

**Fundamentals of**  
**Composites**  
**Manufacturing**

**Fundamentals of**  
**Composites**  
**Manufacturing**

**Materials, Methods, and Applications**

**Second Edition**

**A. Brent Strong**



Society of Manufacturing Engineers  
Dearborn, Michigan

Copyright © 2008 Society of Manufacturing Engineers

987654321

All rights reserved, including those of translation. This book, or parts thereof, may not be reproduced by any means, including photocopying, scanning, digitizing, recording, or micro-filming, or by any information storage and retrieval system, without permission in writing of the copyright owners. No liability is assumed by the publisher with respect to use of information contained herein. While every precaution has been taken in the preparation of this book, the publisher assumes no responsibility for errors or omissions. Publication of any data in this book does not constitute a recommendation or endorsement of any patent, proprietary right, or product that may be involved.

Library of Congress Catalog Card Number: 2007935302

International Standard Book Number (ISBN): 0-87263-854-5

ISBN 13: 978-087263854-9

*Additional copies may be obtained by contacting:*

Society of Manufacturing Engineers

Customer Service

One SME Drive, P.O. Box 930

Dearborn, Michigan 48121

1-800-733-4763

[www.sme.org/store](http://www.sme.org/store)

*SME staff who participated in producing this book:*

Rosemary Csizmadia, Senior Production Editor

Steve Bollinger, Manager, Book & Video Publications

Frank Bania, Cover Design

Frances Kania, Administrative Coordinator

Printed in the United States of America

## Acknowledgments

Special thanks to Rik Heselhurst, Ph.D. at the School of Aerospace, Civil and Mechanical Engineering, University College, The University of New South Wales who was the principal author for the chapter on design and who contributed significantly to the chapter on repair. Also thanks to Scott Beckwith who made special contributions to the chapter on resin transfer molding (RTM) and to many figures and tables throughout the text.

Many thanks also to the American Composites Manufacturers Association (ACMA). In particular, thanks to Andy Rusnak, the editor of *Composites Manufacturing* magazine. I have been a contributing editor to this magazine and have had many published articles. With ACMA's permission, substantial portions of these articles have been used in this text. In that regard, I also give thanks to the co-authors that assisted in writing many of the ACMA articles. Those co-authors include: Scott Beckwith, Perry Carter, Tom Erekson, John Green, Charles Harrell, Val Hawks, Mike Hoke, David Jensen, Barry Lunt, William McCarvill, Mike Miles, Frédérique Mutel, John Richards, Christopher Rotz, Deryl Snyder, and Troy Takash.

Similarly, I am the author of a text entitled *Plastics: Materials and Processing*, which is currently in its third edition. As some of the topics in that plastics text and in this present composites text overlap, I have borrowed some concepts and text from that text. My thanks go to Prentice Hall, the

publisher of this text, for permission to use these materials.

Special thanks to David Sorensen of the Utah Manufacturing Extension Partnership who has developed and taught me much of the information on the methods of planning. I also thank Bill Angstadt of Angstadt Consulting for insights into the new planning methods that must be used in today's world. Further thanks to Dixon Abell of Poly Processing Company for his insightful discussions. And thanks to Whitney Lewis of the Manufacturing Leadership Forum who helped greatly in the production of the figures.

I want to especially thank Rosemary Csizmadia of the Society of Manufacturing Engineers who has edited this book. She has gone far beyond just checking for grammar and agreement errors. She has also given insightful help in content and organization.

