Metal Matrix Composites

Nikhilesh Chawla • Krishan K. Chawla

Metal Matrix Composites

Second Edition

Springer

Nikhilesh Chawla
Arizona State University
Tempe, AZ, USA

Krishan K. Chawla
University of Alabama at Birmingham
Birmingham, AL, USA

ISBN 978-1-4614-9547-5 ISBN 978-1-4614-9548-2 (eBook)
DOI 10.1007/978-1-4614-9548-2
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013955046

© Springer Science+Business Media New York 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Cover Illustration: Cover image is a high speedway railroad coach bogey with four metal matrix composite brake disks produced by SAB Wabco (courtesy of H. Ruppert).

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

मनःप्रसादः सौम्यत्वं मौनमात्मविनिग्रहः ।
भावसंशुद्धिरित्येतत्तपो मानसमुच्यते ॥

*Serenity, simplicity, gravity, self-control, and purity
of thought are the austerities of the mind.*

*Bhagvad Gita,
Chapter 17, shloka 16*

Dedicated to

*Kunal Chawla and Kush Chawla Who have Brightened
our Lives From the Moment they were Born*

Preface to the 2nd Edition

Metal matrix composites (MMCs) represent an important category of the modern field of composites. Since the first edition, our scientific understanding and the use of MMCs have increased. With the increasing need to improve fuel economy in the transportation sector, MMCs are increasingly becoming important. Since the first edition of this book, there have been consistent and important contributions to the field from the academia and industry. These contributions involve developments in processing, microstructural characterization, testing, and analysis. In particular, the advent of many cutting-edge experimental tools, such as X-ray synchrotron tomography and focused ion beam, has significantly enhanced the community's understanding of the field. Similar improvements in computational modeling capabilities and speed have resulted in important strides in theoretical modeling of the behavior of MMCs.

The aim of the book remains the same as in the first edition: relationship among processing, microstructure, properties, and performance of MMCs. To that end, we use a balanced mechanics-materials approach supplemented with a wealth of graphics, many in color, which make it easy for the reader to grasp the underlying operating mechanisms. We emphasize our conviction that the microstructure of the composite controls its properties.

The second edition of the book, like the first, is aimed at upper division undergraduate students and beginning graduate students in departments of engineering (mechanical, electrical, materials, chemical) and physical sciences (physics and chemistry). The book will serve as a useful reference of the practicing scientist, engineer, and researcher in the industry.

We would like to acknowledge assistance from a number of sources without which this project would not have been possible. N.C. would like to acknowledge several current and former students and postdocs in his research group: N.C. Chapman, P. Hruby, J. Silva, D. Singh, S. S. Singh, J. L. Walters (Stewart), and J. J. Williams. He acknowledges many fruitful discussions and interactions with the following colleagues and collaborators: F. De Carlo, P. Portella, and

X. Xiao, N.C. would also like to thank a few key individuals in the administration at Arizona State University for providing the means and encouragement to carry out this endeavor; in particular his school's Director Kyle Squires, Dean Paul Johnson, and President Michael Crow. Peter Hruby was also instrumental in making several figures, movies, and diagrams in the 2nd edition. This work would not be possible without the unwavering encouragement and support of his wife Anita and sons Kunal and Kush.

K.K.C. would like to acknowledge the students and postdocs in his group at University of Alabama at Birmingham: K. Carlisle, Z. Chen, A. Goel, M. Koopman, R. Kulkarni, and B. V. Patel. He also thanks G. M. Gladysz, A. Mortensen, B. R. Patterson, P. D. Portella, and J. M. Rigsbee, for useful discussions.

Tempe, AZ, USA
Birmingham, AL, USA

Nikhilesh Chawla
Krishan K. Chawla

Preface to 1st Edition

Metal matrix composites (MMCs) have been around for a long time, but have only been recognized as legitimate engineering composite materials in the second half of the twentieth century. From their humble research beginnings, MMCs have gone from “niche” materials to several high-performance applications in aerospace, electronic packaging, automotive, and recreational products. Much of the significant research advances have been published in several journal articles, conference proceedings, and multi-authored volumes. It is surprising that only two texts have been published in this area. Taya and Arsenault (1989) published the first book on MMCs, which was followed by that of Clyne and Withers (1993). Thus, it has been a long time since a textbook on MMCs has been published. During this period, there has been a myriad of new and exciting advances and applications in the field. These include continuous fiber-reinforced MMCs for cables in power transmission, high-temperature superconducting wires, particulate MMCs in civilian aircraft and automotive applications, and high-volume fraction, high thermal conductivity substrates for electronic packaging. All these factors make this a very opportune time to bring out the present text.

