ASM International is proud to offer Composites as Volume 21 of the ASM Handbook. The nominal basis for this volume was the Engineered Materials Handbook, Volume 1, published in 1987. However, this new edition is, to a large degree, a brand new volume. New or greatly expanded coverage is provided, in particular, in the Sections on constituent materials, analysis and design, and processing. New sections have been added to address the important topics of maintenance, repair, and recycling. Coverage of polymer-matrix composites has been enhanced to address the latest materials advances and new application areas. Coverage of metal-matrix and ceramic-matrix composites has been revamped and greatly expanded to reflect the increasing industrial importance of these materials.

With the release of this new edition of the Composites volume, it seems like a natural transition for it to become part of the ASM Handbook series. The Metals Handbook series was renamed the ASM Handbook in the mid-1990s to reflect the increasingly interrelated nature of materials and manufacturing technologies. Since that time the ASM Handbook has incorporated increasing amounts of information about nonmetallic materials in each new and revised volume. ASM expects that other volumes in the Engineered Materials Handbook will become part of the ASM Handbook when they are revised.

Creating the new edition of this monumental reference work was a daunting task. We extend thanks and congratulations on behalf of ASM International to the Volume Chairs, Dan Miracle and Steve Donaldson, and the Volume’s 13 Section Chairs for the outstanding job they have done in developing the outline for the revision and guiding its development. Our gratitude is also due to the over 300 international experts from industry, academia, and research who contributed as authors and reviewers to this edition. In addition, we express our appreciation to the ASM International editorial and production staff for their dedicated efforts in preparing this volume for publication.

Aziz I. Asphahani
President
ASM International

Michael J. DeHaemer
Managing Director
ASM International
Policy on Units of Measure

By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d’Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne (kg) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units usually appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with IEEE/ASTM SI-10, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to IEEE/ASTM SI-10; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of g/cm³ rather than kg/m³ as the unit of measure for density (mass per unit volume). SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.
Preface

It should be apparent with just a quick glance through this Volume that a great deal of technical progress has been made since the first edition was published in 1987 (as Engineered Materials Handbook, Volume 1). Much of the earlier promise of high performance organic-matrix composites (OMCs) has been fulfilled. These materials are now the preferred design solution for an expansive scope of applications. Earlier concerns related to high cost and marginal manufacturability have been satisfactorily addressed through high volume and innovative design and manufacturing, including extensive use of unitized design and construction. A clear example of the success in these areas is illustrated by the growing use of high-performance composites in the commodity applications of civil infrastructure. Nonetheless, cost and manufacturability continue to be areas of vigorous development and hold hope for significant future advancements, along with the development of composite materials with higher specific properties, higher operating temperatures, and improved supportability. One can expect to see broad advances in innovative structural concepts and certification methods in the future.

The progress in metal-matrix composites (MMCs) has been equally remarkable. Although only marginal coverage was warranted in the first edition, MMCs now represent a significant material option in the international marketplace. The world market for MMCs was over 2.5 million kg (5.5 million pounds) in 1999, and an annual growth rate of over 17% has been projected for the next several years. Significant applications are in service in the aeronautical, aerospace, ground transportation, thermal management/electronic packaging, and recreation industries. The ability to offer significant improvements in structural efficiency and to excel in several other functional areas, including thermal management and wear, and to utilize existing metalworking infrastructure have aided this progress. Continued future extension into both new and existing markets is expected.

While ceramic-matrix composite (CMC) technology is still largely centered in the research and development phase, significant advancements have been made. Some commercial applications now exist, and strategies for growing market insertion are being pursued. The traditional motivation of structural performance and environmental resistance at the highest application temperatures continue to provide incentive for development. Recent important research accomplishments provide growing optimism that significant aeropropulsion structural applications will be fielded in the coming decade.

The primary objective of ASM Handbook, Volume 21, Composites is to provide a comprehensive, practical, and reliable source of technical knowledge, engineering data, and supporting information for composite materials. Coverage of OMCs and MMCs is provided in a balanced fashion that reflects the maturity of each material class. Given the current status of CMC materials, less coverage is provided, but it, too, is focused in areas of current industrial importance. This Handbook is intended to be a resource volume for nonspecialists who are interested in gaining a practical working knowledge of the capabilities and applications of composite materials. Thus, coverage emphasizes well-qualified information for materials that can be produced in quantities and product forms of engineering significance. This Volume is not intended to be a presentation of fundamental research activities, although it certainly provides an important reference for scientists engaged in the development of new composite materials. The full range of information of importance to the practical technologist is provided in this Volume, including topics of constituent materials; engineering mechanics, design, and analysis; manufacturing processes; post-processing and assembly; quality control; testing and certification; properties and performance; product reliability, maintainability, and repair; failure analysis; recycling and disposal; and applications.

This new edition builds on the success of the version published as Volume 1 of the Engineered Materials Handbook. Information on OMCs has been updated to reflect advancements in this technology field, including improvements in low cost manufacturing technologies and significantly expanded applications in areas such as infrastructure. Progress in MMCs has been particularly dramatic since the previous edition, and new information on these materials provides an up-to-date comprehensive guide to MMC processing, properties, applications, and technology. CMCs also have entered service in limited applications since the previous edition, and the coverage of these materials reflects this progress. These three classes of composites are covered in each Section of the Volume as appropriate to provide a unified view of these engineered materials and to reduce redundancies in the previous edition.

We would like to offer our personal, heartfelt appreciation to the Section Chairpersons, article authors, reviewers, and ASM staff for sharing both their expertise and extensive efforts for this project.

Daniel B. Miracle
Steven L. Donaldson
Air Force Research Laboratory

Aziz I. Asphahani  
President and Trustee  
Carus Chemical Company  

Gordon H. Geiger  
Vice President and Trustee  
University of Arizona  

Michael J. DeHaemer  
Secretary and Managing Director  
ASM International  

John W. Pridgeon  
Treasurer  
Allvac  

Ash Khare  
Immediate Past President and Trustee  
National Forge Company  

Trustees  

Thomas G. Stoehr  
University of Washington  

Robert C. Tucker, Jr.  
Praxair Surface Technologies, Inc.  

E. Daniel Albrecht  
Advanced Ceramics Research, Inc.  

W. Raymond Cribb  
Alloy Products  
Brush Wellman Inc.  

Walter M. Griffith  
Air Force Research Laboratory  

Kathleen B. Alexander  
Los Alamos National Laboratory  

Subi Dinda  
DaimlerChrysler Corporation  

R.G. (Gil) Gilliland  
Oak Ridge National Laboratory  
UT-Battelle, LLC  

Andrew R. Nicoll  
Sulzer Metco Europe GmbH  

Members of the ASM Handbook Committee (2000–2001)

Craig V. Darragh  
(Chair 1999–; Member 1989–)  
The Timken Company  

Bruce P. Bardes  
(1993–)  
Materials Technology Solutions Company  

Rodney R. Boyer  
Boeing Company  

Toni M. Brugger  
(1993–)  
Carpenter Technology Corporation  

Larry D. Hanke  
(1994–)  
Materials Evaluation and Engineering Inc.  