# Contents

|  |    |  |     |
|--|----|--|-----|
| <b>Preface</b> .....   | xi | Polymerization of Unsaturated Polyesters .....                     | 48  |
| <b>1 Introduction to Composites</b>  |    | Effects of Various Diacid, Glycol, and Specialized Monomers .....  | 51  |
| Chapter Overview.....  | 1  | Crosslinking Mechanisms .....                                      | 57  |
| Concept of Composites.....   | 1  | Cure Control Additives .....                                       | 65  |
| Roles of the Matrix and Reinforcement in Composites .....                    | 2  | Molding Compounds .....  | 66  |
| History of Composites .....  | 4  | Property Optimization .....  | 70  |
| Composite Types—Advanced and Engineering.....                                | 7  | Case Study 3-1 .....   | 76  |
| Markets.....   | 10 | Case Study 3-2.....  | 78  |
| Composites Industry Structure.....   | 13 | Summary .....  | 79  |
| Case Study 1-1 .....   | 15 | Laboratory Experiment 3-1 .....                                    | 80  |
| Summary .....  | 16 | Questions.....   | 82  |
| Laboratory Experiment .....  | 17 |  |     |
| Questions.....   | 17 | <b>4 Epoxies</b>   |     |
| <b>2 Matrices and their Properties</b>                                       |    | Chapter Overview.....  | 85  |
| Chapter Overview.....  | 1  | Overview of Epoxy and Its Uses .....                               | 85  |
| Polymers, Plastics and Resins Defined .....                                  | 19 | Structure of the Polymer.....                                      | 85  |
| Polymerization, Naming, Characteristics, and Molecular Weight.....           | 21 | Crosslinking and Processing Parameters....                         | 91  |
| Thermoplastics and Thermosets.....   | 27 | Physical and Mechanical Properties of Cured Epoxy Composites ..... | 104 |
| Aromatic and Aliphatic Materials .....                                       | 31 | Special Composite Applications .....                               | 109 |
| Wet-out of Fibers .....  | 41 | Case Study 4-1 .....   | 111 |
| Additives: Fillers, Pigments, Viscosity Control Agents, Surface Agents ..... | 42 | Summary .....  | 112 |
| Case Study .....   | 43 | Laboratory Experiment 4-1 .....                                    | 112 |
| Summary .....  | 44 | Questions.....   | 113 |
| Laboratory Experiment 2-1 .....  | 45 |  |     |
| Laboratory Experiment 2-2 .....  | 45 | <b>5 Specialty and High-performance Thermosets</b>                 |     |
| Questions.....   | 46 | Chapter Overview.....  | 115 |
| <b>3 Unsaturated Polyesters</b>  |    | Introduction.....  | 115 |
| Chapter Overview.....  | 47 | Vinyl Esters .....   | 115 |
| Overview of Polyester Resins and Their Uses .....                            | 47 | Phenolics.....   | 122 |
|  |    | Carbon Matrix.....   | 130 |
|  |    | Polyimides and Related Polymers.....                               | 136 |
|  |    | Cyanate Esters .....   | 140 |
|  |    | Polyurethanes .....  | 142 |
|  |    | Silicones.....   | 146 |

