

Ceramic Materials

Ceramic Materials

Science and Engineering

C. Barry Carter
M. Grant Norton

Second Edition

 Springer

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Praise for *Ceramic Materials*

“The unprecedented completeness of this book makes it a bible on ceramic materials. It is a must read textbook for researchers, graduate students, and undergraduate students who are interested in ceramics.” —Zhong Lin Wang, Regents’ Professor, The Hightower Chair in Materials Science and Engineering, Georgia Institute of Technology

“...an outstanding introduction to the subject, clearly written, very detailed, and actually fun and quite easy to read for anyone with some basic scientific background. Each chapter contains several exercises, which this reviewer found to be very helpful. I also found extremely useful the shaded boxes on almost every page with short definitions plus “people in history.” After being exposed to many books on ceramic science during my 40-year career, I finally found a book with which I can restart my ceramic education again.” —Dr. Antoni Tomsia, Lawrence Berkeley National Laboratory

“...a valuable resource for the materials science and engineering community, both as a textbook and as a general reference to this important field ... recommended reading and a serious study source for anyone interested in ceramics....” —Professor Richard W. Siegel, Director, Rensselaer Nanotechnology Center, Rensselaer Polytechnic Institute

“The book is just wonderful, and one can only envy what the authors have done! It is the best book I have seen to date. Very clearly written with excellent examples and explanations [as well as] beautiful figures and photographs.” —Professor Safa Kasap, Canada Research Chair in Electronic and Optoelectronic Materials, University of Saskatchewan

“This new book...covers all important topics including history, microstructures, tools, defects, mechanical properties, and processing of ceramics for understanding and solving the problems of ceramic science and engineering,....” —Professor Yuichi Ikuhara, The University of Tokyo

“This is a comprehensive text covering, as the title suggests, both the science and engineering of ceramic materials. What I particularly like about the presentation of the material is that it is broken down into useful themed sections where related topics are grouped together.... This will be a very useful text for MSE undergraduate ceramic courses and for post graduates starting M.Sc. or Ph.D. work and who are new to the field of ceramic materials.” —Professor John Kilner, BCH Steele Chair in Energy Materials, Department of Materials, Imperial College London

“Ceramic Materials: Science and Engineering is a very thorough book.... Its uniqueness lies in the coverage of fundamentals...[as well as] properties and applications...at an unparalleled level, while also providing excellent sections on defects and processing.... Carter and Norton’s book is a must have in the ceramics field.” —Juan Claudio Nino, UFRF Professor, Department of Materials Science and Engineering, University of Florida, Gainesville

“It is no mean task to compete with Kingery et al.’s classic textbook on the subject, but the authors have managed to provide a fresh new perspective on the subject with their unique and student-friendly writing style coupled with spectacular graphics and

micrographs ... a truly remarkable text that is bound to become a benchmark in the field.” —Professor N. Ravishankar, Materials Research Centre, Indian Institute of Science

“...an excellent introductory textbook and basic reference for students and professionals interested in the field of technical ceramics.... There are two aspects which set this book apart from most specialty engineering textbooks. First, this book is replete with micrographs, photographs, and diagrams that complement the refreshingly easy-to-read text. Second, the authors discuss the field of technical ceramics in a societal context that will help novices understand why ceramics are important to our past and future. In summary, I highly recommend this text.” —Doreen Edwards, Dean and Professor of Materials Science, Inamori School of Engineering at Alfred University

“As a practitioner of ceramic science and technology over the last 25 years, I was truly amazed with the easy to understand and quite innovative presentation approach of various contents in the book.... This book provides a comprehensive look at various topics from the fundamental aspects of ceramics to the properties required for various applications.... I am sure this book will serve a key reference to students, technology developers, and end users all over the world.” —Dr. Mrityunjay (Jay) Singh, Chief Scientist, Ohio Aerospace Institute, NASA Glenn Research Center