Jeffrey A. Hawk  
(1997–)  
U.S. Department of Energy  

Dennis D. Huffman  
(1982–)  
The Timken Company  

Dwight Janoff  
(1995–)  
FMC Corporation  

Kent L. Johnson  
(1999–)  
Engineering Systems Inc.  

Paul J. Kovach  
(1995–)  
Stress Engineering Services Inc.  

Donald R. Lesuer  
(1999–)  
Lawrence Livermore National Laboratory  

Huimin Liu  
(1999–)  
Ford Motor Company  

William L. Mankins  
(1989–)  
Metallurgical Services Inc.  

Dana J. Medlin  
(1998–)  
Zimmer Inc.  

Srikanth Raghunathan  
(1999–)  
Nanomat Inc.  

Mahi Sahoo  
(1993–)  
Natural Resources Canada  

Karl P. Stauchhammer  
(1997–)  
Los Alamos National Laboratory  

Kenneth B. Tator  
(1991–)  
KTA-Tator Inc.  

George F. Voort  
(1997–)  
Buehler Ltd.  

George A. Wildridge  
(2000–)  
Borg Warner Morse TEC Corporation  

Dan Zhao  
(1996–)  
Johnson Controls Inc.  

Previous Chairs of the ASM Handbook Committee

R.J. Austin  
(1992–1994) (Member 1984–)  

L.B. Case  
(1931–1933) (Member 1927–1933)  

T.D. Cooper  

E.O. Dixon  

R.L. Dowdell  
(1938–1939) (Member 1935–1939)  

M.M. Gauthier  
(1997–1998) (Member 1990–)  

J.P. Gill  
(1937) (Member 1934–1937)  

J.D. Graham  

J.F. Harper  
(1923–1926) (Member 1923–1926)  

C.H. Herty, Jr.  
(1934–1936) (Member 1930–1936)  

D.D. Huffman  
(1986–1990) (Member 1982–)  

J.B. Johnson  
(1948–1951) (Member 1944–1951)  

L.J. Korb  

R.W.E. Leiter  

G.V. Luerssen  
(1943–1947) (Member 1942–1947)  

G.N. Maniar  

W.L. Mankins  
(1994–1997) (Member 1989–)  

J.L. McCall  

W.J. Merten  
(1927–1930) (Member 1923–1933)  

D.L. Olson  

N.E. Promisel  

G.J. Shubat  

W.A. Stadler  

R. Ward  

M.G.H. Wells  

D.J. Wright  
(1964–1965) (Member 1959–1967)
Authors and Contributors

R.C. Adams
Lockheed Martin Aeronautical Systems

Suresh Advani
University of Delaware

David E. Alman
U.S. Department of Energy

Finn Roger Andressen
Reichhold AS

Keith B. Armstrong
Consultant

B. Tomas Åström
IFP SICOMP AB

Amit Bandyopadhyay
Washington State University

Yoseph Bar-Cohen
Jet Propulsion Laboratory

Robert J. Basso
Century Design Inc.

Mark Battley
Industrial Research Limited

Joseph J. Beaman, Jr.
University of Texas at Austin

John H. Belk
The Boeing Company

Tia Benson Tolle
Air Force Research Laboratory

Barry J. Berenberg
Caldera Composites

John Bootle
XC Associates Inc.

Chris Boshers
Composite Materials Characterization Inc.

Richard H. Bossi
The Boeing Company

David L. Bourell
University of Texas at Austin

Dennis Bowles
Northrop Grumman Corporation

Jack Boyd
CyTech Fiberite Inc.

Maureen A. Boyle
Hexcel Corporation

Shari Bugaj
FiberCote Industries Inc.

Frank Burzese
XC Associates Inc.

Flake C. Campbell
The Boeing Company

Karl K. Chang
DuPont

K.K. Chawla
University of Alabama

N. Chawla
Arizona State University

Eric Chesmar
United Airlines

Richard J. Chester
Aeronautical and Maritime Research Laboratory

S. Christensen
The Boeing Company

William F. Cole II
United Airlines

Bruce Crawford
Deakin University

George Dallas
TA Instruments

Joseph R. Davis
Davis & Associates

J.A. DiCarlo
NASA Glenn Research Center

Cynthia Powell Doğan
U.S. Department of Energy

Roderick Don
University of Delaware

Steven L. Donaldson
Air Force Research Laboratory

Louis C. Dorworth
Abaris Training Resources Inc.

Richard Downs-Honey
High Modulus New Zealand Limited

T.E. Drake
Lockheed Martin Aerospace

Lawrence T. Drzal
Michigan State University

G. Ehner
Menzolit-Fibron GmbH

D. Emahiser
GKN Aerospace

Roger W. Engelbart
The Boeing Company

Don O. Evans
Cincinnati Machine

Richard E. Fields
Lockheed Martin Missiles and Fire Control

Lynda Fiorini
XC Associates Inc.

Gerald Flanagan
Materials Sciences Corporation

Mark S. Forte
Air Force Research Laboratory

Marvin Foston
Lockheed Martin Aeronautical Systems

Luther M. Gammon
The Boeing Company

C.P. Gardiner
Defence Science & Technology Organisation, Australia

Nicholas J. Gianaris
Visteon Corporation

Ian Gibson
The University of Hong Kong

Lawrence A. Gintert
Concurrent Technologies Corporation

Jonathan Goering
Albany International Techniweave Inc.

John W. Goodman
Material Technologies Inc.

J.H. Gosse
The Boeing Company

Michael N. Grimshaw
Cincinnati Machine

Olivier Guillermin
Vistagy Inc.

H. Thomas Hahn
Air Force Office of Scientific Research

Paul Hakes
High Modulus New Zealand Limited

William C. Harrigan
MMC Engineering Inc.

L.J. Hart-Smith
The Boeing Company

Brian S. Hayes
University of Washington

Dirk Heider
University of Delaware

Edmund G. Henneke II
Virginia Polytechnic Institute and State University

John M. Henshaw
University of Tulsa

G. Aaron Henson III
Design Alternatives Inc.
Reviewers

John W. Aaron  
The Boeing Company

R.C. Adams  
Lockheed Martin Aeronautical Systems

John C. Adelmann  
Sikorsky Aircraft

Suresh Advani  
University of Delaware

Suphal P. Agrawal  
Northrop Grumman Corporation

Klaus Ahlborn  
Miras Composites Systems

Bob Allanson  
GKN Westland Aerospace

David P. Anderson  
University of Dayton Research Institute

Donald A. Anderson  
The Boeing Company

Douglas L. Armstrong  
Fiber Innovations Inc.

Keith B. Armstrong  
Consultant

B. Tomas Åström  
IFP SICOMP AS

Mohan Aswani  
Mark Battley  
Industrial Research Limited, New Zealand

Behzad Bavarian  
California State University, Northridge

Matthew R. Begley  
University of Connecticut

Arie Ben-Dov  
Israel Aircraft Industry

Tia Benson Tolle  
Air Force Research Laboratory

Albert Bertram  
Naval Surface Weapons Center

Edward Bernardon  
Vistagy Inc.