|  |     |  |  |
|--|-----|--|--|
| Dicyclopentadiene (DCPD) .....                             | 151 |  |  |
| Case Study 5-1 .....                                       | 154 |  |  |
| Summary .....  | 154 |  |  |
| Laboratory Experiment 5-1 .....                            | 155 |  |  |
| Questions.....   | 156 |  |  |
| <b>6 Thermoplastic Composites</b>                          |     |  |  |
| Chapter Overview.....                                      | 159 |  |  |
| Review of Thermoset and Thermoplastic<br>Composites .....  | 159 |  |  |
| Engineering Thermoplastic Composites...                    | 164 |  |  |
| High-performance Thermoplastic<br>Composites .....         | 168 |  |  |
| Case Study 6-1 .....                                       | 174 |  |  |
| Summary .....  | 175 |  |  |
| Laboratory Experiment 6-1 .....                            | 176 |  |  |
| Questions.....   | 176 |  |  |
| <b>7 Ceramic and Metal Matrix<br/>Composites</b>           |     |  |  |
| Chapter Overview.....                                      | 179 |  |  |
| Non-polymeric Matrix Composites .....                      | 179 |  |  |
| Properties and Uses of Ceramic Matrix<br>Composites .....  | 182 |  |  |
| Manufacturing of Ceramic Matrix<br>Composites .....        | 186 |  |  |
| Properties and Uses of Metal Matrix<br>Composites .....    | 188 |  |  |
| Manufacturing of Metal Matrix<br>Composites .....          | 191 |  |  |
| Case Study 7-1 .....                                       | 193 |  |  |
| Summary .....  | 193 |  |  |
| Laboratory Experiment 7-1 .....                            | 194 |  |  |
| Questions.....   | 194 |  |  |
| <b>8 Reinforcements</b>                                    |     |  |  |
| Chapter Overview.....                                      | 197 |  |  |
| General Fiber Characteristics .....                        | 197 |  |  |
| Glass Fibers .....   | 203 |  |  |
| Carbon/Graphite Fibers.....                                | 207 |  |  |
| Aramid and Other Organic Fibers .....                      | 218 |  |  |
| Boron, Silicon Carbide, and Other<br>Specialty Fibers..... | 226 |  |  |
| Natural Fibers .....                                       | 228 |  |  |
| Fiber-matrix Interactions.....                             | 230 |  |  |
| Case Study 8-1 .....                                       | 240 |  |  |
| Summary .....  | 241 |  |  |
| Laboratory Experiment 8-1 .....                            | 242 |  |  |
| Questions.....   | 242 |  |  |
| <b>9 Reinforcement Forms</b>                               |     |  |  |
| Chapter Overview.....                                      | 245 |  |  |
| Introduction .....   | 245 |  |  |
| Filaments, Strands, Tows, Rovings,<br>and Yarns.....       | 245 |  |  |
| Woven and Knitted Fabrics (Cloth) .....                    | 247 |  |  |
| Non-woven Fabrics (Mat) .....                              | 252 |  |  |
| Prepregs.....  | 253 |  |  |
| Braided, Stitched, and<br>Three-dimensional Laminates..... | 255 |  |  |
| Preforms .....   | 258 |  |  |
| Hybrids .....  | 260 |  |  |
| Whiskers .....   | 261 |  |  |
| Case Study 9-1 .....                                       | 261 |  |  |
| Summary .....  | 262 |  |  |
| Laboratory Experiment 9-1 .....                            | 262 |  |  |
| Questions.....   | 263 |  |  |
| <b>10 Quality and Testing</b>                              |     |  |  |
| Chapter Overview.....                                      | 265 |  |  |
| History of Composite Materials Testing....                 | 265 |  |  |
| Quality Control Principles.....                            | 266 |  |  |
| Component Material Testing .....                           | 272 |  |  |
| Mechanical Testing.....                                    | 275 |  |  |
| Thermal and Environmental Testing .....                    | 287 |  |  |
| Flammability Testing.....                                  | 292 |  |  |
| Non-destructive Testing and Inspection....                 | 298 |  |  |
| Case Study 10-1 .....                                      | 303 |  |  |
| Summary .....  | 303 |  |  |
| Laboratory Experiment 10-1 .....                           | 304 |  |  |
| Questions.....   | 305 |  |  |
| <b>11 Composite Design</b>                                 |     |  |  |
| Chapter Overview.....                                      | 307 |  |  |
| Introduction .....   | 307 |  |  |
| Methodology of Composite Structure<br>Design .....         | 308 |  |  |
| Basic Stress Types.....                                    | 311 |  |  |
| Laminate Theory .....                                      | 313 |  |  |
| Rule of Mixtures .....                                     | 315 |  |  |
| Modeling and Finite Element Analysis ....                  | 317 |  |  |
| Lay-up Notation.....                                       | 321 |  |  |
| Symmetry and Balanced Laminates.....                       | 323 |  |  |
| Cracking in Composites .....                               | 325 |  |  |
| Vibration and Damping .....                                | 327 |  |  |
| Smart Structures.....                                      | 329 |  |  |
| Fatigue.....   | 329 |  |  |
| Composites versus Metals .....                             | 333 |  |  |
| Residual Stresses.....                                     | 339 |  |  |