We have several goals in writing this textbook on MMCs: (1) to provide a thorough and coherent coverage of MMCs that will be useful to the beginning student who wants to learn about this exciting field, as well as the practicing scientist or engineer who may be familiar with some aspects of MMCs, but has not been able to keep with all the exciting new developments in the field; (2) summarize and consolidate the vast body of work that has been done in the last 50 years or so; and (3) illustrate several examples of MMC applications, with the hope that this will spur further research and innovation and have an even bigger impact on MMCs for future applications.

Throughout this textbook, the reader will encounter a recurring theme, which is the synergistic relationship among processing, microstructure, and properties of MMCs. In this regard, we begin with a brief definition and introduction of metal matrix composites. This is followed by a chapter each on reinforcements and common matrix materials. A chapter on the very important topic of processing of MMC is then presented. This is followed by a chapter on interfaces in MMCs, their

characterization, and techniques to obtain interfacial properties. Next there are chapters on monotonic mechanical and physical properties, followed by cyclic fatigue, creep, and wear resistance. We conclude with a chapter on applications of MMCs.

Acknowledgments N.C. would like to acknowledge long-term support for research in the MMC arena from the Office of Naval Research (A. K. Vasudevan, Program Manager) and the US Automotive Partnership, through the Department of Energy (W. Jandeska, *GM*; R. Chermekoff, *Ford*; and J. Lynn, *Daimler–Chrysler*, Program Managers). Several individuals were instrumental in whetting his appetite and enhancing his knowledge of MMCs, through fruitful interactions, collaborations, and discussions: W. H. Hunt, Y.-L. Shen, J. J. Lewandowski, J. LLorca, J. W. Jones, and J. E. Allison. N.C. would like to thank a few key individuals in the administration at Arizona State University for providing the means and encouragement to carry out this endeavor; in particular his Department Chair S. Mahajan, Dean P. Crouch, and President M. M. Crow. This book would not have been possible without the outstanding work and inquisitive nature of his current and former students and postdocs: A. Ayyar, G. Crawford, X. Deng, M. Dudek, V. V. Ganesh, M. Kerr, G. Piotrowski, R. Saha, R. S. Sidhu, J. J. Williams, and B. Wunsch. G. Piotrowski was also instrumental in making several figures and diagrams in the text.

K.K.C. would like to acknowledge the grant of a sabbatical leave from the University of Alabama at Birmingham, part of which was spent at Arizona State University (ASU) where the hospitality of Professor S. Mahajan was a great help in the writing of this book. During other parts of the sabbatical, K.K.C. had the pleasure of stimulating discussions with P. D. Portella (BAM, Berlin), M. Elices and J. LLorca (University of Madrid), and G. M. Gladysz (Los Alamos National Laboratory). He is also grateful to the researchers in his group, K. Carlisle, M. Koopman, and R. Kulkarni at University of Alabama at Birmingham for their cheerfulness, sincerity, and hard work. He is very thankful to B. A. MacDonald, National Science Foundation, and S. Fishman and A. K. Vasudevan, Office of Naval Research, who over the years have funded his research program. He also thanks A. Mortensen, B. R. Patterson, B. V. Patel, J. M. Rigsbee, and N. Stoloff who were always there to discuss things.

The following individuals were particularly generous in providing us with micrographs and figures of their work: H. Devé, A. Dlouhy, A. Drake, G. Eggeler, J. Eldridge, D. Herling, P. Krajewski, J. Liu, J. Llorca, D. Lloyd, D. Miracle, M. Ochionero, W. Nix, S. Rawal, H. Ruppert, and T. Wang. We are very thankful to Greg Franklin and Carol Day for their patience and understanding during the course of writing this book.

Finally, for the curious reader who might be wondering about the common last names of the authors, we should let the cat out of the bag. This book is collaboration between two colleagues and friends, who happen to be father (K.K.C.) and son (N.C.). As such, it was a mutually fulfilling and special family endeavor. Furthermore, this book would not have been possible without the support and encouragement of the rest of the Chawla family: Anita Chawla (wife and daughter-in-law), Kanika Chawla (sister and daughter), and Nivedita Chawla (mother and wife). Special thanks to Anita Chawla for her invaluable assistance with formatting and index preparation.