R.T. Bhatt  
NASA Glenn Research Center

Greg Black  
Northrop Grumman Corporation

Tom Blankenship  
The Boeing Company

George A. Blann  
Buehler Ltd.

Ben R. Bognar  
BP Amoco Chemicals

Gregg R. Bogucki  
The Boeing Company

Raymond Bohlmann  
The Boeing Company

Collin Bohn  
The Boeing Company

Chris Bosher  
Composite Materials Characterization Inc.

Dennis Bowles  
Northrop Grumman Corporation

Alfonso Branca  
Top Glass s.p.a.

Mike Brun  
General Electric

Doug Brunner  
Lockheed Martin

Bruce L. Burton  
Huntsman Corporation

Mark Bush  
University of Western Australia

Rick Callis  
Creative Tooling

Flake C. Campbell  
The Boeing Company

Gene Camponeschi  
NSWCCD

Jay Carpenter  
Creative Tooling

Mark T. Carroll  
Lockheed Martin Aeronautics

Patrick E. Cassidy  
Southwest Texas State University

Gilbert B. Chapman II  
DaimlerChrysler Corporation

K.K. Chawla  
University of Alabama

N. Chawla  
Arizona State University

Steven J. Chen  
The Boeing Company

Richard J. Chester  
Aeronautical and Maritime Research Laboratory

Mark Chris  
Bell Helicopter Textron

Stan Chichanoski  
Steinerfilm Inc.

Bruce Choate  
Northrop Grumman Corporation

Linda L. Clements  
C & C Technologies

Todd Coburn  
Adroit Engineering

William F. Cole II  
United Airlines

Doug Condel  
John Cooney

Bruce Cox  
DaimlerChrysler Corporation

Jim Criss  
Lockheed Martin Aeronautics

Alan Crosky  
University of New South Wales

Maxwell Davis  
J.G. Dean  
General Motors Corporation

Leen Deurloo  
Adzel bv

Herve Deve  
3M Company

Jose Manuel Luna Diaz  
EADS-CASA Airbus

George DiBari  
International Nickel

Jack Dini  
Consultant

John Dion  
BAE Systems

Alan Dobyns  
Sikorsky Aircraft

Jim Door  
Duke Engineering

Louis C. Dorworth  
Abaris Training Resources Inc.

Timothy E. Easler  
COI Ceramics Inc.

Jim Epperson  
Jay Fiebig  
Warner Robins Air Logistics Center
Richard E. Fields
Lockheed Martin Missiles and Fire Control

Lynda Fiorini
XC Associates Inc.

John Fish
Lockheed Martin Aeronautics Company

Gerald Flanagan
Materials Sciences Corporation

Marvin Foston
Lockheed Martin Aeronautical Systems

Rob Fredell
U.S. Air Force Academy

David H. Fry
The Boeing Company

H. GangaRao
West Virginia University

Samuel P. Garbo
Sikorsky Aircraft

Slade Gardner
Lockheed Martin Aeronautics

C.P. Gardiner
Defence Science and Technology Organisation

Rikard Gebart
Luleå University of Technology

Gerald A. Gelg

Guy M. Genin
Washington University

Dipankar K. Ghosh
Vanderplaats R&D Inc.

Nicholas J. Gianaris
Visteon Corporation

A.G. Gibson
University of Newcastle upon Tyne

John W. Goodman
Materials Technologies Inc.

Peter Grant
The Boeing Company

Stephen A. Green
Sikorsky Aircraft

John Griffith
The Boeing Company

John Gruss
The Boeing Company

John W. Halloran
University of Michigan

Gail Hahn
The Boeing Company

William C. Harrigan
MMC Engineering Inc.

Neil M. Hawkins
University of Illinois

Randy Hay
Air Force Research Laboratory

Paul Hergenrother
NASA Langley Research Center

Mike Hinton
DERA Farnborough

Michael J. Hoke
Abaris Training Resources Inc.

Richard C. Holzwarth
Air Force Research Laboratory

DeWayne Howell
CompositeTek

Kuang-Ting Hsiao
University of Delaware

Donald Hunston
National Institute of Standards and Technology

Warren H. Hunt, Jr.
Aluminum Consultants Group Inc.

Frances Hurwitz
NASA Glenn Research Center

John W. Hutchinson
Harvard University

William Janeska

Dave Jarmon
United Technologies

Michael G. Jenkins
University of Washington

Paul D. Jero
Air Force Research Laboratory

Richard A. Jeryan
Ford Motor Company

Eric Johnson
Virginia Polytechnic Institute and State University

Robert M. Jones
Virginia Polytechnic Institute and State University

Ronald J. Kander
Virginia Polytechnic Institute and State University

Vistasp M. Karbhari
University of California, San Diego

Allan Kaye
BAE Systems

Ronald J. Kerans
Air Force Research Laboratory

Hamid Kia

Christopher J. Kirschling
Reichold Chemicals Inc.

James Klett
Oak Ridge National Laboratory

Eric S. Knudsen
Fiberline Composites A/S

Greg Kress
Delta Air Lines

Raymond B. Krieger, Jr.
Cytec-Fiberite Inc.

Arun Kumar
Seal Laboratories

Murray Kuperman
United Airlines (retired)

Jeremy Leggoe
Texas Tech University

Bradley A. Letch
NASA Glenn Research Center

James Leslie
ACPT Inc.

Chris Levan
BP Amoco Carbon Fibers

Stanley Levine
NASA Glenn Research Center

John Lewandowski
Case Western Reserve University

Jian Li
The Boeing Company

Denny Liles
BGF Industries Inc.

Mike Lindsey
Lockheed Martin

Steve Loud
Composites Worldwide Inc.

David Maas
Flightware

Tōnu Malm
Metallvägen

John F. Mandell
Montana State University

Rod Martin
Materials Engineering Research Laboratory

Frederick J. McGarry
Massachusetts Institute of Technology

Lee McKague
Composites-Consulting Inc.

Stewart E. McKinzy
TWA Inc.

Aram Mekjian
Mektek Composites Inc.

Greg Mellem
Abaris Training Resources Inc.

James D. Miller
Cool Polymers

Robert J. Miller
Pratt & Whitney

Andrew Mills
Cranfield University

Daniel B. Miracle
Air Force Research Laboratory

Jack Mitrey
Ashland Chemicals

Peter Mitschang
Institute für Verbundwerkstoffe GmbH

Dale Moore
Naval Air Systems

A.P. Mouritz
RMIT University

Alvin Nakagawa
Northrup Grumman Corporation

James Newell
Air Force Research Laboratory

Theodore Nicholas
Air Force Research Laboratory

T. Kevin O’Brien
U.S. Army Research Laboratory

Mark Occhionero
Ceramic Process Systems

Tim A. Osswald
University of Wisconsin

Steve Owens
Lockheed Martin

Ron Parkinson
Nickel Development Institute
Steven Peake  
Cytec-Fiberite Inc.