*This text is dedicated to our wives
Bryony Carter and Christine Wall*

*Words still cannot explain, describe, or say enough
Thanks to you both*

About the Authors



C. Barry Carter joined the Department of Chemical, Materials, & Biomolecular Engineering at the University of Connecticut in Storrs in July 2007 and began a 5-year term as the Department Head. Before that he spent 12 years (1979–1991) on the Faculty at Cornell University in the Department of Materials Science and Engineering (MS&E) and 16 years as the 3M Heltzer Multidisciplinary Endowed Chair in the Department of Chemical Engineering and Materials Science (CEMS) at the University of Minnesota (1991–2007). He worked as a research assistant to Oxford University Professor H.M. (Tiny) Powell on inclusion compounds before going up to Cambridge in 1967. He obtained his BA (1970), MA (1974), and ScD (2001) from Cambridge University; his M.Sc. (1971) and DIC from Imperial College, London; and his D.Phil. (1976) from Oxford University. He was Sir Peter Williams's first student at Imperial College, working with him on the intercalation of layer materials. After a postdoctoral interval in Oxford with his D.Phil. thesis advisor Sir Peter Hirsch, Barry moved to Cornell University in 1977, initially as a postdoctoral fellow, then becoming an Assistant Professor (1979), Associate Professor (1983), and Professor (1988) and directing the Electron Microscopy Facility (1987–1991). At Minnesota, he was the founding Director of the High-Resolution Microscopy Center and then the Associate Director of the Center for Interfacial Engineering; he created the Characterization Facility as a unified facility, including many forms of microscopy and diffraction in one physical location. He has held numerous visiting scientist positions: in the United States at the Sandia National Laboratories, Los Alamos National Laboratory, and Xerox PARC; in Sweden at Chalmers University (Gothenburg); in Germany at the Max Planck Institut für Metallforschung (Stuttgart), the Forschungszentrum Jülich, Hannover University, and IFW (Dresden); in France at ONERA (Chatillon); in the United Kingdom at Bristol University and Cambridge University (Peterhouse); and in Japan at the ICYS at NIMS (Tsukuba).

Dr. Carter is the co-author of two textbooks (the other is *Transmission Electron Microscopy: A Textbook for Materials Science* with David Williams) and the co-editor of six conference proceedings. He has published more than 290 refereed journal

papers and more than 400 extended abstracts/conference proceedings papers. Since 1990 he has given more than 120 invited presentations at universities, conferences, and research laboratories. Among numerous awards, he has received the Simon Guggenheim Award (1985–1986), the Berndt Matthias Scholar Award (1997–1998), and the Alexander von Humboldt Senior Award (1997). He organized the 16th International Symposium on the Reactivity of Solids (ISRS-16 in 2007). He was an Editor of the *Journal of Microscopy* (1995–1999) and of *Microscopy and Microanalysis* (2000–2004); he continues to serve on the Editorial Board of both journals. He became Editor-in-Chief of the *Journal of Materials Science* in 2004, sharing this task with Rees Rawlings until 2007; the journal’s impact factor rose from 0.826 for 2003 to 2.015 for 2011.

Barry is a Fellow of the American Association for the Advancement of Science (AAAS), the Materials Research Society (MRS), the Microscopy Society of America (MSA), the American Ceramic Society (ACerS), and the Royal Microscopical Society (RMS). His research group has won the American Ceramics Society’s Roland B. Snow Award six times, including the three consecutive years 2000–2002. He was the 1997 President of MSA and served on the Executive Board of the International Federation of Societies for Electron Microscopy (IFSEM) (1999–2002). He was elected General Secretary of the International Federation of Societies for Microscopy (IFSM) for the period 2003–2010 and was then elected President of IFSM for the period 2011–2014 in 2010. He was elected to the Connecticut Academy of Science and Engineering in 2010.



