Composite Materials

Krishan K. Chawla

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Science and Engineering

Third Edition

With 278 Illustrations

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Cover illustration: Fan blades made of carbon fiber/epoxy composite in the GEnx jet engine. [Courtesy of General Electric.]

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आ नो भद्राः क्रतवो यन्तु विश्वतः

Ā no bhadrāḥ kratavo yantu viśvataḥ
Let noble thoughts come to us from every side
Rigveda 1-89-i

Dedicated affectionately to A, K^3, and N^3

Preface to the Third Edition

Since the publication of the second edition of this book, there has been a spate of activity in the field of composites, in the academia as well as in the industry. The industrial activity, in particular, has been led by the large-scale use of composites by aerospace companies, mainly Boeing and Airbus. It would not be far off the mark to say that the extensive use of carbon fiber/epoxy resin composites in Boeing 787 aircraft and a fairly large use of composites in Airbus's A 380 aircraft represent a paradigm shift. Boeing 787 has composites in the fuselage, windows, wings, tails, stabilizers, etc., resulting in 50% in composites by weight. Nevertheless, it should be pointed out that in reality, the extensive use of composites in aircraft is a culmination of a series of earlier steps over the decades since mid-1960s. Besides the large-scale applications in the aerospace industry, there have been impressive developments in other fields such as automotive, sporting goods, superconductivity, etc.

All of this activity has led to a substantial addition of new material in this edition. Among these are the following: Carbon/carbon brakes, nanocomposites, biocomposites, self-healing composites, self-reinforced composites, fiber/metal laminate composites, composites for civilian aircraft, composites for aircraft jet engine, second-generation high-temperature superconducting composites, WC/metal particulate composites, new solved examples, and new problems. In addition, I have added a new chapter called nonconventional composites. This chapter deals with some nonconventional composites such as nanocomposites (polymer, metal, and ceramic matrix), self-healing composites, self-reinforced composites, biocomposites, and laminates made of bidimensional layers.

Once again, I plead guilty to the charge that the material contained in this edition is more than can be covered in a normal, semester-long course. The instructor of course can cut the content to his/her requirements. I have always had the broader aim of providing a text that is suitable as a source of reference for the practicing researcher, scientist, and engineer.

Finally, there is the pleasant task of acknowledgments. I am grateful to National Science Foundation, Office of Naval Research, Federal Transit Administration, Los Alamos National Laboratory Sandia national Laboratory, Oak Ridge National

Laboratory, Smith International Inc., and Trelleborg, Inc. for supporting my research work over the years, some of which is included in this text. Among the people with whom I have had the privilege of collaborating over the years and who have enriched my life, professional and otherwise, I would like to mention, in alphabetical order, C.H. Barham, A.R. Boccaccini, K. Carlisle, K. Chawla, N. Chawla, X. Deng, Z. Fang, M.E. Fine, S.G. Fishman, G. Gladysz, A. Goel, N. Gupta, the late B. Ilschner, M. Koopman, R.R. Kulkarni, B.A. MacDonald, A. Mortensen, B. Patel, B.R. Patterson, P.D. Portella, J.M. Rigsbee, P. Rohatgi, H. Schneider, N.S. Stoloff, Y.-L. Shen, S. Suresh, Z.R. Xu, U. Vaidya, and A.K. Vasudevan. Thanks are due to Kanika Chawla and S. Patel for help with the figures in this edition. I owe a special debt of gratitude to my wife, Nivi, for being there all the time. Last but not least, I am ever grateful to my parents, the late Manohar L. and Sumitra Chawla, for their guidance and support.

Birmingham, AL, USA
March, 2011

Krishan K. Chawla

Supplementary Instructional Resources

An Instructor's Solutions Manual containing answers to the end-of-the-chapter exercises and PowerPoint Slides of figures suitable for use in lectures are available to instructors who adopt the book for classroom use. Please visit the book Web page at `www.springer.com` for the password-protected material.