John Peters  
A&P Technology

Bruce Pfund  
Special Projects LLC

Fred Policelli  
FPI Composites Engineering

Richard D. Pistole  

Kevin Potter  
University of Bristol

(Paul) Mack Puckett  

Naveen Rastogi  
Visteon Chassis Systems

Suraj P. Rawal  
Lockheed Martin Astronautics

James Reeder  
NASA Langley Research Center

David L. Rose  
Polese Company

Tom Rose  

Carl Rousseau  
Bell Helicopter

Roger Rowell  

C.D. Rudd  
University of Nottingham

Daniel R. Ruffner  
The Boeing Company

John Russell  
Air Force Research Laboratory

Adam J. Sawicki  
The Boeing Company

Robert E. Schafrik  
GE Aircraft Engines

Warren C. Schimpf  
Advanced Fiber Technology

John R. Schlup  
Kansas State University

Daniel A. Scola  
University of Connecticut

Mark Shea  
The Boeing Company

Bill Schweinberg  
Warner Robins Air Logistics Center

R. Ajit Shenoi  
University of Southampton

Robert L. Sierakowski  
Air Force Research Laboratory

Raymond J. Sinatra  
Rolls Royce Corporation

J.P. Singh  
Argonne National Laboratory

Lawrence H. Sobel  
Northrop Grumman Corporation (retired)

Jonathan E. Spowart  
UES Incorporated

David A. Steenkamer  
Ford Motor Company

W. Kent Stewart  
Bell Helicopter Textron

Bob Stratton  

Brent Strong  
Brigham Young University

Brent Stucker  
University of Rhode Island

Patricia L. Stumpf  
Hartzell Propeller Inc.

Susan Sun  
Kansas State University

Jerry Sundsrud  
3M Company

John Taylor  
Borden Chemical

Roland Thevenin  
Airbus

L. Scott Thiebert  
Air Force Research Laboratory

Rodney Thomson  
CRC for Advanced Composites Structures Ltd.

Katie E.G. Thorp  
Air Force Research Laboratory

Richard E. Tressler  
Pennsylvania State University

Francois Trochu  
Ecole Polytechnique de Montreal

Willem van Dreumel  
Ten Cate Advanced Composites bv

Richard Van Luven  
Northrup Grumman Corporation

Barry P. Van West  
The Boeing Company

James Vaughan  
University of Mississippi

Albert A. Vicario  
Alliant Techsystems Inc.

Anthony J. Vizzini  
University of Maryland

Shawn Walsh  
Army Research Laboratory

Steve Wanthal  
The Boeing Company

Stephen Ward  
SW Composites

Charles R. Watson  
Pratt & Whitney

Kevin Waymack  
The Boeing Company

David Weiss  
Eck Industries Inc.

Dan White  
dmc² Electronic Components Corporation

Mary Ann White  
Alliant Techsystems Inc.

Paul D. Wienhold  
Johns Hopkins University

J.L. Willet  
USDA/ARS/NCAUR

Martin Williams  
ADI Limited

Mark Wilhelm  
The Boeing Company

D.J. Williamson  
The Boeing Company

Dale W. Wilson  
Johns Hopkins University

David Wilson  
3M Company

Warren W. Wolf  
Owens Corning

Ernest Wolff  
PMIC

Hugh Yap  
Aerocell Inc.

Chun Zhang  
Florida State University
Contents

Introduction to Composites ................................................. 1
Chairpersons: Daniel B. Miracle and
Steven L. Donaldson, Air Force Research Laboratory

Introduction to Composites ................................................ 3
A Brief History of Composite Materials ............................. 4
General Use Considerations ........................................ 5
Technology Overview .................................................. 7
Applications ..................................................................... 12
View of the Future ....................................................... 16

Constituent Materials ...................................................... 19
Chairperson: Steven R. Nutt, University of Southern California

Introduction to Constituent Materials ................................. 21
Constituent Material Forms ........................................... 21
Selection Factors ..................................................... 22
Introduction to Reinforcing Fibers ...................................... 23
Overview ....................................................................... 23
PMC Reinforcing Fibers ................................................ 24
CMC and MMC Reinforcing Fibers ................................ 25
Summary and Conclusions ............................................ 25

Glass Fibers ................................................................ 27
Glass Fiber Types ....................................................... 27
General-Purpose Glass Fibers .......................................... 28
Special-Purpose Glass Fibers .......................................... 29
Glass Melting and Fiber Forming ..................................... 30
Important Commercial Products ..................................... 31
Carbon Fibers ............................................................ 35
History ......................................................................... 35
Manufacture of Carbon Fibers ......................................... 35
Properties and Characteristics of Carbon Fibers .............. 36
Typical Applications of Carbon Fibers .............................. 38
Anticipated Developments in Carbon Fibers ...................... 39
Aramid Fibers ............................................................. 41
Fiber Manufacturing ..................................................... 41
Fiber Forms and Applications ......................................... 41
Materials Properties .................................................... 43
Future Developments ................................................... 45

Ceramic Fibers ............................................................. 46
Fiber Production .......................................................... 46
Composite Applications ............................................... 46
Properties of Commercial Fibers ..................................... 46
Fibers for High-Temperature CMC Applications .............. 48
Future Directions ....................................................... 49

Discontinuous Reinforcements for Metal-Matrix Composites
Reinforcement Roles .................................................... 51
DRMMC Reinforcements ............................................... 51
Reinforcement Chemistry ............................................. 55
Continuous Fiber Reinforcements for Metal-Matrix Composites
Aluminum Oxide Fibers ................................................ 56
Silicon Carbide Fibers .................................................. 56
Boron Fibers ............................................................. 56
Carbon Fibers ............................................................ 56
Future Outlook ......................................................... 57

Fabrics and Preforms ..................................................... 59
Unidirectional and Two-Directional Fabrics ....................... 59
Hybrid Fabrics ............................................................ 60
Multidirectionally Reinforced Fabrics ............................... 60
Prepreg Resins ........................................................... 62
Woven Fabric Prepregs .................................................. 63
Unidirectional Tape Prepregs ........................................... 64
Multidirectional Tape Prepregs ........................................ 65
Tape Manufacturing Processes ........................................ 65
Prepreg Tow .............................................................. 66

Braiding ................................................................. 69
Braiding Classifications ................................................... 70
Two-Dimensional Braiding ............................................. 70
Three-Dimensional Braiding ........................................... 72
Properties of Braided Composites ..................................... 74

Epoxy Resins ............................................................. 78
Base Resins .............................................................. 78
Epoxy Resin Curatives .................................................. 80
Modifiers ................................................................. 84
Epoxy Resin Model Formulations .................................... 86
Safety .......................................................................... 88
Future Trends ............................................................ 88

Polyester Resins .......................................................... 90
Polyester Resin Chemistry ............................................. 90
Mechanical Properties .................................................. 91
Thermal and Oxidative Stability ....................................... 92
Chemical Resistance .................................................... 93
Ultraviolet (UV) Resistance ........................................... 94
Electrical Properties .................................................... 94
Flame-Retardant Polyester Resins .................................... 95

Bismaleimide Resins ...................................................... 97
BMI Resin Chemistry ................................................... 97
Bismaleimide Building Blocks ....................................... 97
Bismaleimide Resin Systems .......................................... 98