M. Grant Norton is Professor of Materials Science and Engineering in the School of Mechanical and Materials Engineering at Washington State University. From 2005 to 2011 he served as Associate Dean of Research and Graduate Programs in the College of Engineering and Architecture. Professor Norton obtained his Ph.D. in Materials from Imperial College, London in 1989 under the direction of Professor B.C.H. Steele and spent a 2-year postdoctoral interval at Cornell University with Professor C. Barry Carter before joining the Washington State University faculty in 1991. In 2003 and 2004 he was an Air Force Office of Scientific Research (AFOSR) Faculty Research Associate at Wright-Patterson Air Force Base in Ohio and spent the 1999–2000 academic year as a Visiting Professor in the Department of Materials at Oxford University. From 2000 to 2005 Professor Norton was Chair of Materials Science at Washington State University and from 2004 to 2007 he held the Herman and Brita Lindholm Endowed Chair in Materials Science. He is author or co-author of about 200 papers in the archival literature, several book chapters, and two textbooks. Professor Norton serves as Deputy Editor-in-Chief of the *Journal of Materials Science*, is on the Editorial Board of *Journal of Nanotechnology*, and is on the International Editorial Board of the *Journal of Materials Education*. Prior to entering academia, Norton worked for two major European multinational companies: Cookson Group PLC and Heraeus GmbH. He has consulted for a number of companies and organizations, including the United States Air Force and REC Silicon, the world's largest producer of silicon materials. In 2009, Governor Christine Gregoire appointed Professor Norton to the Board of Directors of the Washington Technology Center. In 2007, Norton co-founded GoNano Technologies, Inc., a university spin-off company focused on clean energy and life science applications of silica Nanosprings. Most recently, Dr. Norton co-founded Cataluna, Inc., which is commercializing a novel catalyst that has applications in fuel reforming and fuel-flexible fuel cells.

Preface to the First Edition

In today's materials science curriculum, there is often only time for one course on ceramic materials. Students will usually take courses on mechanical properties, thermodynamics and kinetics, and the structure of materials. Many will also have taken an introductory overview of materials science. In each of these courses, the students will have encountered ceramic materials. The present text assumes background knowledge at this introductory level but still provides a review of such critical topics as bonding, crystal structures, and lattice defects.

The text has been divided into seven parts and 37 chapters: we will explain the thinking behind these decisions. Part I examines the history and development of ceramic materials: how they have literally shaped civilization. We include this material in our introductory lectures and then make the two chapters assigned reading. Part II discusses the bonding, structure, and the relationship among phases. Students often find this part of the course to be the most difficult because structures are implicitly 3-dimensional. However, so many properties depend on the structure whether crystalline or amorphous. We have limited the number of structures to what we think the students can manage in one course, we give references to texts that the students can spend a lifetime studying and recommend our favorite software package. Part III consists of two chapters on our tools of the trade. Most ceramics are heated at some stage during processing. Unfortunately heat treatments are rarely exactly what we would like them to be; the heating rate is too slow, the furnace contaminates the sample, the environment is not what we want (or think it is), etc. Techniques for characterizing materials fill books and the students are familiar with many already from their studies on metals. So, the purpose of this chapter is, in part, to encourage the student to find out more about techniques that they might not have heard of or might not have thought of applying to ceramics; you could certainly skip Part III and make it assigned reading especially if the students are taking overlapping courses. Part IV discusses defects in ceramics and aims at providing a comprehensive overview while again not being a dedicated book on the subject. Part IV leads straight into Part V—a basic discussion of mechanical properties applied specifically to ceramics. The last two parts contain just over half the chapters. The two topics are Processing (Part VI) and Properties (Part VII) and are, of course, the reason we study ceramic materials. The warning is—these topics form the second half of the book because the student should understand the materials first, but it then becomes too easy to miss them in a one-semester course due to lack of time. We know, we have done this and the students miss the part that they would often appreciate most. Chapter 36 is probably the most fun for half the students and both the authors; Chapter 37 is the most important for all of us.

Many modern ceramists will acknowledge their debt to the late David Kingery. His pioneering 1960 text was one of the first to regard ceramics as a serious scientific subject. Both his book and his research papers have been referenced throughout the present text. Our definition of a ceramic material follows directly from Kingery's definition: a nonmetallic, inorganic solid. Nonmetallic refers to the bonding: in ceramics, it is predominantly covalent and/or ionic. Ceramics are always inorganic solids although they also may be major or minor components of composite materials.

