Ceramic Materials

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Science and Engineering

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Springer

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Library of Congress Control Number: 2006938045

ISBN-10: 0-387-46270-8
ISBN-13: 978-0-387-46270-7
e-ISBN-10: 0-387-46271-6
e-ISBN-13: 978-0-387-46271-4

Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

springer.com

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

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

Preface

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 Web site (http:/web.mac.com/ceramicsbook/iweb), 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 commonsense. 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, Göttingen and Buntenbock. 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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