BMI Composites ........................................................ 100
Mechanical Properties .................................................. 101
Composite Applications ............................................... 101
Resin Transfer Molding ............................................... 103
Cure and Post Cure Requirements .................................. 103
Elevated-Temperature Applications ................................. 103
Conclusions .............................................................. 104

Polyimide Resins ........................................................ 105
Properties and Applications .......................................... 105
Chemistry of Condensation-Type Polyimides .................... 107
Chemistry of Addition-Type Polyimides ......................... 109
Preparation of Nadic End-Capped Amic Acid
Oligomer Resin Solutions ............................................. 112
Constituent Properties of PMR-15 ................................. 113
Current State of the Art ................................................ 113
Outlook ....................................................................... 113

Phenolic Resins .......................................................... 120
Phenolic Resin Chemistry ............................................. 120
Phenolic Prepregs ....................................................... 121
Phenolic Honeycomb ................................................... 121
Phenolic Pultrusion ..................................................... 122
<table>
<thead>
<tr>
<th>Fundamentals of Shear Load Transfer through Composite Sandwich Panels</th>
<th>293</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer Programs</td>
<td>334</td>
</tr>
<tr>
<td>Damage Tolerance</td>
<td>295</td>
</tr>
<tr>
<td>Implementation of a Damage Tolerance Analysis Methodology</td>
<td>300</td>
</tr>
<tr>
<td>Finite Element Analysis</td>
<td>321</td>
</tr>
<tr>
<td>Local Strength Analysis Methods</td>
<td>317</td>
</tr>
<tr>
<td>Panel Stiffness Analysis Methods</td>
<td>319</td>
</tr>
<tr>
<td>Computer Programs</td>
<td>334</td>
</tr>
<tr>
<td>Testing and Analysis Correlation</td>
<td>344</td>
</tr>
<tr>
<td>Design Allowables</td>
<td></td>
</tr>
<tr>
<td>- Coupons</td>
<td>345</td>
</tr>
<tr>
<td>- Joints</td>
<td>347</td>
</tr>
<tr>
<td>- Elements and Subcomponents</td>
<td>349</td>
</tr>
<tr>
<td>Conclusions</td>
<td>351</td>
</tr>
<tr>
<td>Design Criteria</td>
<td>353</td>
</tr>
<tr>
<td>Overview of Design Criteria for Composites</td>
<td>355</td>
</tr>
<tr>
<td>Cost</td>
<td>354</td>
</tr>
<tr>
<td>Size</td>
<td>355</td>
</tr>
<tr>
<td>Mechanical Properties</td>
<td>355</td>
</tr>
<tr>
<td>Repeatability and Precision</td>
<td>357</td>
</tr>
<tr>
<td>Damage Tolerance and Durability</td>
<td>357</td>
</tr>
<tr>
<td>Environmental Constraints</td>
<td>358</td>
</tr>
<tr>
<td>Conclusions</td>
<td>358</td>
</tr>
<tr>
<td>Design Allowables</td>
<td>360</td>
</tr>
<tr>
<td>Need for Design Allowables</td>
<td>360</td>
</tr>
<tr>
<td>Development of Design Allowables</td>
<td>360</td>
</tr>
<tr>
<td>Factors Affecting Design Allowables</td>
<td>360</td>
</tr>
<tr>
<td>Lamina Versus Laminate Allowables</td>
<td>361</td>
</tr>
<tr>
<td>Extending Laminate Results</td>
<td>362</td>
</tr>
<tr>
<td>Statistical Determination of Allowables</td>
<td>363</td>
</tr>
<tr>
<td>Ensuring the Validity of Allowables</td>
<td>365</td>
</tr>
<tr>
<td>Computer-Aided Design and Manufacturing</td>
<td>366</td>
</tr>
<tr>
<td>Overview</td>
<td>366</td>
</tr>
<tr>
<td>Composite Draping Simulation</td>
<td>366</td>
</tr>
<tr>
<td>Composite Hierarchy</td>
<td>367</td>
</tr>
<tr>
<td>Core Sample and Ply Analysis</td>
<td>368</td>
</tr>
<tr>
<td>Productivity and Flat-Panel Evaluations</td>
<td>368</td>
</tr>
<tr>
<td>Laminate Surface Offset</td>
<td>368</td>
</tr>
<tr>
<td>Engineering Documentation</td>
<td>369</td>
</tr>
<tr>
<td>Flat-Panel Export</td>
<td>369</td>
</tr>
<tr>
<td>Structural Analysis Interface</td>
<td>370</td>
</tr>
<tr>
<td>Resin Transfer Molding Interface</td>
<td>371</td>
</tr>
<tr>
<td>Fiber Placement and Tape-Laying Interfaces</td>
<td>371</td>
</tr>
<tr>
<td>Laser Projection Interface</td>
<td>371</td>
</tr>
<tr>
<td>Design, Tooling, and Manufacturing Interaction</td>
<td>373</td>
</tr>
<tr>
<td>Selection of Composites Manufacturing Processes</td>
<td>373</td>
</tr>
<tr>
<td>Process Considerations</td>
<td>374</td>
</tr>
<tr>
<td>Preparation</td>
<td>374</td>
</tr>
<tr>
<td>Forming Processes</td>
<td>375</td>
</tr>
<tr>
<td>Post-Processing and Fabrication</td>
<td>376</td>
</tr>
<tr>
<td>Repair</td>
<td>377</td>
</tr>
<tr>
<td>Conclusions</td>
<td>377</td>
</tr>
<tr>
<td>Cost Analysis</td>
<td>379</td>
</tr>
<tr>
<td>Composite Cost Tools</td>
<td>379</td>
</tr>
<tr>
<td>Savings</td>
<td>381</td>
</tr>
<tr>
<td>Engineering Mechanics and Analysis of Metal-Matrix Composites</td>
<td>396</td>
</tr>
<tr>
<td>Micromechanics of Fiber-Reinforced MMCs</td>
<td>396</td>
</tr>
<tr>
<td>Micromechanics of Discontinuously Reinforced MMCs</td>
<td>400</td>
</tr>
<tr>
<td>Local Failures of Fiber-Reinforced MMCs</td>
<td>401</td>
</tr>
<tr>
<td>Macromechanics</td>
<td>402</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>403</td>
</tr>
<tr>
<td>Fatigue</td>
<td>405</td>
</tr>
<tr>
<td>Fracture Analysis of Fiber-Reinforced Ceramic-Matrix Composites</td>
<td>407</td>
</tr>
<tr>
<td>General Framework for Fracture Analysis</td>
<td>408</td>
</tr>
<tr>
<td>Classes of Material Behavior</td>
<td>408</td>
</tr>
<tr>
<td>Constitutive Laws for Inelastic Straining</td>
<td>409</td>
</tr>
<tr>
<td>Stress Distributions in Notched Specimens</td>
<td>411</td>
</tr>
<tr>
<td>Fracture Initiation</td>
<td>412</td>
</tr>
<tr>
<td>Crack Propagation</td>
<td>413</td>
</tr>
<tr>
<td>Environmental Degradation</td>
<td>415</td>
</tr>
<tr>
<td>Conclusions</td>
<td>416</td>
</tr>
<tr>
<td>Manufacturing Processes</td>
<td>419</td>
</tr>
</tbody>
</table>