Throughout the text we ask the question “what is special for ceramics?” The answer varies so much that it can be difficult to generalize, but that is what we are attempting where possible. Having said that, ceramics are always providing surprises. Indium tin oxide is a transparent conductor of electricity. Yttrium barium copper oxide is a superconductor at 90 K. Doped gallium nitride is revolutionizing home lighting and is becoming a critical component for all traffic lights. Neodymium-doped garnet is the basis of many solid-state lasers.

A feature of this text is that we keep in mind that many of today’s high-tech ceramic materials and processing routes have their origin in the potter’s craft or in the jeweler’s art, and materials that are new to the materials scientist may be old friends to the mineralogist and geologist. Throughout the text we will make connections to these related fields. The history of ceramics is as old as civilization, and our use of ceramics is a measure of the technological progress of a civilization.

The text covers ceramic materials from the fundamentals to industrial applications including a consideration of safety and their impact on the environment. We also include throughout the text links to economics and art. So many choices in ceramics have been determined by economics. We often think of ceramics as being inexpensive materials: bottles, bricks, and tiles certainly are. Ceramics are also the most valuable materials we have: per gram, emerald still holds the record.

No modern materials text can be complete without considering materials at the nanoscale. Nanoceramics appear throughout this text, but we decided not to create a special chapter on the topic. What we have done is to highlight some of these topics as they appear naturally in the text. It is worth noting that nanoscale ceramics have been used for centuries; it is just recently that we have had a name for them.

The figures generally contain much more information than is given in the text. We use this fact in some of the homework questions and hope that the extra detail will encourage the students to delve into the literature to learn more about the topic. One place to start this search is, of course, with the original citation if there is one. These citations are grouped together at the end of the text, in part for this purpose, but also to recognize the contributions of our colleagues.

On the website (www.ceramat.org), we are developing supplementary material including an extensive list of suggestions for filling any weak or missing areas in the student’s background and will update these suggestions periodically. We give annotated references to the original studies that have been quoted in the text. We also include further examples of images that supplement those in the text. The Web site will also house two sets of questions to complement those at the end of each chapter. One set consists of shorter questions that we use in pop quizzes but are also useful for students, especially those working alone, to assess their own progress. The second set includes questions, which we use for homework and take-home exams.

After reviewing some history, we consider bonding and structures (Chapters 3–8). Essentially, this set of chapters examines the science that underpins our definition of a ceramic material. The way atoms are connected together by covalent or ionic bonds is illustrated by considering simple and complex structures. We introduce glasses as a natural subsection of complex structures rather than as a separate branch of ceramics. Window glass is a ceramic material, just like lithium niobate, mica or silicon. The difference is that glasses are not crystalline: crystalline quartz has more in common with amorphous silica glass than it does with alumina. The final chapter in this sequence is important in most branches of materials science: which ceramics are compatible with other ceramics, which are not, and which of these materials react to form new compounds. We emphasize that these are equilibrium phase diagrams and that ceramics often need high temperatures and long times to attain equilibrium. (Geological times are needed in some cases.)

The next two topics (Chapters 9–10) examine two tools (in the broadest sense) that we will use: we need to prepare the ceramic material and this usually involves heating. Then we need to characterize it.

In Chapters 11 thru 15 we explore the whole topic of defects in ceramics, from point defects to voids, and elaborate on why they are important in the rest of the text. In Chapter 13 the combination of surfaces, nanoparticles and foams builds on the common theme of the surface as a defect but does not treat it in isolation from properties or real ceramic processing. The positioning of the next three chapters (Chapters 16–18) on mechanical properties was decided because of the authors' bias. This allows us to integrate mechanical behavior into processing, thin films, glass ceramics, and such in the immediately following chapters.

