CERAMIC MATRIX COMPOSITES

SECOND EDITION

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by

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तमसो मा ज्योतिर्गमय

Lead me from darkness to light

Brihadaranyaka Upanishad
Ch. II.3

To

Kanika, Anita, Nikhilesh, and Nivedita
for putting up with him and it, once more

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PREFACE TO THE SECOND EDITION

Charles Dickens starts his *A Tale of Two Cities* with the following words:
"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredibility, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair... " These words provide a good characterization of the state of affairs in the field of Ceramic Matrix Composites (CMCs) during the last decade of the twentieth century and the first decade of the twenty first century. New continuous ceramic fibers have become available and new innovative techniques of processing CMCs have been developed. The Achilles' heel of monolithic ceramics is their extreme brittleness. Since the publication of the first edition of this book, substantial progress has been made in processing of continuous ceramic fibers and their composites. A reinforcing phase (particle, short fiber or continuous fiber) can improve the toughness of these materials without sacrificing the well known advantages of ceramic materials, viz., enhanced wear resistance, hardness, corrosion resistance, and high-temperature capability. A range of ceramic matrix composites (CMCs) has been developed that combine a matrix material with a reinforcing phase of different composition (such as alumina and silicon carbide) or the same composition (alumina/alumina or silicon carbide/silicon carbide). Major applications of ceramic matrix composites include cutting tools and wear resistant parts. Other minor but significant applications include hot gas filters, high pressure and heat exchangers, and gas turbine seals. On the other hand, persistent problems include lack of toughness and poor oxidation resistance at high temperatures. High cost (both raw materials and processing) continues to be a major obstacle to widespread application of CMCs. Another major obstacle is the lack of reliability in current materials. Some niche applications involving the use of CMCs have appeared but the ceramic engine remains a distant goal. All this points to a belief I have held for a long time. That belief is that, just as in the economics, in research also *there is no such thing as a free lunch.* Invariably, it is a road that involves a painstaking and persistent effort to study various problems involved and find solutions to them. Along the way, there will be advances, some incremental, some more than that. Eventually, there will be results to show. Research and development work in the areas of CMCs will continue to be of paramount importance for the foreseeable future. Notable progress has been made yet more work needs to be done because the challenges are indeed daunting. My effort at bringing out the second edition of Ceramic Matrix Composites is a step in that direction.

In this revised second edition, I have updated the information in regard to the material systems for ceramic matrix composites, the reinforcements and matrices, processing, properties, and applications of CMCs. I have brought it up to date on the work done in the decade since the first edition came out. I have added new sections and new figures in all the chapters. Based on inputs I received from various faculty members and students, I have tried to clarify concepts where needed. I am grateful to all these people who talked to me personally or sent email messages in this regard. I am grateful to my program managers at the US Office of Naval Research (primarily, Dr. S. Fishman and later Dr. A.K. Vasudevan) who thought it fit to fund my research work in this area. Other people who have been helpful, in tangible or intangible ways, to make this second edition see the light of the day include: (in alphabetical order) are: A. Boccaccini, K. Carlisle, N. Chawla, Z. Chen, C. Coffin, G. Gladysz, G. Gouadec, M. Koopman, R. Kulkarni, B.A. MacDonald, D. Mendoza, A. Mortensen, K.L.Murty, B.R. Patterson, B.V. Patel, J.J. Petrovic, J.M. Rigsbee, S. Scarritt, H. Schneider, N. Stoloff, Y.K. Vohra, and A. Tobin. Finally I am in an everlasting debt of gratitude to my family members, Nivi, Nikhil, Anita, and Kanika for their forbearance. Anita and Kanika cheerfully bore all the burden of producing a camera-ready typescript.

K.K. Chawla
Birmingham, AL
August, 2002

PREFACE TO THE FIRST EDITION

Materials science and engineering (MS&F,) is by its very nature an interdisciplinary activity. Researchers from a wide variety of disciplines, metallurgy, ceramics, physics, chemistry, mechanics, electrical and electronic engineering, etc. can and do participate in the MS&E activities. The need and desirability of such an interdisciplinary effort is understandable inasmuch as advanced or high-performance materials are critical for any of the modern industries. It is almost axiomatic that progress in any field (energy, building materials, transportation, electronics, aerospace, electric power, consumer products, etc.) depends on the availability of suitable materials having specific characteristics. In this regard, let me quote from another work of mine:

It is a truism that technological development depends on advances in the field of materials. One does not have to be an expert to realize that a most advanced turbine or aircraft design is of no use if adequate materials to bear the service loads and conditions are not available. Whatever the field may be, the final limitation on advancement depends on materials (Chawla, 1987).