Chairperson: B. Tomas Åström, IFP SICOMP AB, Sweden
Process Modeling ............................................................423
Classification Based on Dominant Flow Process ....................424
Usefulness of Process Models ..............................................425
Ingredients of a Process Model .........................................426
Formulation of Models ..................................................429

Composite Tooling ..........................................................434
Advantages of Composite Tools ........................................434
Disadvantages of Composite Tools ..................................435
Tool Design Overview ....................................................435
Master Model or Pattern Design ......................................437
Fiber and Fabric Selection ..............................................437
Resins ...........................................................................437
Surface Coat and Surface Ply .........................................437
Tool Laminate Construction Techniques ............................438
Curing and Demolding ....................................................438
Cutting and Trimming .....................................................438
Substructure Design .......................................................438
Future Outlook ..............................................................440

Electroformed Nickel Tooling ............................................441
Electroforming Process ...................................................441
Mandrel Cost and Design Considerations .........................442
Comparison of Nickel and Other Tooling Materials ..............443
Future Developments .....................................................444

Elastomeric Tooling ........................................................445
Bag-Side Elastomeric Cauls .............................................445
Thermal Expansion Molding Methods ...............................447
Volumetric Analysis .......................................................448

Open Molding: Hand Lay-Up and Spray-Up .........................450
Process Characteristics ..................................................450
Applications ................................................................450
Materials ...................................................................451
Component Properties and Characteristics .......................453
Basic Design Guidelines ...............................................455
Outlook ....................................................................456

Custom Sailing Yacht Design and Manufacture ....................457
Yacht Structure .............................................................457
Design Guidelines .........................................................458
Material Types and Forms ..............................................460
Technique Characteristics ..............................................461
Outlook ....................................................................465

Prepreg and Ply Cutting ....................................................466
History of Composites Ply Cutting ....................................466
Creating the Data .........................................................466
Nesting the Pieces ........................................................467
Kitting ........................................................................467
Cutting .......................................................................468
Labeling .....................................................................469

Manual Prepreg Lay-Up ....................................................470
Technique Characteristics and Applications .......................470
Technique Description ....................................................471
Component Properties ....................................................474
Design Guidelines .........................................................475
Outlook ....................................................................475

Fiber Placement .............................................................477
Applications ...............................................................477
Materials .................................................................478
Part Design Considerations ............................................478
Outlook ....................................................................479

Automated Tape Laying ....................................................480
History ........................................................................480
Process Overview .........................................................480
Applications ...............................................................481
Description of Equipment ..............................................481
Tape Laying Process Description ....................................483
Typical Material Types and Forms ..................................484
Design Guidelines .........................................................484
Outlook ....................................................................484

Curing ........................................................................486
Preparation for Curing ....................................................486
Autoclave Cure Systems ..................................................487

Control Systems ............................................................488
Other Process Cures .......................................................490
Thermoplastic Composites ..............................................491

Resin Transfer Molding and Structural Reaction Injection Molding ................................................492
Technique Characteristics ..............................................492
Applications ...............................................................493
Technique Description ....................................................494
Material Types and Forms ..............................................495
Representative Component Properties ............................497
Design Guidelines .........................................................497
Outlook ....................................................................499

Vacuum Infusion .............................................................501
Technique Characteristics ..............................................501
Applications ...............................................................503
Technique Description: Theory and Background ................505
Technique Description: How Parts Are Made ....................508
Equipment and Material Types and Forms .......................510
Representative Component Properties ............................513
Design Guidelines .........................................................513
Outlook ....................................................................514

Compression Molding .....................................................516
Process Description and Characteristics .........................516
Part Design and Process Engineering ...............................517
Compression Molding of Glass Mat Thermoplastics ............518
Compression Molding of Long-Fiber Thermoplastics ..........522
Compression Molding of Sheet Molding Compounds .......525

Filament Winding ............................................................531
Advantages and Disadvantages .......................................532
Effects of Fiber Tension ..................................................531
Materials ..................................................................539
Shapes ....................................................................540
Winding Patterns ..........................................................541
Tooling and Equipment ..................................................542
Applications ...............................................................544
Representative Component Properties ............................545
Design Guidelines .........................................................546
Fabrication Recommendations .......................................547
Outlook ....................................................................548

Pultrusion ..................................................................550
Technique Characteristics ..............................................550
Process Advantages ......................................................550
Applications ...............................................................551
Key Technology Areas ...................................................552
Process Equipment .......................................................552
Process Tooling ...........................................................555
Materials .................................................................555
Properties of Pultruded Products ....................................559
Design Guidelines .........................................................561
Future Outlook ............................................................562

Tube Rolling ..................................................................565
Process Description ......................................................565
Process Equipment and Techniques ...............................565
Material Forms .............................................................566
Wrapping Techniques .....................................................567
Outlook ....................................................................569

Thermoplastic Composites Manufacturing .........................570
Characteristics of Thermoplastic Composites ......................570
Material Forms .............................................................571
Technique Descriptions ..................................................571
Outlook ....................................................................577

Processing of Metal-Matrix Composites ............................579
Processing of Discontinuously Reinforced Aluminum ..........579
Processing of Continuous Fiber-Reinforced Aluminum ..........584
Processing of Discontinuously Reinforced Titanium ..........585
Processing of Continuous Fiber-Reinforced Titanium ..........585
Processing of Other Metal-Matrix Composites .................586
Processing of Ceramic-Matrix Composites ............................................589
Cold Pressing and Sintering ...........................................................589
Hot Pressing ...................................................................................590
Reaction-Bonding Processes ............................................................590
Infiltration ........................................................................................590
Directed Oxidation (Lanxide) Process ........................................591
In Situ Chemical Reaction Techniques ........................................592
Sol-Gel Techniques .........................................................................593
Polymer Infiltration and Pyrolysis ..................................................595
Self-Propagating High-Temperature Synthesis ................................597
Electrophoretic Deposition ...............................................................598
Processing of Carbon-Carbon Composites ......................................600
Preform Fabrication ........................................................................600
Densification Processing ..................................................................601
Protective Coatings ..........................................................................603
Joining ..............................................................................................605
Properties of Carbon-Carbon Composites .......................................606

Post-Processing and Assembly ..........................................................613
Chairperson: flake C. Campbell, The Boeing Company

Introduction to Post-Processing and Assembly ..................................615
Polymer-Matrix Composites .............................................................615
Metal-Matrix and Ceramic-Matrix Composites ................................615
Machining, Trimming, and Routing of Polymer-Matrix Composites .........................................................616
Machining Operations .....................................................................616
Cutting Tools For Machining ..........................................................616
Peripheral Milling ...........................................................................617
Face Milling ......................................................................................617
Trimming ..........................................................................................618