We begin the section on processing with a discussion of minerals and then consider the different forms and shapes of ceramic powders. The topic of glass is separated into Chapters 21 and 26 with the use of organic chemistry, the principles of shaping, and the processes that occur during shaping (sintering, grain growth and phase transformations) separating them. In this text we do not want to separate processing from the science; where we have separated them, this is only done to help the student absorb the concepts serially rather than in parallel! We discuss making films and growing crystals in Chapters 27–29. This group of chapters really gets to the heart of ceramic processing and mixes liquids (whether due to a solvent or to melting) in with the powders. We do not emphasize the mechanical aspects but make it clear that a full understanding requires that we think about them and not just for hot-pressing or for crystalline ceramics.

The remaining eight chapters cover the applications of ceramics with the emphasis on what property is being exploited, how we optimize it, and just how far we can still go with these materials; remember how the development of glass optical fibers has changed society forever in less than 40 years. Again our bias is clear. Ceramics are amazing materials and the underlying physics is fascinating but the subject of physics can easily obscure this excitement. Physicists are often not fully aware of the value of chemistry and all too often underestimate the *feel* a ceramist has for these materials. Before concluding the text with the most rapidly changing topic of industry and the environment in Chapter 37, we examine two groups of ceramics that affect us all even though we may not think about them—ceramics in biology/medicine and ceramics as gemstones. Whether as objects of beauty or symbols of something more lasting, polished natural single crystals of ceramics have inspired awe for centuries and challenged scientists for nearly as long.

We would like to thank our students and postdocs, past and present, who have helped us so much to appreciate and enjoy ceramic materials. The students include Katrien Ostyn, Karen Morrissey, Zvi Elgat, Bruno De Cooman, Yonn Rasmussen (formerly Simpson), David Susnitzky, Scott Summerfelt, Lisa Moore (formerly Tietz), Chris Scarfone, Ian Anderson, Mike Mallamaci, Paul Kotula, Sundar Ramamurthy, Jason Heffelfinger, Matt Johnson, Andrey Zagrebelny, Chris Blanford, Svetlana Yanina, Shelley Gilliss, Chris Perrey, Jeff Farrer, Arzu Altay, Jessica Riesterer, Jonathan Winterstein, Maxime Guinel, Dan Eakins, Joel LeBret, Aaron LaLonde, and Tyler Pounds. The postdocs include John Dodsworth, Monica Backhaus-Ricoult, Hermann Wendt, Werner Skrotski, Thomas Pfeiffer, Mike Bench, Carsten Korte, Joysurya Basu and Divakar Ramachandran and especially Ravi Ravishankar and Stuart McKernan. We thank Carolyn Swanson for carefully drawing so many diagrams for this text and Janet McKernan for her expert proofreading, continued patience, and rare common sense. Janet generated the index, negotiated hyphens, and tried to remove all our errors and typos; those that remain that should not or are missing that should be present are solely the responsibility of the authors. We thank our many colleagues for providing figures and understanding on some of the special topics. In particular, we thank Richard Hughes, Rosette Gault, Peter Ilsley, Liz Huffman, and Fred Ward.

We thank our colleagues and collaborators. David Kohlstedt who introduced CBC to ceramics. Herman Schmalzried who is not only our guru on solid-state reactions but the model of a truly wonderful Professor and mentor. Gisela Schmalzried who provided meals and company during many visits to Hannover, Gottingen and Buntentrock. Paul Hlava has been our guide and guru on everything to do with gems

and minerals: he is one of the world's natural teachers. MGN thanks Brian Cantor for hosting his sabbatic at Oxford University where parts of this text were written. Likewise, CBC thanks Eva Olssen at Chalmer's University, Yoshio Bando at NIMS, and Paul Midgley, Colin Humphreys and the Master and Fellows of Peterhouse at Cambridge University.

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Preface to the Second Edition

As nearly everything we said in the Preface to the first edition still holds, we suggest you read that first. The text is divided into seven parts. The first three parts discuss the fundamentals of ceramic materials. In the next two parts we consider defects and how they determine the mechanical behavior of ceramics. The sixth part is really critical to ceramics—how they are processed. In the final part, we relate all these earlier considerations to the properties, performance, and applications of ceramics.