Tempe, AZ, USA
Birmingham, AL, USA

Nikhilesh Chawla
Krishan K. Chawla

About the Authors

Nikhilesh Chawla is Fulton Professor of Materials Science and Engineering at Arizona State University. He received his Ph.D. from the University of Michigan. His research interests encompass the mechanical behavior and modeling of advanced materials at bulk and small length scales and 4D Materials Science. Professor Chawla is a fellow of ASM international. He's the recipient of the 2013 Brimacombe Medalist Award from TMS; 2011 Distinguished Lectureship given by Tsinghua University, China; 2009 Raymond Award for Best Paper by the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME); 2004 Bradley Stoughton Award for Young Teachers, given by ASM International; and the 2006 TMS Young Leaders Tutorial Lecture. He's also won the National Science Foundation Early Career Development Award and the Office of Naval Research Young Investigator Award. He serves as editor of *Materials Science and Engineering A*, as well as on the editorial board of several journals.

Krishan K. Chawla is Professor of Materials Science and Engineering at the University of Alabama at Birmingham, USA. He received his Ph.D. from the University of Illinois at Urbana-Champaign. His research interests encompass processing, microstructure, and mechanical behavior of materials. He has taught and/or done research at several universities around the world. Professor Chawla has served as a Program Director for metals and ceramics in the Division of Materials Research, National Science Foundation. He is a fellow of ASM international. Among his other awards are Distinguished Researcher Award at New Mexico Tech, Distinguished Alumnus Award from Banaras Hindu University, Eshbach Society Distinguished Visiting Scholar award at Northwestern University, President's award for Excellence in Teaching at UAB, and Faculty Fellow award at Oak Ridge National Laboratory. Professor Chawla is the author or coauthor of various textbooks in the area of materials and serves on the editorial boards of a number of journals. He is editor of the journal *International Materials Reviews*.

Contents

1	Introduction	1
1.1	Types of MMCs	2
1.2	Characteristics of MMCs	3
2	Reinforcements	5
2.1	Fibrous Materials	5
2.2	Fiber Flexibility	6
2.3	Carbon Fibers	8
2.3.1	Fabrication of Carbon Fibers	9
2.3.2	PAN-Based Carbon Fibers	10
2.3.3	Pitch-Based Carbon Fibers	12
2.3.4	Spinning and Rheology of Mesophase Pitch	13
2.3.5	Structure and Properties of Carbon Fibers	14
2.3.6	Structure of Carbon Fibers	15
2.3.7	Carbon Nanotubes, Nanoparticles, and Graphene	16
2.4	Boron Fibers	17
2.4.1	Residual Stresses	19
2.5	Oxide Fibers	20
2.5.1	Alumina-Type Oxide Fibers	20
2.6	Nonoxide Fibers	24
2.6.1	Silicon Carbide Fibers	24
2.6.2	Silicon Carbide Fibers Made by CVD	24
2.6.3	Nonoxide Fibers via Polymer Precursors	26
2.6.4	Structure and Properties of Nicalon Fiber	28
2.6.5	Other SiC-Type Fibers	29
2.7	Whiskers	29
2.8	Particles	30
2.8.1	Particulate Silicon Carbide	30
2.8.2	Particulate Tungsten Carbide	31
2.9	Comparison of Fibers	32
2.10	Statistical Analysis of Fiber Strength	32

3	Matrix Materials	37
3.1	Bonding and Crystalline Structure in Metals	37
3.2	Crystalline Defects in Metals	38
3.3	Strengthening Mechanisms in Metals	41
3.3.1	Dislocation Strengthening	41
3.3.2	Grain Boundary Strengthening	41
3.3.3	Solute and Precipitation Strengthening	42
3.3.4	Fracture in Metals	44
3.4	Common Matrix Materials	45
3.4.1	Aluminum and Aluminum Alloys	45
3.4.2	Titanium Alloys	46
3.4.3	Magnesium and Its Alloys	47
3.4.4	Cobalt	47
3.4.5	Copper	47
3.4.6	Silver	48
3.4.7	Nickel	48
3.4.8	Niobium	48
3.4.9	Intermetallics	48
3.5	Superconductivity	49
3.5.1	Types of Superconductors	50
3.5.2	Flux and Flux Pinning	51
3.5.3	Ductile Alloys: Niobium-Titanium Alloys	52
3.5.4	A-15 Superconductors: Nb_3Sn	53
4	Processing	55
4.1	Liquid-State Processing	55
4.1.1	Casting or Liquid Infiltration	56
4.1.2	Spray Co-deposition	62
4.1.3	In Situ Processes	64
4.1.4	Infiltration Mechanics	65
4.1.5	Microstructure Evolution During Liquid-Phase Processing	68
4.1.6	Casting	71
4.2	Solid-State Processing	75
4.2.1	Powder Metallurgy Processing	76
4.2.2	Extrusion	78
4.2.3	Forging	83
4.2.4	Pressing and Sintering	84
4.2.5	Roll Bonding and Co-extrusion	85
4.2.6	Diffusion Bonding	89
4.2.7	Explosive Shock Consolidation	91
4.3	Gaseous-State Processing	91
4.3.1	Physical Vapor Deposition	91
5	Interface	99
5.1	Crystallographic Nature of the Interface	100
5.2	Wettability	101