Preface to the Second Edition

The first edition of this book came out in 1987, offering an integrated coverage of the field of composite materials. I am gratified at the reception it received at the hands of the students and faculty. The second edition follows the same format as the first one, namely, a well-balanced treatment of materials and mechanics aspects of composites, with due recognition of the importance of the processing. The second edition is a fully revised, updated, and enlarged edition of this widely used text. There are some new chapters, and others have been brought up-to-date in light of the extensive work done in the decade since publication of the first edition. Many people who used the first edition as a classroom text urged me to include some solved examples. In deference to their wishes I have done so. I am sorry that it took me such a long time to prepare the second edition. Things are happening at a very fast pace in the field of composites, and there is no question that a lot of very interesting and important work has been done in the past decade or so. Out of necessity, one must limit the amount of material to be included in a textbook. In spite of this view, it took me much more time than I anticipated. In this second edition, I have resisted the temptation to cover the whole waterfront. So the reader will find here an up-to-date treatment of the fundamental aspects. Even so, I do recognize that the material contained in this second edition is more than what can be covered in the classroom in a semester. I consider that to be a positive aspect of the book. The reader (student, researcher, practicing scientist/engineer) can profitably use this as a reference text. For the person interested in digging deeper into a particular aspect, I provide an extensive and updated list of references and suggested reading.

There remains the pleasant task of thanking people who have been very helpful and a constant source of encouragement to me over the years: M.E. Fine, S.G. Fishman, J.C. Hurt, B. Ilschner, B.A. MacDonald, A. Mortensen, J.M. Rigsbee, P. Rohatgi, S. Suresh, H. Schneider, N.S. Stoloff, and A.K. Vasudevan. Among my students and post-docs, I would like to acknowledge G. Gladysz, H. Liu, and Z.R. Xu. I am immensely grateful to my family members, Nivi, Nikhil, and Kanika. They were

patient and understanding throughout. Without Kanika's help in word processing and fixing things, this work would still be unfinished. Once again I wish to record my gratitude to my parents, Manohar L. Chawla and the late Sumitra Chawla for all they have done for me!

Birmingham, AL, USA Krishan K. Chawla
February, 1998

Preface to the First Edition

The subject of composite materials is truly an inter- and multidisciplinary one. People working in fields such as metallurgy and materials science and engineering, chemistry and chemical engineering, solid mechanics, and fracture mechanics have made important contributions to the field of composite materials. It would be an impossible task to cover the subject from all these viewpoints. Instead, we shall restrict ourselves in this book to the objective of obtaining an understanding of composite properties (e.g., mechanical, physical, and thermal) as controlled by their structure at micro- and macro-levels. This involves a knowledge of the properties of the individual constituents that form the composite system, the role of interface between the components, the consequences of joining together, say, a fiber and matrix material to form a unit composite ply, and the consequences of joining together these unit composites or plies to form a macrocomposite, a macroscopic engineering component as per some optimum engineering specifications. Time and again, we shall be emphasizing this main theme, that is structure–property correlations at various levels that help us to understand the behavior of composites.

In Part I, after an introduction (Chap. 1), fabrication and properties of the various types of reinforcement are described with a special emphasis on microstructure–property correlations (Chap. 2). This is followed by a chapter (Chap. 3) on the three main types of matrix materials, namely, polymers, metals, and ceramics. It is becoming increasingly evident that the role of the matrix is not just that of a binding medium for the fibers but it can contribute decisively toward the composite performance. This is followed by a general description of the interface in composites (Chap. 4). In Part II a detailed description is given of some of the important types of composites (Chap. 5), metal matrix composites (Chap. 6), ceramic composites (Chap. 7), carbon fiber composites (Chap. 8), and multifilamentary superconducting composites (Chap. 9). The last two are described separately because they are the most advanced fiber composite systems of the 1960s and 1970s. Specific characteristics and applications of these composite systems are brought out in these chapters. Finally, in Part III, the micromechanics (Chap. 10) and macromechanics (Chap. 11) of composites are described in detail, again emphasizing the theme of how structure (micro and macro) controls the properties.

This is followed by a description of strength and fracture modes in composites (Chap. 12). This chapter also describes some salient points of difference, in regard to design, between conventional and fiber composite materials. This is indeed of fundamental importance in view of the fact that composite materials are not just any other new material. They represent a total departure from the way we are used to handling conventional monolithic materials, and, consequently, they require unconventional approaches to designing with them.

