name, I would like them to know that each of them has been a contributor to this effort.

I would also like to thank my secretary, administrative assistant, and friend Karuna Mohindra, who has helped me enormously with this book, working weekends and evenings and doing whatever it took to get the job done.

Finally, and with much pleasure, I would like to acknowledge the help and support of my family: my wife, Jane, and my two daughters, Laura and Ellie. In their individual ways they have supported me and stimulated me throughout this project. I would like them to know that they too did a great job.

TIMOTHY G. GUTOWSKI

Cambridge, MA
January 1997

CONTENTS

Introduction

TIMOTHY G. GUTOWSKI
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
Cambridge, Massachusetts

Advanced composite materials are the ultimate "designer" material. By using various configurations of highly packed long slender fibers, one can obtain an enormous range of material properties. Furthermore, by changing the fibers and/or the matrix, intermingling the components, and designing the interface, the material options can become even more expansive, almost uncountable. The real limits to all of these dazzling opportunities are usually set by the manufacturing process. All too often otherwise good ideas cannot be produced, or cannot be produced at reasonable cost. Many of the problems faced in the manufacturing process are of a fundamental nature; that is, they are rooted in the basic nature of an advanced composite, specifically, a material made up of an intricate and exact arrangement of high-performance fibrous materials encapsulated in a polymer matrix. The fabrication of high-quality advanced composite parts therefore requires some measure of control over the local mechanical and chemical environment that can both generate and disrupt the desired microstructure. Knowledge in this area is key to the future development of useful advanced composites applications.

This book is about the fundamentals of manufacturing with advanced composites. It is intended to provide an in-depth treatment of the key issues that face the further development of advanced composites manufacturing processes. As such, it consists of rigorous technical material, engineering models, experimental results, and general information about the manufacturing processes. All chapters are written by leading experts on the various topics. Some of the chapters were presented in an early form as papers at an international conference at MIT in the summer of 1992 entitled "Science and Innovation in Polymer Composites Processing." Since then all papers have been updated, many have

Advanced Composites Manufacturing Edited by Timothy G. Gutowski
ISBN 0-471-15301-X

been extensively revised and several new chapters have been added to provide breadth and unity.

The structure of this book can be broken down roughly into three major sections. The first section (Chapters 1–5) provides an overview and addresses fundamental issues that are generally common to advanced composites manufacturing processes. Hence, Chapter 1 provides a brief engineering overview of composite materials and their manufacturing processes. Chapters 2 and 3 address the processing science of thermosetting and thermoplastic polymers, respectively. These chapters cover such issues as mass and heat transport, flow, adhesion, and consolidation for their respective material. Chapters 4 and 5 address the behavior of the fibers. Chapter 4 develops the treatment of the elastic behavior of aligned fibers during the processing of composites, with an appendix that covers the consolidation of composites. Chapter 5 reviews the basics and limits of using reinforcing fibers in textile processes, such as knitting, weaving, and braiding.

The second section (Chapters 6–10) addresses the specific manufacturing processes. Hence detailed treatments and engineering models of the major processes are given. Chapter 6 is on the autoclave processing of both thermoset and thermoplastic composites. The basic techniques, tooling, and cure and consolidation issues are reviewed. Chapter 7 provides a detailed discussion of the pultrusion process as well as key modeling and control issues. Chapter 8 addresses the advanced composites forming process, including a process overview, a very thorough discussion of forming kinematics, and a discussion on defect formation during forming. Chapter 9 provides a brief overview and a detailed model of the filament winding process. Chapter 10 addresses the key issues for liquid composite molding [which includes both resin transfer molding (RTM) and structural reaction injection molding (SRIM)]. Hence the chapter reviews chemistry and kinetic models, rheological models, as well as flow and heat transfer modeling, with a good discussion of permeability modeling.

The third section (Chapters 11–13) addresses common issues for all processes, and key issues for the future development of advanced composites. In Chapter 11 the general requirements for the control of manufacturing processes are reviewed and discussed in terms of existing and potential applications to advanced composites manufacturing. In Chapter 12 the critical issue of joining, bonding, and assembly of advanced composites parts is addressed. Finally, in Chapter 13, the issue of cost and the major strategies to reduce it are presented. Here the major cost drivers for current fabrication techniques are reviewed, and the major new automation and textile processes are discussed and compared with metals processing strategies. Then, the issues of redesign, including parts integration and cost estimating, are discussed, and a new approach for advanced composites cost estimating is outlined.