It is pertinent to quote from some other sources about a fundamental change that is occurring in the materials field:
A fundamental reversal in the relationship between human beings and materials [has occurred]. Its economic consequences are likely to be profound. Historically humans have adapted such natural materials as stone, wood, clay, vegetable fiber and animal tissue to economic uses. The smelting of metals and the production of glass represented a refinement in this relationship. Yet it is only recently that advances in the theoretical understanding of the structure of physical and biological matter, in experimental technique and in processing technology have made it possible *to start with a need and then develop a material to meet...* (Clark and Flemings, 1986).

And:

... the classical model of materials application has been inverted. We once sought applications for materials. We now have applications driving the creation of materials. We now design materials for what we need (Press, 1990).

Designing materials for specific applications is, indeed, the underlying philosophy of composite materials. The materials marketplace is increasingly becoming a highly competitive arena where substitution of traditional materials by engineered materials is the norm; quality and value added to the material as well as the energy cost are critical in the final cost. A study by the US National Research Council (1989) has emphasized in no uncertain terms the importance of synthesis, processing, characterization and performance of materials for success in the international marketplace. Add to this the ever-important public demand for a clean and healthy environment, and one can easily realize how important the whole material life cycle of a given component is. I wish to emphasize the item of environmental impact of the new materials and processes, including the recyclability of materials. Ultimately, the engineered materials must last longer, reduce material waste, be more energy efficient. I believe that composite materials can contribute to a safe and healthy environment.

Although metals, ceramics, and polymers make the three legs of what might be called the tripod of MS&E, increasingly it is becoming evident that the lines of demarcation between traditional disciplines such as metallurgy, ceramics and polymers are getting quite blurry. Consider the following. Ceramic materials are being made from polymeric precursors, metals are being produced with a glassy rather than crystalline structure while semi-crystalline polymers are finding commercial applications. This intermingling of materials is most evident in the field of composite materials where one has the ultimate objective of tailoring a material having a specific set of characteristics starting from components having different characteristics. Tying together process and microstructural control to the desired performance goals in the final component or product is the ultimate goal. In fact it is now recognized on all hands that in order to meet the diverse and exacting demands, materials must be *engineered* at every step. In this regard, mother nature has an abundance of lessons for us. Materials in nature are tailored over a very large spectrum of length scale, from atomic or molecular level to micro to macroscopic dimensions. Some very interesting examples of nature's work can be found in collagen-based composite materials such as skin, cartilage, bone, sea shells, etc. Nature has designed these composites for multifunctional applications requiring sometimes flexibility and strength and at other times resistance to various environments.

The theme of this book is: processing, structure, properties and performance of ceramic matrix composites. My definition of the ceramic matrix is rather broad for the purposes of this book. It includes inorganic silica-based glasses, crystalline ceramics, glass-ceramics, intermetallics, and that very special material, in elemental form, called carbon. All of these have an implicit unifying thread in that they are fairly high-temperature structural materials. This, I believe, is the first dedicated text on the subject of ceramic matrix composites. There are, of course, many conference proceedings or multi-author books available on the subject, for example, Warren, 1991 and Mazdiyasni, 1990. In this book, I have excluded cement and similar building materials, mainly because they are not high-temperature structural materials. For anyone interested in the topic of fiber-reinforced cement-based composites, there are books available on the subject (Balaguru and Shah, 1992; Benkur and Mindess, 1990).

The plan of the book is as follows. After an introductory chapter, we first examine ceramic **matrix** materials (Chapter 2) and the processing, microstructure and properties of **reinforcement** (Chapter 3). Inasmuch as rather dramatic developments have occurred in the area of ceramic fibrous reinforcements, Chapter 3 is rather large. This is followed by **processing** of ceramic matrix composites (Chapter 4). We examine the **interface** region in CMCS, in some detail, in Chapter 5. **Properties** of ceramic matrix composites are then examined in detail in Chapters 6 through 10. Chapter 6 describes the micromechanical aspects of elastic, physical, and thermal properties. Chapter 7 gives a description of the mechanical behavior of composites: monotonic, fatigue, and creep. Chapter 8 gives a thorough description of thermal stresses in composites. The important subject of interface mechanics and the various mechanisms that can be exploited to obtain improved toughess in a ceramic matrix composite are discussed in Chapter 9. This is followed by a discussion of laminated composites in Chapter 10. Finally, I discuss the various **applications and performance**-related topics in Chapter 11. I have tried to derive every important relationship not requiring very complex mathematical treatments.

I have aimed this book at the final-year undergraduate and first-year graduate students in materials science and engineering as well as the practicing engineer or scientist. I have used portions of the material contained in this text for a senior undergraduate course, a first-year graduate course, and in short courses for engineers from the industry. The response was very heartening. I hope that the book will also obtain the same response from a much broader audience. Except for the very basic ideas of materials science and engineering, I have assumed very little prior knowledge of any special kind on the part of the reader that is required to follow the material. The book may thus appear to be rather pedantic, at places, to the more experienced reader. I apologize for that. There are plenty of references and suggested reading material for the reader who wants to dig deeper. I have provided problems at the end of each chapter in the hope that by solving them, the reader will add to her/his understanding of the material in the text.