Our definition of a ceramic material still follows directly from Dave Kingery's: A ceramic is a nonmetallic, inorganic solid. Nonmetallic refers to the bonding, where in ceramics it is predominantly covalent and/or ionic. The approach throughout the text is unchanged, as we repeatedly ask the question: "What is special about ceramics?" After all, those are the main messages that you should take from a textbook entitled *Ceramic Materials*.

We remind our students to think of the special cases that are not as unique as we once thought.

- ITO is a transparent conductor of electricity, but it is not the only oxide with this property.
- YBCO is a superconductor at 90 K, but other oxides are superconductors at much higher temperatures.
- GaN is in the home, your flashlight, and your traffic lights (or at least it will be when your town catches up).

As with many aspects of materials science, we always need to be willing to readjust our thinking. For example, some of yesterday's insulators are today's wide-band-gap semiconductors; and it is always important to be able to connect to the broader influences, such as the potter's craft and the jeweler's art, to understand that ceramic materials are the foundation of many businesses. Many people around the world make a living by making and using ceramics.

As you'll see, there is still no chapter devoted to "nano" ceramics. Nanoceramics have been with us for centuries. They are spread throughout the text, although sometimes they may be difficult to see. We have added a full chapter on energy production and storage and then enhanced our discussion of industry. The hope is that students will be able to read these chapters on their own and work on the questions when they have time. Most semester- or quarter-long courses will not reach Chapter 38!

Yes, we have tried to be a little provocative at times. The title to Chapter 12 asks a question. It could be rephrased as: "Are the Properties of Dislocations Unimportant?" Then you'd get a resounding "No!" but that is too obvious. We ask students to think about why we linked three topics in the title of Chapter 15. Why do we ask "Conducting Charge or Not" rather than state "Electrical Properties?" Because the latter would be wrong, of course. The titles may not be (aren't) perfect, but we hope the students will think about them before, during, and after reading the chapter.

We continue to work on the website (www.ceramicmaterials.org) to include supplementary material, and teachers should feel free to contact the authors directly (cbarrycarter@gmail.com and mgrantnorton@gmail.com). We thanked our students and postdocs, past and present, and several colleagues in the original Preface. None of

that gratitude is diminished. To this group, we would like to add (and apologize for earlier omissions) Eray Aydil, Bill Gerberich, Uwe Kortshagen, Joe Michael, Dave Williams (of course), Su Ha, Julia Nowak, Timothy Turba, Caleb Ellefson, and Jonathan Winterstein, who was an undergraduate with M.G.N. and a Ph.D. student with C.B.C. and survived! Timothy took classes with C.B.C. and then was a Ph.D. student with M.G.N.! We also thank Sanjit Bhowmick, Maria Josefina Arellano-Jimenez, and Uttara Sahaym, our recent postdocs.

We are pleased to thank our new colleagues and collaborators at the University of Connecticut (including Mark Aindow and Pamir Alpay—editors on the *Journal of Materials Science* with us) and in the EU-supported MACAN project (especially Mehmet A. Gülgün and Wayne Kaplan).

Finally, we would like to thank some of those who have helped us in so many other ways: Walter Dennis Carter and the late Mary Isabel Carter; Benjamin Carter; Emily, Robert, Oscar, and Vincent Hein; Adam and Aditya Carter; Mamta Tahliliani; Betty Gilbert and the late John Gilbert; and Ted Norton.

Foreword

Ceramics are both the oldest materials made by humans and among the most recent and most sophisticated today. Not so long ago, students used to be taught—much like the Greeks were taught that everything was made of earth, fire, and wind—that there are three types of material: metals, plastics, and ceramics. This division clearly doesn't even come close to classifying, let alone describing, the enormous variety of materials available to either the engineer or the artist today. Nor does it begin to give a feel for the untold wealth that has been generated from utilizing the properties of ceramics to create products that have enriched so many people's lives in recent years. Indeed, it is impossible to imagine anything in today's most advanced technology—including cellular networks, mobile devices, computers, airplanes, electrical systems, and cars—that doesn't depend on the properties of ceramics and the ability to manufacture them with exquisite control.