A quick overview of advanced composites manufacturing processes and the major issues facing their successful development can be obtained from reading only Chapters 1 and 13. For the next level of detail concerning this topic, it is suggested that the reader then read Chapters 2, 3, 5, 6, and 12. Textile processes are discussed in detail in Chapter 5; however, Chapters 7, 8, 10, and 13 are also relevant. New automation, such as that in the "automatic tow placement" machines, is discussed mainly in Chapter 13, with some comments in Chapter 1. Advanced composites forming is discussed mainly in Chapter 8, but also in Chapters 5, 6, and 13. Composites consolidation is discussed in many chapters, including Chapters 2, 4, and 6 for thermosets and Chapter 3 for thermoplastics. An appendix to Chapter 4 (Appendix 4A) reviews consolidation theory in some detail. Resin kinetics are discussed primarily in Chapters 2 and 10. The deformation behavior of fibers receives considerable attention outside Chapter 4; see also Chapters 2, 3, 6, and 7. In addition to Chapter 12, the assembly and joining of composites is also discussed in Chapters 1, 6, and 13.

CHAPTER 1

A Brief Introduction to Composite Materials and Manufacturing Processes

TIMOTHY G. GUTOWSKI

Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
Cambridge, Massachusetts

The purpose of this chapter is to provide an overview of the basic issues in composites processing and a roadmap for the following chapters. Most of this material should be comprehensible to the newcomer to composites but is intended for the engineer or scientist with some previous knowledge of the field. For those new to composites, it is highly recommended that they review one of the excellent solid mechanics texts; see for example [1–5, 11–14].

1.1 MATERIAL HETEROGENEITY AND ANISOTROPY

Advanced polymer composites are made of high-strength fibers and moderately high-temperature resins at very high fiber volume fractions. Generally, the average fiber volume fraction $\bar{V}_f$ is between 0.5 and 0.7 with a typical target value for aerospace applications of $V_f = 0.62$. The reason for this high value is simple. Since the fibers are the stiffening and strengthening agent, generally speaking, the more fibers the stiffer and stronger the structure.* To obtain these high fiber volume fractions, the fibers must be aligned like cords of wood or matches, in a matchbox. This naturally leads to an anisotropic structure, as

* This rule is correct for on-axis properties but may not be for off-axis properties. The reader will find a good discussion of the solid mechanics of composites in the references.

Advanced Composites Manufacturing, Edited by Timothy G. Gutowski
ISBN 0-471-15301-X

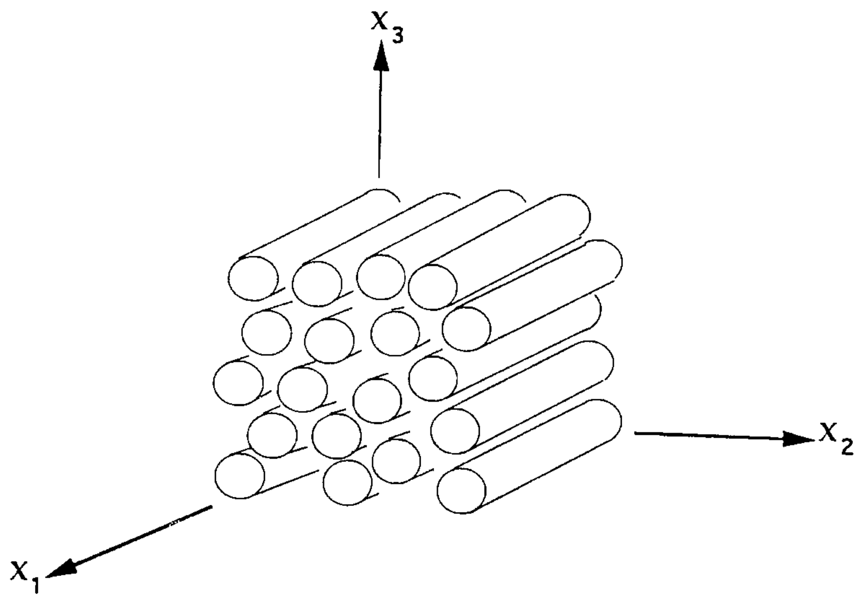

Figure 1.1 Representative element of an aligned-fiber bundle.