|  |     |  |  |
|--|-----|--|--|
| Case Study 11-1 .....  | 341 |  |  |
| Summary .....  | 345 |  |  |
| Laboratory Experiment 11-1 .....                                       | 346 |  |  |
| Questions.....   | 347 |  |  |
| <b>12 Sandwich Structures, Joints, and Post-processing Operations</b>  |     |  |  |
| Chapter Overview.....  | 349 |  |  |
| Sandwich Structures—Concept and Design .....                           | 349 |  |  |
| Core Material .....  | 353 |  |  |
| Other Z-direction Stiffeners.....                                      | 357 |  |  |
| Joints .....   | 359 |  |  |
| Post-processing Operations .....                                       | 366 |  |  |
| Case Study 12-1 .....  | 370 |  |  |
| Case Study 12-2 .....  | 370 |  |  |
| Case Study 12-3.....   | 372 |  |  |
| Summary .....  | 373 |  |  |
| Laboratory Experiment 12-1 .....                                       | 373 |  |  |
| Questions.....   | 373 |  |  |
| <b>13 Open Molding of Engineering Composites</b>                       |     |  |  |
| Chapter Overview.....  | 375 |  |  |
| Process Overview.....  | 375 |  |  |
| Gel Coat Considerations.....   | 375 |  |  |
| Lay-up Molding .....   | 378 |  |  |
| Spray-up Molding .....   | 381 |  |  |
| Tooling (Molds).....   | 383 |  |  |
| Quality Control and Safety.....  | 386 |  |  |
| Case Study 13-1 .....  | 386 |  |  |
| Summary .....  | 386 |  |  |
| Laboratory Experiment 13-1 .....                                       | 387 |  |  |
| Questions.....   | 387 |  |  |
| <b>14 Open Molding of Advanced Composites</b>                          |     |  |  |
| Chapter Overview.....  | 389 |  |  |
| Process Overview.....  | 389 |  |  |
| Prepreg Lay-up .....   | 390 |  |  |
| Vacuum Bagging .....   | 395 |  |  |
| Curing .....   | 398 |  |  |
| Roll Wrapping .....  | 400 |  |  |
| Tooling (Molds).....   | 401 |  |  |
| Case Study 14-1 .....  | 402 |  |  |
| Summary .....  | 402 |  |  |
| Laboratory Experiment 14-1 .....                                       | 405 |  |  |
| Questions.....   | 406 |  |  |
| <b>15 Compression Molding</b>  |     |  |  |
| Chapter Overview.....  | 407 |  |  |
| Process Overview.....  | 407 |  |  |
| Equipment.....   | 408 |  |  |
| Bulk Molding Compound (BMC)/Sheet Molding Compound (SMC) Molding ....  | 408 |  |  |
| Preform Compression Molding .....                                      | 412 |  |  |
| Prepreg Compression Molding .....                                      | 413 |  |  |
| Part Complexity, Properties, and Other Performance Considerations..... | 413 |  |  |
| Case Study 15-1 .....  | 414 |  |  |
| Summary .....  | 415 |  |  |
| Laboratory Experiment 15-1 .....                                       | 415 |  |  |
| Questions.....   | 416 |  |  |
| <b>16 Resin Infusion Technologies</b>                                  |     |  |  |
| Chapter Overview.....  | 417 |  |  |
| Process Overview.....  | 417 |  |  |
| Resin Infusion Technologies .....                                      | 420 |  |  |
| Equipment and Process Parameters.....                                  | 424 |  |  |
| Preform Technology for Infusion.....                                   | 425 |  |  |
| Resin Characteristics .....  | 427 |  |  |
| Core and Flow Media Materials.....                                     | 429 |  |  |
| Part Design for Resin Infusion .....                                   | 431 |  |  |
| Centrifugal Casting.....   | 432 |  |  |
| Case Study 16-1 .....  | 432 |  |  |
| Summary .....  | 432 |  |  |
| Laboratory Experiment 16-1 .....                                       | 434 |  |  |
| Questions.....   | 435 |  |  |
| <b>17 Filament Winding and Fiber Placement</b>                         |     |  |  |
| Chapter Overview.....  | 437 |  |  |
| Process Overview.....  | 437 |  |  |
| Filament Winding .....   | 437 |  |  |
| Variations in Filament Winding .....                                   | 448 |  |  |
| Fiber Placement.....   | 449 |  |  |
| Case Study 17-1 .....  | 450 |  |  |
| Summary .....  | 450 |  |  |
| Laboratory Experiment 17-1 .....                                       | 451 |  |  |
| Questions.....   | 451 |  |  |
| <b>18 Pultrusion</b>   |     |  |  |
| Chapter Overview.....  | 453 |  |  |
| Process Overview.....  | 453 |  |  |
| Reinforcement Preforming .....   | 454 |  |  |
| Resin Impregnation.....  | 455 |  |  |
| Die Forming and Curing .....   | 457 |  |  |
| Pulling.....   | 457 |  |  |