There remains the pleasant task of acknowledging a number of people without whose valuable input, tangible and intangible, this work would not have been possible. In alphabetical order, they are: A. Choudhury, M.K. Ferber, F. Gerstle, J.R. Hellmann, J.C. Hurt, O.T. lnal, M.G. Jenkins, B.A. MacDonald, T.A. Michalske, J.M. Rigsbee, P.K. Rohatgi, S. Suresh, K. Upadhya, and A.K. Vasudevan. An immense debt of gratitude is owed to S.G. Fishman and R. Pohanka, my program managers at the US Office of Naval Research, for their understanding, patience, and encouragement over the years. I should also like to thank my graduate students and post-doctoral research associates whose work has contributed to my understanding of the subject matter. The ones who stand out in this group are: J.-S. Ha, R. Venkatesh, R.U. Vaidya, and Z.R. Xu. Portions of the text were read and commented upon by N. Chawla, V. Gupta, E. Kroshe, T.A. Parthasarathy, R.U. Vaidya, and Z.R. Xu. I am truly thankful to these people for important feedback. I am also very thankful to the following for their generous hospitality during my sabbatical in 1992-93: J. Cohen, Y.-P. Chung, I. Daniel, K.T. Faber, M.E. Fine, S.P. Shah and J.R. Weertman (all at Northwestern University, Evanston, IL), B. Ilschner and F. Rezai-Aria (Ecole Polytechnique, Lausanne, Switzerland).

Thanks are also due to my family members, Nivi, Nikhil and Kanika, for understanding my compulsion to undertake such time-consuming ventures. That is the intangible part. They also rendered more tangible help in sorting things out, preparation of figures, copy-editing and indexing. As always, I can never thank enough my parents, Manohar Lai and Sumitra Chawla, for their selflessness, constant encouragement and inspiration. I have always considered the book-writing assignments that I have undertaken as educational in nature. This one was no exception. In this regard, I wish to record my appreciation of N. Hancox and M. Dunn for inviting me to undertake this work.

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ABOUT THE AUTHOR

Professor Chawla obtained his B.S. 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 at (in alphabetical order) Ecole Polytechnique Federale de Lausanne (Switzerland), Instituto Militar de Engenharia (Brazil), Laval University (Canada), New Mexico Tech (USA) Northwestern University (USA), University of Alabama at Birmingham (USA), and University of Illinois *at* Urbana-Champaign (USA).

He has published extensively in the areas of processing, microstructure, and mechanical behavior of materials, in general, and composite materials, in particular. Professor Chawla is author or coauthor of about 200 papers. His other books include the following: *Composite Materials: Science & Engineering*, 2nd Ed., Springer-Verlag, New York, 1998; *Fibrous Materials*, Cambridge University Press, Cambridge, 1998; *Mechanical Metallurgy,* Prentice-Hall, Englewood Cliffs, NJ, 1984 (co-author); *Mechanical Behavior of Materials*, Prentice-Hall, Englewood Cliffs, NJ, 1998 (co-author); *Princípios de Metallurgia Mecânica,* Editora Edgard Blücher, São Paulo, Brazil, 1981(co-author)

He has organized international symposia and edited books in the area do composites and fibers. He is on the editorial boards of various journals. During 1989-1990, Professor Chawla served as a Program Director for metals and ceramics in the Division of Materials Research, National Science Foundation, Washington, DC. Among his other honors are: *Eshbach Society Distinguished Visiting Scholar Award* (Northwestern University); *US Dept. of Energy Faculty Fellow* at Oak Ridge National Lab.; *Distinguished Researcher Award* (New Mexico Tech); *Distinguished Alumnus Award* (Banaras Hindu University). He was the chair of Materials & Mechanical Eng. Department (UAB) during 1998-2001.Professor Chawla is a *Fellow of ASM international.*

A NOTE TO THE READER

In this text, I have followed the standard American usage. This will be immediately evident in the spellings of certain words such as fiber, center, behavior, etc. rather than fibre, centre, behaviour, respectively. In general, compound words are not hyphenated. Prefixes such as co, pre, semi are closed up with the word they modify. For example, pushout rather than push-out, preexisting rather than pre-existing, etc. However, I have left the spellings unchanged in the journal title in a reference or a book title in a citation. While I have bowed to the American usage in the language of the text, I have rigorously followed the Systeme International (SI) units. This stems from my belief that sooner or later the American scientists, engineers, and industry will be using SI units. The widespread use of SI units in the US has suffered a long delay. The scientific merits of the SI units are overwhelming. If not the scientific merits of the SI units, then the force of economic necessity will do the job. By using SI units, I am hereby contributing my mite in that direction. I am, however, fully cognizant that one should be able to convert from one system of units to another. Hence, detailed information on this topic is given in Appendix B.