Secondary Adhesive Bonding of Polymer-Matrix Composites ....620
Adhesive Joint Design ......................................................................620
Selection Criteria .............................................................................620
Highly Loaded Joint Considerations ..............................................622
Epoxy Adhesives ............................................................................624
Surface Preparation .........................................................................626
Sandwich Structures ........................................................................627
Honeycomb Core ............................................................................628
Honeycomb Processing .....................................................................628
Syntactic Core ................................................................................628
Foam Core .......................................................................................628
Adhesive-Bonding Process .............................................................628
Adhesive Application ......................................................................629
Tooling ..............................................................................................630
Inspection ........................................................................................632
Processing and Joining of Thermoplastic Composites ................633
Economic Considerations ................................................................633
Material Options .............................................................................634
Processing Methods .........................................................................636
Joining ..............................................................................................638

Hole Drilling in Polymer-Matrix Composites .................................646
Part Fit-Up .........................................................................................646
Drilling Considerations ....................................................................647
Reaming ............................................................................................649
Countersinking ................................................................................649
Hole Quality ......................................................................................649

Mechanical Fastener Selection ..........................................................651
Corrosion Compatibility ...................................................................651
Fastener Materials and Strength Considerations ........................651
Bolt Bending .....................................................................................652
Head Configuration Selection ..........................................................652
Clamp-Up ..........................................................................................653
Chamfering of Holes ........................................................................653
Interference Fit Fasteners ...............................................................654
Lightning-Strike Protection ..............................................................655
Hi-Lok and Lockbolt Fasteners .......................................................656
Eddie-Bolt Fasteners ......................................................................657
Blind Fasteners in Composite Structures ......................................657
Screws and Nutplates in Composite Structures ..........................658

Environmental Protection and Sealing .............................................659
Corrosion Control .............................................................................659
Design Considerations ....................................................................660
Sealing ...............................................................................................660
Primer and Topcoat Systems ...........................................................663
Extrusion of Particle-Reinforced Aluminum Composites ..........666
Dies and Shapes ...............................................................................666
Effects of Reinforcements ...............................................................667

Post-Processing and Assembly of Ceramic-Matrix Composites ....668
Machining and Finishing of CMCs ...................................................668
Coating and Surface Treatments for CMCs ................................669
Joining of CMCs ..............................................................................669
Assembly of CMCs .........................................................................670
Nondestructive Evaluation ...............................................................670

Quality Assurance ...........................................................................675
Chairperson: G. Aaron Henson III, Design Alternatives Inc.

Introduction to Quality Assurance ....................................................677
In-Process Monitoring ......................................................................677
Quality Assurance Factors ...............................................................677
Tooling and Assembly Considerations ...........................................677
Quality Assurance for Commercial Applications ........................678
Nondestructive Testing and Data Fusion .........................................678
Conclusions ......................................................................................678
Resin Properties Analysis ...............................................................679
Component Material Tests ...............................................................679
Mixed Resin System Tests ...............................................................680
Prepreg Tests ....................................................................................680
Cured Resin and Prepreg Mechanical Properties .......................681
Tooling and Assembly Quality Control ..........................................682
Tooling Quality Control .................................................................682
Documentation ................................................................................682
Hand-Faired Master Models ............................................................682
Machined Master Models ...............................................................683
Second-Generation Patterns ..........................................................683
Composite Tooling ..........................................................................683
Metallic Tooling ...............................................................................683

Composites Assembly Quality Control ........................................683
Methods for Simplifying and Improving Assembly Operations ..........684
Assembly Process Monitoring .........................................................684
Outlook for Composites Assembly ................................................684

Reinforcing Material Lay-Up Quality Control .................................685
Facilities and Equipment ...............................................................685
Material Control ..............................................................................687
Lay-Up .............................................................................................687
Automated Tape Laying and Fiber Placement ..............................690
Numerically Aided Lay-Up .............................................................690

Cure Monitoring and Control ..........................................................692
Process Control .................................................................................692
Resin Cure Sensing .........................................................................692
Flow Sensing ....................................................................................697
Practical Issues in Sensing Resin Cure and Flow ...........................698

Nondestructive Testing .................................................................699
Ultrasonics .......................................................................................699
Air-Coupled Ultrasonics .................................................................702
Laser Ultrasound ............................................................................703
 Ultrasonic Spectroscopy .................................................................707
 Lamb Waves .....................................................................................708
 Nonlinear Ultrasonics ......................................................................711
 Acousto-Ultrasonics .......................................................................711
 Radiography .......................................................................................712
 Computed Tomography ...................................................................715
 Thermography ..................................................................................717
 Low-Frequency Vibration Methods ...............................................718
 Acoustic Emission ............................................................................718
 Eddy Current ...................................................................................719
 Optical Holography and Shearography .......................................719
 Data Fusion .......................................................................................720
 Standards .........................................................................................721
Quality Assurance of Metal-Matrix Composites .............................................. 726
Characterization Techniques ................................................................. 726
Mechanical Testing .................................................................................. 727
Nondestructive Evaluation ........................................................................ 728

Testing and Certification ............................................................................. 731
Chairperson: Richard E. Fields, Lockheed Martin Missiles and Fire Control
Introduction to Testing and Certification ................................................... 733
Section on Testing and Certification .......................................................... 733
Overview of Testing and Certification ....................................................... 734
Differences Between Testing of Composites and Testing of Isotropic Materials ......................................................................................... 734
Involvement of Certification Agencies ...................................................... 734
Understanding the Building-Block Approach ......................................... 735
Building-Block Levels ............................................................................... 735
Determining the Purposes of Testing ......................................................... 736
Data Normalization .................................................................................. 736
Statistical Data Reduction ......................................................................... 738
Test Program Planning ................................................................................ 739
Development of Test Matrices .................................................................. 741
Testing Standards .................................................................................... 742
Specimen Preparation ............................................................................... 743
Environmental Conditioning ..................................................................... 745
Instrumentation and Data Acquisition ...................................................... 747
Failure Modes .......................................................................................... 747
Data Interpretation and Recording ............................................................ 747
Constituent Materials Testing .................................................................... 749
Tests for Reinforcement Fibers and Fabrics ............................................. 749
Tests for Matrix Resins and Prepregs ....................................................... 751
Lamina and Laminate Nonmechanical Testing ........................................ 759
Per Ply Thickness ...................................................................................... 759
Constituent Content .................................................................................. 759
Density ...................................................................................................... 760
Coefficient of Thermal Expansion and Coefficient of Moisture Expansion ........................................................................................................ 760
Glass Transition Temperature .................................................................... 761
Thermal Conductivity, Diffusivity, and Specific Heat ................................ 762
Lamina and Laminate Mechanical Testing ................................................. 766
Failure Mode Analysis .............................................................................. 766
Tensile Property Test Methods .................................................................. 767
Compressive Property Test Methods ....................................................... 769
Shear Property Test Methods ................................................................... 772
Flexure Property Test Methods ................................................................. 774
Fatigue Toughness Test Methods ................................................................. 775
Fatigue Property Test Methods .................................................................. 776
Element and Subcomponent Testing ......................................................... 778
Test Methodology and Considerations ...................................................... 778
Standard Elements .................................................................................. 781
Nonstandard Elements and Subcomponents ........................................... 789
Durability and Damage-Tolerance Testing ............................................... 790
Full-Scale Structural Testing ....................................................................... 794
Static Test .................................................................................................. 794
Durability (Fatigue) Test ........................................................................... 795
Damage Tolerance Test ............................................................................. 798