|   |     |  |            |
|---|-----|--|------------|
| Cutting and Trimming .....                    | 458 | Planning.....                          | 529        |
| Shapes and Applications .....                 | 458 | Corporate Creativity.....              | 531        |
| Case Study 18-1 .....                         | 459 | The Ethical Process.....               | 534        |
| Summary .....                                 | 460 | Managing Technology.....               | 535        |
| Laboratory Experiment 18-1 .....              | 460 | Case Study 22-1 .....                  | 538        |
| Questions.....                                | 461 | Summary .....                          | 538        |
| <b>19 Thermoplastic Composites Processing</b> |     | Laboratory Experiment 22-1 .....       | 539        |
| Chapter Overview.....                         | 463 | Questions.....                         | 540        |
| Wet-out of Thermoplastic Composite            |     | <b>23 Composites Applications</b>      |            |
| Materials.....                                | 464 | Chapter Overview.....                  | 543        |
| Processing Short-fiber Thermoplastic          |     | Introduction.....                      | 543        |
| Composites .....                              | 467 | Traditional Composites Markets.....    | 543        |
| Thermoplastic Composites Molding              |     | Learning Lessons—Space Structures..... | 553        |
| by Traditional Thermoset Processes .....      | 470 | The Ultimate Composite Structure—      |            |
| Thermoplastic Composites Molding              |     | ISOTRUSS® .....                        | 559        |
| by Unique Processes .....                     | 474 | Critical Market—Armor .....            | 561        |
| Case Study 19-1 .....                         | 478 | Breakthrough Markets—Commercial        |            |
| Summary .....                                 | 478 | and Corporate Airplanes.....           | 564        |
| Laboratory Experiment 19-1 .....              | 479 | Future-today Markets—Unmanned          |            |
| Questions.....                                | 480 | Vehicles.....                          | 567        |
| <b>20 Damage Prevention and Repair</b>        |     | Case Study 23-1 .....                  | 573        |
| Chapter Overview.....                         | 481 | Summary .....                          | 577        |
| Damage and Its Effects .....                  | 481 | Laboratory Experiment 23-1 .....       | 577        |
| Damage Prevention .....                       | 483 | Questions.....                         | 577        |
| Damage Assessment.....                        | 487 | <b>Glossary .....</b>                  | <b>579</b> |
| Smart Structures.....                         | 491 | <b>Index.....</b>                      | <b>599</b> |
| Repair .....                                  | 495 |  |            |
| Case Study 20-1 .....                         | 501 |  |            |
| Summary .....                                 | 502 |  |            |
| Laboratory Experiment 20-1 .....              | 503 |  |            |
| Questions.....                                | 504 |  |            |
| <b>21 Factory Issues</b>                      |     |  |            |
| Chapter Overview.....                         | 505 |  |            |
| Problem of Emissions and How to               |     |  |            |
| Deal with Them .....                          | 505 |  |            |
| Government Regulation .....                   | 509 |  |            |
| Material Storage.....                         | 513 |  |            |
| Contamination in the Plant.....               | 514 |  |            |
| Disposal, Waste, and Recycling.....           | 516 |  |            |
| Factory Simulation .....                      | 516 |  |            |
| Case Study 21-1 .....                         | 521 |  |            |
| Summary .....                                 | 522 |  |            |
| Laboratory Experiment 21-1 .....              | 523 |  |            |
| Questions.....                                | 523 |  |            |
| <b>22 The Business of Composites</b>          |     |  |            |
| Chapter Overview.....                         | 525 |  |            |
| Economics of Composites                       |     |  |            |
| Manufacturing Processes.....                  | 525 |  |            |



## THE PURPOSE OF THIS BOOK

People entering the composites field need a way to learn the basics. Whether they are learning about composites in a college course or in the workplace, they need a simple text that gives enough detail to help with understanding. They also need a reference book that presents material in an easily understandable format. The first edition of this book has filled that need but is now over a decade old. This second edition describes advances that have been developed in the recent past, expands upon the explanations of the first edition to give further understanding, and adds key information that will serve as a reference for refreshing and expanding your knowledge of composites.