Throughout this book examples are given from practical applications of composites in various fields. There has been a tremendous increase in applications of composites in sophisticated engineering items. Modern aircraft industry readily comes to mind as an ideal example. Boeing Company, for example, has made widespread use of structural components made of "advanced" composites in 757 and 767 planes. Yet another striking example is that of the Beechcraft Company's Starship 1 aircraft. This small aircraft (eight to ten passengers plus crew) is primarily made of carbon and other high-performance fibers in epoxy matrix. The use of composite materials results in 19% weight reduction compared to an identical aluminum airframe. Besides this weight reduction, the use of composites made a new wing design configuration possible, namely, a variable-geometry forward wing that sweeps forward during takeoff and landing to give stability and sweeps back 30° in level flight to reduce drag. As a bonus, the smooth structure of composite wings helps to maintain laminar air flow. Readers will get an idea of the tremendous advances made in the composites field if they would just remind themselves that until about 1975 these materials were being produced mostly on a laboratory scale. Besides the aerospace industry, chemical, electrical, automobile, and sports industries are the other big users, in one form or another, of composite materials.

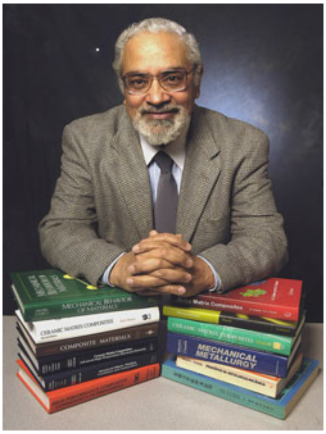
This book has grown out of lectures given over a period of more than a decade to audiences comprised of senior year undergraduate and graduate students, as well as practicing engineers from industry. The idea of this book was conceived at Instituto Militar de Engenharia, Rio de Janeiro. I am grateful to my former colleagues there, in particular, J.R.C. Guimarães, W.P. Longo, J.C.M. Suarez, and A.J.P. Haiad, for their stimulating companionship. The book's major gestation period was at the University of Illinois at Urbana-Champaign, where C.A. Wert and J.M. Rigsbee helped me to complete the manuscript. The book is now seeing the light of the day at the New Mexico Institute of Mining and Technology. I would like to thank my colleagues there, in particular, O.T. Inal, P. Lessing, M.A. Meyers, A. Miller, C.J. Popp, and G.R. Purcell, for their cooperation in many ways, tangible and intangible. An immense debt of gratitude is owed to N.J. Grant of MIT, a true gentleman and scholar, for his encouragement, corrections, and suggestions as he read the manuscript. Thanks are also due to R. Signorelli, J. Cornie, and P.K. Rohatgi for reading portions of the manuscript and for their very constructive suggestions. I would be remiss in not mentioning the students who took my courses on composite materials at New Mexico Tech and gave very constructive feedback. A special mention should be made of C.K. Chang, C.S. Lee, and N. Pehlivanturk for their relentless queries and discussions. Thanks are also due to my wife,

Nivedita Chawla, and Elizabeth Fraissinet for their diligent word processing; my son, Nikhilesh Chawla, helped in the index preparation. I would like to express my gratitude to my parents, Manohar L. and Sumitra Chawla, for their ever-constant encouragement and inspiration.

Socorro, NM, USA
June, 1987

Krishan K. Chawla

About the Author



Professor Krishan K. Chawla received his B.S. degree from Banaras Hindu University and his M.S. and Ph.D. degrees from the University of Illinois *at* Urbana-Champaign. He has taught and/or done research work at Instituto Militar de Engenharia, Brazil; University of Illinois at Urbana-Champaign; Northwestern University; Université Laval, Canada; Ecole Polytechnique Federale de Lausanne, Switzerland; the New Mexico Institute of Mining and Technology (NMIMT); Arizona State University; German Aerospace Research Institute (DLR), Cologne, Germany; Los Alamos National Laboratory; Federal Institute for Materials Research and Testing (BAM) Berlin, Germany; and the University of Alabama at Birmingham. Among the honors he has received are the following: Eshbach Distinguished Scholar at Northwestern University, U.S. Department of Energy Faculty Fellow at Oak Ridge National Laboratory, Distinguished Researcher Award at NMIMT, Distinguished Alumnus Award from Banaras Hindu University, President's Award for Excellence in Teaching at the University of Alabama at Birmingham, and Educator Award from The Minerals, Metals and Materials Society (TMS). In 1989–1990, he served as a program director for Metals and Ceramics at the U.S. National Science Foundation (NSF). He is a Fellow of ASM International.

Professor Chawla is editor of the journal International Materials Reviews.

Among his other books are the following: Ceramic Matrix Composites, Fibrous Materials, Mechanical Metallurgy (coauthor), Metalurgia Mecânica (coauthor), Mechanical Behavior of Materials (coauthor), Metal Matrix Composites (coauthor), and Voids in Materials (coauthor).

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