Properties and Performance ...................................................................... 801
Chairperson: Jeffrey Schaff, United Technologies Research Center
Properties and Performance of Polymer-Matrix Composites .................. 803
Materials and Properties Description ....................................................... 803
AxeS Definitions, Symbols, and Special Property Calculations .................. 805
Overview of Constituent Materials ............................................................ 806
Thermoplastic-Matrix Composites ............................................................ 807
Thermoset-Matrix Composites ................................................................. 807
Properties of Metal-Matrix Composites .................................................... 838
Discontinuously Reinforced MMCs ........................................................ 838
Hybrid Laminal and Ductile Phase Composites ......................................... 848
Continuous Fiber Reinforced Composites ............................................... 851

Properties and Performance of Ceramic-Matrix and Carbon-Carbon Composites ................................................................. 859
Discontinuously Reinforced Ceramic-Matrix Composites ......................... 859
Continuous Fiber Ceramic Composites ..................................................... 862
Carbon-Carbon Composites ..................................................................... 865

Product Reliability, Maintainability, and Repair .......................................... 869
Chairpersons: Michael J. Hoke, Abaris Training Resources, Inc.
Rikard B. Heselhurst, Australian Defence Force Academy
Introduction to Product Reliability, Maintainability, and Repair ............... 871
Facilitating Effective Repair of Composite Structures ................................ 871
Repair Issues for Specific Applications ..................................................... 871
Repair Standardization and Reliability Considerations .............................. 871
Designing for Repairability ....................................................................... 872
Introduction to Designing for Repairability ............................................ 872
Design Guidelines .................................................................................... 874
Design for Supportability .......................................................................... 880
Specific Examples ..................................................................................... 882
Repair Engineering and Design Considerations ........................................ 885
Types of Repairs to Composite Structures ............................................. 885
Repair Requirements ................................................................................ 885
Considerations Prior to, During, and After Repair Action .......................... 887
Validation and Certification of Repairs ................................................... 888
Design Guidelines .................................................................................... 889
Pinfalls and Problems ............................................................................... 891
Repair Applications, Quality Control, and Inspection ............................... 893
Types of Damage ..................................................................................... 893
Damage Detection in Field Conditions .................................................... 893
Component Identification .......................................................................... 894
Paint Removal ............................................................................................ 895
Repair Design ............................................................................................ 895
Repair Design Considerations ................................................................. 896
Repair Instructions .................................................................................... 897
Repair Materials ........................................................................................ 897
Curing Methods ......................................................................................... 897
Ship Structure Repairs ............................................................................... 899
Repair Classification, Characterization, and Cycle .................................... 899
Repair to Gel Coats ................................................................................... 900
Composite Patch Repairs .......................................................................... 901
Scarf Repairs .............................................................................................. 901
Step Repairs ............................................................................................. 903
Resin-Infusion Repairs ............................................................................. 904
Rehabilitation of Reinforced Concrete Structures ..................................... 907
Using Fiber-Reinforced Polymer Composites .......................................... 906
Structural Assessment .............................................................................. 906
Composite Materials Reinforcing Systems for Concrete Strengthening ........ 907
Properties of Polymer Composite Reinforcing Systems .......................... 908
Materials Property Requirements for Design .......................................... 909
FRP-Reinforced Concrete Behavior ......................................................... 910
Surface Preparation .................................................................................. 912
Composite Materials Applications ............................................................ 912
Records ....................................................................................................... 912
Acceptance Criteria ................................................................................ 912
Maintainability Issues ............................................................................. 914
Types of Composite Structures .................................................................. 914
Designing for Maintainability .................................................................. 915
Sources of Defects and Damage ............................................................... 915
Nondestructive Inspection Requirements ............................................... 916
Design Recommendations ......................................................................... 917
Personnel, Facilities, and Equipment ........................................................ 918
Bonded Repair of Metal Structures Using Composites ............................. 922
Damage Assessment .................................................................................. 922
Repair Design ............................................................................................ 922
Repair Application .................................................................................... 924
Repair Certification ................................................................................... 926
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycling</td>
<td>1072</td>
</tr>
<tr>
<td>Winter Sports</td>
<td>1072</td>
</tr>
<tr>
<td>Aquatic Sports</td>
<td>1073</td>
</tr>
<tr>
<td>Track and Field Equipment</td>
<td>1075</td>
</tr>
<tr>
<td>Archery Equipment</td>
<td>1076</td>
</tr>
<tr>
<td>Conclusions</td>
<td>1076</td>
</tr>
<tr>
<td><strong>Thermal Management and Electronic Packaging</strong></td>
<td></td>
</tr>
<tr>
<td>Application Requirements and Candidate Materials</td>
<td>1078</td>
</tr>
<tr>
<td>Reinforcements</td>
<td>1080</td>
</tr>
<tr>
<td>Thermal Management Composites and Other Advanced Materials</td>
<td>1081</td>
</tr>
<tr>
<td>Applications</td>
<td>1082</td>
</tr>
<tr>
<td>Future Trends</td>
<td>1082</td>
</tr>
<tr>
<td><strong>Marine Applications</strong></td>
<td>1085</td>
</tr>
<tr>
<td>Naval Applications of FRP Composites</td>
<td>1085</td>
</tr>
<tr>
<td>Leisure, Sporting, and Commercial FRP</td>
<td></td>
</tr>
<tr>
<td>Composite Craft</td>
<td>1088</td>
</tr>
<tr>
<td>Offshore Applications of FRP Composites</td>
<td>1089</td>
</tr>
<tr>
<td>Civil Infrastructure Applications</td>
<td>1091</td>
</tr>
<tr>
<td>The Need for Infrastructure Renewal</td>
<td>1091</td>
</tr>
<tr>
<td>Conventional Materials versus Composites</td>
<td>1091</td>
</tr>
<tr>
<td>Seismic Retrofit Applications</td>
<td>1092</td>
</tr>
<tr>
<td>Repair and Strengthening of Beams and Slabs</td>
<td>1093</td>
</tr>
<tr>
<td>Repair of Large-Diameter Pipes</td>
<td>1095</td>
</tr>
<tr>
<td>Replacement Bridge Decks</td>
<td>1096</td>
</tr>
<tr>
<td>New Structural Systems</td>
<td>1097</td>
</tr>
<tr>
<td>Outlook</td>
<td>1098</td>
</tr>
<tr>
<td><strong>Applications of Ceramic-Matrix Composites</strong></td>
<td></td>
</tr>
<tr>
<td>Applications for Discontinuously Reinforced CMCs</td>
<td>1101</td>
</tr>
<tr>
<td>Applications for Continuous Fiber Ceramic Composites</td>
<td>1106</td>
</tr>
<tr>
<td><strong>Reference Information</strong></td>
<td></td>
</tr>
<tr>
<td>Glossary of Terms</td>
<td>1113</td>
</tr>
<tr>
<td>Metric Conversion Guide</td>
<td>1137</td>
</tr>
<tr>
<td>Abbreviations and Symbols</td>
<td>1140</td>
</tr>
<tr>
<td>Index</td>
<td>1143</td>
</tr>
</tbody>
</table>