shown in Fig. 1.1 with the material coordinate system (x_1, x_2, x_3). For advanced composites, almost all (tensor) physical properties are anisotropic. For example, the stiffness (fourth-order tensor) is anisotropic and the permeability (second-order tensor) is anisotropic, while the mass density (which is a scalar quantity) is not. The anisotropy of advanced composites greatly complicates their analysis but also provides unique opportunities for optimization and tailoring. Figure 1.2 illustrates the dependence of the elastic modulus, E, on angle θ; $E(\theta)$. Note that $E(\theta = 0^\circ) = E_{11}$ is the axial modulus (using contracted notation), and $E(\theta = 90^\circ) = E_{22}$ is the transverse modulus. For the graphite epoxy system shown in the figure, the ratio E_{11}/E_{22} is about 16; similarly, the ratio of axial to transverse resin permeability for the fiber bundle, S_{11}/S_{22}, is on the same order. Hence the degree of anisotropy in advanced composites can be quite large.

A second important consequence of the high fiber volume fractions required for advanced composites is a small interfiber spacing. For example, if the actual microstructure is approximated as a square array (see Fig. 1.3), where the maximum available fiber volume fraction is $\pi/4$, the average interfiber spacing δ can be calculated as

$$\delta = d_f\left(\sqrt{\frac{\pi/4}{V_f}} - 1\right) \tag{1.1}$$

where d_f is the fiber diameter. Hence for a typical case (graphite/epoxy) with $d_f = 7\ \mu$m and $V_f = 0.62$, one gets $\delta = 0.88\ \mu$m.

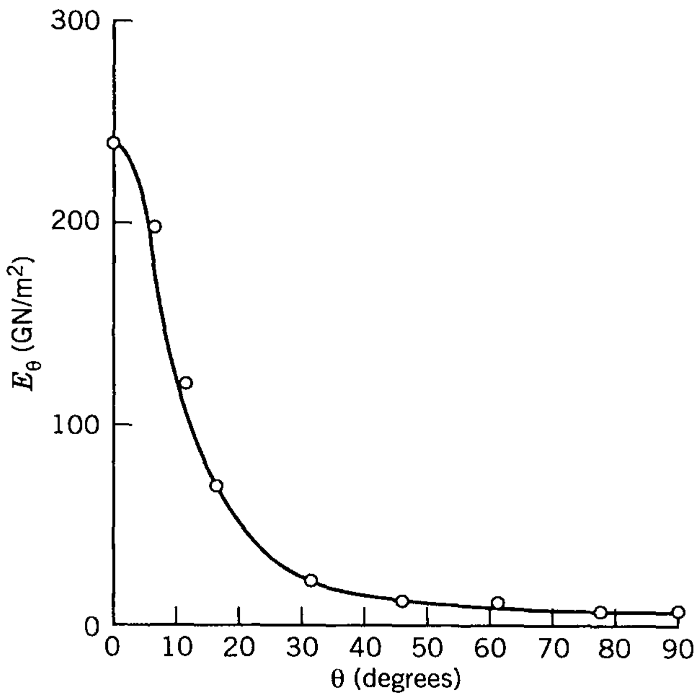

Figure 1.2 Stiffness of a unidirectional carbon epoxy laminate as a function of test angle relative to the fiber direction [6].

There are several important consequences of this small interfiber spacing. In the solid composite, the resin is highly constrained in small volumes between the fibers, which results in stress concentrations and reduced strength in the matrix-dominated directions. During processing, the small interfiber spacing also has important consequences. For one, because there is much variation in fiber spacing for real composites, a small average δ suggests considerable fiber–fiber contact. This can make the fiber bundle potentially load-bearing when compressed in the transverse direction. A direct consequence of this can be reduced resin pressure during cure, and potential voids in the matrix. Another important effect is the resultant large shear resistance of the prepreg. This affects properties such as "drape", which translates into poor handling properties during manufacture. And finally, since the permeability of the fiber bundle scales roughly as δ^2, the small interfiber spacing results in very small permeability values. These four factors act to limit the maximum obtainable fiber volume fraction, generally making it much below the theoretical maximum values of 0.785 for square packing, and 0.907 for hexagonal packing. The effects of decreasing interfiber spacing (and therefore increasing V_f) on the axial permeability S_{11} and the transverse load-carrying capacity of the bundle are shown in Figs. 1.4 and 1.5.

The heterogeneous and anisotropic nature of advanced composites presents major challenges to their modelling and analysis. In many cases the heterogeneity is averaged in some way that allows the composite to be treated as