The processing of ceramic materials—by which we mean the selection of constituent powders and chemicals and their synthesis, forming, and shaping—was once a high-level craft practiced after years of apprenticeship, with practical knowledge passed down from one skilled person to the next. In many cases, the ingredients and the processing were secrets and little more than alchemy, as is wonderfully told in the delightful book, *The Arcanum*. The author, Janet Gleeson, recounts the trials and tribulations of Johann Frederick Bottger, a brilliant eighteenth-century apothecary and alchemist who worked in isolation in Meissen (under the penalty of death) to discover the secrets for making porcelain.

During the early decades of the last century, this craft began to change with the work of Norton, culminating in a series of books, most notably *Refractories* (McGraw-Hill, First Edition, 1931). Combining advances in other fields, *Refractories* brought together the central ideas of shaping, phase equilibria, sintering, and properties that are the cornerstones of much of ceramics today. That set the stage for a series of rapidly accumulating scientific breakthroughs in topics central to understanding the behavior of ceramics. The next seminal book was Kingery's *Introduction to Ceramics*, published in 1960 (Wiley), which was later expanded and extensively revised. For many years, it is probably the case that no course in ceramics at the college or university level around the world was complete unless it was based on this seminal text.

As new ceramic materials have been identified and characterized and new devices developed based on one or another of the exceptional properties of ceramics, the scientific and technical literature has exploded. This has generated new subfields of ceramics and has identified new intellectual problems, as well as producing many highly specialized texts. Concurrently, there have been staggering advances in characterization that enable us to see all the way from the atomic arrangement in crystals and their grain boundaries to the magnetic and electrical structure of ceramics and how they change with temperature or field.

How can all these advances be communicated and the knowledge passed on? In these times, when technical information, and in some cases even the detailed derivation of equations, can be readily accessed and downloaded from the World Wide Web, it is becoming apparent that there are two main types of undergraduate and introductory graduate textbook: one, a comprehensive but limited-in-scope text

using a consistent mathematical description together with full derivation of equations; and the other, a text that effectively introduces concepts and ideas. With technological advances in printing and the plummeting cost of high-quality images, these concept-based texts are becoming more affordable and suitable for publication in multiple forms.

This beautifully and profusely illustrated text, *Ceramic Materials*, belongs to the second category. It encompasses the intellectual breadth of ceramics as we know it today, introducing the field in its broadest sense to any interested student. It was thought that long gone are the days when a single book could cover the field of materials science in any detail, but this text with superbly crafted and clear illustrations does indeed cover the entire field of ceramics. Other, more specialized texts describe or reproduce the mathematical development of the phenomenon underlying the behavior and properties of ceramics. This text takes a different tack, introducing the key concepts through words, diagrams, images (black and white as well as color), and photographs. Only when it is necessary to explain an essential concept are equations presented—in many cases, just a few equations or even a single one, such as the Herring-Nabarro creep equation. Also, in contrast to the majority of texts, each of the photographs is of exceptional quality, sometimes stunning, and so there is little or no ambiguity as to what the photographs are illustrating or why they are being used. Many of the concepts in ceramic materials are, of course, common to other areas of materials science, such as crystal structures, crystal shapes, grain boundaries, defects, and diffusion, to mention a few. Thus, a substantial portion of this text can be profitable reading for students in other areas of materials science.

As in the first edition, the subject matter is grouped into seven major parts, as listed in the table of contents, but this new edition includes a chapter on the applications of ceramics in clean energy technology, including oxide fuel cells, lithium-ion batteries, ultra-capacitors, and ceramics as catalysts. It also has an expanded chapter on the role of ceramics in industry. The other notable change is that many of the diagrams and illustrations are now in color, adding vividness to the text and further emphasizing the important role they play in communicating the ideas and descriptions in the text. The only drawback of this second edition is that, like the original, it is rather heavy to carry around, so I look forward to the iPad edition!

David Clarke

Gordon McKay Professor of Materials
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