## THE IMPORTANCE OF MATERIALS IN COMPOSITES

The field of composites is about materials and the way they are made into products. (In the aerospace world, this is called materials and processing or M&P.) Therefore, the first focus of this text is on materials. This is reflected in several major chapters devoted to understanding the basic materials that are put together to create composite structures. Too often the materials side is viewed by composite engineers as merely a way to get data that will allow design calculations to be made. This text tries to simply and clearly present the details of why composite materials behave the way they do. Thus composites

designers will gain an understanding of the causes of material performance and be able to choose from a wider set of acceptable materials than might otherwise be possible.

## THE IMPORTANCE OF COMPOSITES MANUFACTURING

Improving manufacturing technology is the greatest challenge today in the field of composites. When composites are chosen for an application principally because of their properties, it is natural that the manufacturing methods would be chosen to optimize those properties, even to the point where good manufacturing methods might be adversely affected. This practice has been evident in the aerospace industry where many composite parts have been made by processes that require high labor and costly techniques. Up to recent years, even large airplanes have been primarily hand-made.

In some applications, the practice of property optimization will continue in spite of the problems that might arise in manufacturing. However, those in charge of manufacturing have the challenge of improving the manufacturing process so that the quality of the performance of the part can be maintained. Competitive pressures may also play a part to encourage reduction of costs through manufacturing improvements. These manufacturing improvements must be done while still maintaining or improving

part properties. Applications involving most advanced composites fit into this category.

For other composite parts a different situation occurs with respect to manufacturing. In these the choice of composites is based on *both* material performance and manufacturing efficiencies. Parts made by these criteria are generally engineering composite products. In these parts the need to improve manufacturing is critically important because of the inevitable pressures of the marketplace for reduced costs and improved throughputs.

Regardless of the situation, good initial choices about the type of manufacturing process used and then subsequent improvements to it are critically important. Too often the initial choice of manufacturing method is made based on previous experience or on available equipment. A rigorous method for evaluating the choice of manufacturing process is rarely used. Then, after the method is chosen, there is great reluctance to change it significantly. This is especially true in situations where the part and the manufacturing process have been approved by a governmental agency or a major assembler like an airplane company. These products are locked into technologies that are difficult to modify. However, as experience with long-term performance of composite parts grows and the data bases of composite properties and designs increases, the reluctance to change manufacturing processes will decrease. Experience diminishes risk.

The composites industry will continue struggling to cope with the requirements for superb mechanical properties and the need for economical manufacturing methods. The manufacturing side is changing rapidly and a premium is being placed on the innovative individual.

Manufacturing technologies have been borrowed from many other industries. From plastics came the concepts used in resin curing, composites molding, extrusion, and

finishing. From metals came ideas in casting, forming, and mold making. Some of the reinforcement products are, of course, from the textile industry but other concepts include textile fiber handling, cloth pattern cutting, and lay-up. A broad spectrum of engineering disciplines has contributed—from bridge building to laser cutting. Insight and innovation are key elements to progress and success in the field of composites manufacturing.

## FEATURES OF THE BOOK

For classroom use or individual reading, the book contains many features to make learning easier.

1. Each chapter begins with an overview of the key points to be addressed. The order of the chapter follows the order of the overview so that you can see what is in the chapter and easily find it.
2. Each chapter contains a case study discussing a specific application of one or more principles taught in the chapter.
3. A summary is given in each chapter so that the key learning points can be reviewed.
4. For assistance to college professors, each chapter has a laboratory experiment dealing with the concepts of that chapter.
5. A set of questions is given in each chapter so that individuals can assess learning and professors can use them in preparing questions for exams.
6. A bibliography details additional reading for each chapter.
7. A glossary of important terms is found at the back of book to assist in understanding or remembering terms given in the book. Each of the terms defined in the glossary is marked in bold print the first time it is used in the text.

8. Improving upon the first edition, figures have been enhanced and added to expand the breadth and depth of coverage.
9. Providing a valuable additional resource, the *Composites Manufacturing* video series produced by the Society of Manufacturing Engineers (SME 2005) complements this text. The series offers excellent visual representations of the materials and manufacturing methods addressed in the text. The videos are excellent as supplements to lectures and in laboratories. To learn more about this series, visit SME's website, [www.sme.org/cmvs](http://www.sme.org/cmvs), or call 800-733-4763.

**To order call  
1-800-733-4763**

**or visit**

**[www.sme.org/store](http://www.sme.org/store)**

**and search on book title**