5.3	Types of Bonding	102
5.3.1	Mechanical Bonding	102
5.3.2	Chemical Bonding	104
5.3.3	Interactions at the Interface due to Thermal Mismatch . . .	111
5.4	Measurement of Interfacial Bond Strength	112
5.4.1	Bend Tests	112
5.4.2	Fiber Pullout and Pushout Tests	113
6	Micromechanics	121
6.1	Elastic Constants of a Fiber Reinforced Composite	121
6.1.1	Strength of Materials Approach	124
6.1.2	Micromechanical Approaches	129
6.1.3	Semiempirical Expressions	133
6.1.4	Eshelby Method or Equivalent Homogeneous Inclusion Technique	135
6.1.5	Numerical Methods	138
6.2	Physical Properties	139
6.2.1	Density	139
6.2.2	Coefficient of Thermal Expansion (CTE)	140
6.2.3	Thermal Conductivity	150
6.2.4	Electrical Conductivity	152
6.3	Thermal Stresses in Composites	153
6.3.1	Thermal Stresses in Particulate Composites	154
6.3.2	Thermal Stresses in Fiber Reinforced Composites	157
7	Monotonic Behavior	163
7.1	Strengthening Mechanisms	163
7.1.1	Direct Strengthening	164
7.1.2	Indirect Strengthening	171
7.2	Monotonic Behavior of Continuous Fiber Reinforced MMCs . . .	175
7.2.1	Criteria for Debonding and Crack Deflection at an Interface	179
7.2.2	Work Done in Fiber Pullout	182
7.2.3	Effect of Interfacial Reactions on Monotonic Behavior . . .	184
7.2.4	Modeling of Monotonic Behavior of Continuous Fiber Reinforced MMCs	187
7.3	Monotonic Behavior of Discontinuously Reinforced MMCs . . .	191
7.3.1	Modeling of Monotonic Behavior of Particle-Reinforced MMCs	206
7.4	In Situ Metal Matrix Composites	216
7.5	Fracture Toughness	218
8	Cyclic Fatigue	227
8.1	Stress Versus Cycles (S–N) Fatigue	228
8.1.1	Continuous Fiber-Reinforced MMCs	228
8.1.2	Stiffness Loss	236
8.1.3	Particle-Reinforced MMCs	238

8.2	Fatigue Crack Growth	249
8.2.1	Continuous Fiber-Reinforced MMCs	249
8.2.2	Particle-Reinforced MMCs	260
8.2.3	Hybrid and Laminated Composites	269
8.3	Thermal Fatigue	272
9	Creep	283
9.1	Continuous Fiber Reinforced MMCs	284
9.2	Discontinuously Reinforced MMCs	290
9.3	Superplasticity	304
10	Wear and Corrosion	311
10.1	Introduction	311
10.2	Particle Reinforced Aluminum Matrix Composites	314
10.3	Tungsten Carbide/Cobalt Composites	317
10.3.1	Hardness and Strength of Cemented Carbides	317
10.3.2	Double Cemented Carbide	318
10.4	Wear in Braking Materials	321
10.5	Corrosion of MMCs	322
11	Applications	325
11.1	Aerospace	325
11.1.1	Aircraft Structures	325
11.1.2	Fiber Metal Laminates	328
11.1.3	Missiles	332
11.1.4	Space Structures	333
11.2	Transportation (Automotive and Railway)	335
11.2.1	Railroad Brakes	339
11.3	Electronics and Thermal Management	342
11.4	Filamentary Superconducting Magnets	344
11.5	Power Conductors	348
11.6	Recreational and Sporting Goods	350
11.7	Wear-Resistant Materials	352
	Author Index	357
	Subject Index	367