TRIBOLOGY OF CERAMICS AND COMPOSITES

TRIBOLOGY OF CERAMICS AND COMPOSITES

A Materials Science Perspective

BIKRAMJIT BASU
Department of Materials Science and Engineering
Indian Institute of Technology
Kanpur, India

Materials Research Center
Indian Institute of Science
Bangalore, India

MITJAN KALIN
Faculty of Mechanical Engineering
University of Ljubljana
Ljubljana, Slovenia

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Basu, Bikramjit.
Tribology of ceramics and composites : a materials science perspective / Bikramjit Basu and Mitjan Kalin.
p. cm.
Includes index.
ISBN 978-0-470-52263-9 (cloth)
1. Ceramic materials–Mechanical properties. 2. Ceramic materials–Fatigue. 3. Mechanical wear. 4. Friction. 5. Tribology. I. Kalin, Mitjan. II. Title.
TA455.C43B38 2011
621.8'9–dc22

2010045250

oBook ISBN: 978-1-118-02166-8
ePDF ISBN: 978-1-118-02164-4
ePub ISBN: 978-1-118-02165-1

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

Bikramjit Basu dedicates this book
with a great sense of gratitude
to his parents,
Mr. Manoj Mohan Basu and Mrs. Chitra Basu

Mitjan Kalin would like to dedicate this book
to Matija, his inspiration, pride, and happiness;
and to Janja, for her understanding and support

CONTENTS

PREFACE

Tribology, by definition, is the science and technology of interacting surfaces in relative motion. Such scientific understanding has significant technological relevance for various engineering industries. Broadly, tribology deals with the concepts of friction, wear, and lubrication. Over the last few decades, it has been widely recognized that tribology, being an interdisciplinary area, involves the interaction of concepts drawn from multiple disciplines, including mechanical engineering, materials science, physics, and chemistry. The development of new materials (bulk or coating) with better friction and wear resistance, as well as the progress in tribology research, clearly requires an improved understanding in multiple disciplines as well as the development of new design methodologies in order to obtain better properties in relation to tribological performance. Even though tribology is still not broadly known as a research field to many in industry or academia, we are all intrigued by the topic in everyday life, as well as in almost every engineering application. Across the world, very few universities teach this subject; however, the subject is gaining importance. There are many books on tribology written from different perspectives, such as materials science, mechanics, mechanical engineering, lubrication and additives, physics, and chemistry. This book is intended to cover mostly the materials science aspects applicable to tribology science.

Researchers interested in automotive, aerospace, biomaterials, hardmetals, and related applications would look for a complete set of possible materials for those applications, as well as wear and friction mechanisms. On the other hand, people from the materials science community would look for details of mechanisms, effect of microstructure, working conditions, lubrication, environment, and so on, which again are covered here due to very broad materials selection. This book places the utmost importance on the microstructure–material-properties–tribological-properties relationship for the range of advanced materials that are covered herein. The description of the wear micromechanisms of the various materials will provide a strong background to readers on how to design and develop new tribological materials.

From the aforementioned perspective, this book is structured into various thematic sections, and each section contains a number of chapters. This book was designed to motivate students and young researchers as well as to provide experts in the area with a healthy balance of topics for teaching and academic purposes, primarily for two disciplines: materials science/metallurgy and mechanical engineering. It is expected that this book, if used as a text, would strongly benefit senior undergraduate and postgraduate students.

Section I of this book is designed to provide the readers with a background in the area of tribology and basic materials science. Characteristics of material surfaces in terms of surface roughness and various material properties are discussed, as well as the fundamentals of the friction, wear mechanism, and lubrication.

This is followed by Section II, where the tribological properties of structural ceramics, which include zirconia, sialon, ternary carbides, and high-temperature ceramics, such as borides, are discussed. This selection of materials also represents a class of technologically important and emerging ceramics. It is shown how the microstructure and mechanical properties both determine the wear resistance of these materials.

One area in which ceramics and polymers are increasingly important is biomedical applications. In Section III**,** the tribological properties of hydroxyapatite-based bioceramic composites are discussed first. Polymers are known for their poor wear resistance; it is shown how the development of hybrid polymer-ceramic biocomposites can lead to higher wear resistance while retaining good frictional properties of the polymer matrix. This is followed by a discussion on the wear properties of some of the stabilized zirconia ceramics. The two chapters in this section deal with the materials that are important in dental restoration.

A rather recent development in the materials world is the synthesis of nanoceramic composites. In view of this, Section IV discusses the friction and wear properties of zirconia and WC-based nanocomposites, which are processed using the advanced processing technique of spark plasma sintering. A summary of the literature on the tribological properties of various nanoceramics is also included.

In the last decade, lightweight composites have been considered for use in automotive and other applications requiring good wear resistance. Similarly, new generation cermets, based on TiCN as well as mixed carbide cermets, are also being developed as a replacement for widely used WC-Co cemented carbides. Hence, Section V demonstrates how these new–generation materials will behave at tribological contacts.

While our understanding of the dry, unlubricated tribological properties of various materials is extensive, such understanding in a cryogenic environment and under high speed sliding conditions is rather limited. In view of this, Section VI discusses the tribological properties of oxide and non-oxide ceramics in liquid nitrogen with reference to similar properties under ambient and room temperature sliding conditions.

In Section VII, the tribological properties of various ceramics in aqueous environments are discussed, with reference to regimes and pH regions and their effect on performance.

The book concludes with Section VIII, which covers the various issues to be investigated in the near future in the design and development of materials with better tribological properties. This section summarizes the information provided in the book and gives an insight into the broader knowledge of these materials and advice on how to use them in various applications.

The above-described structure of this book as well as the succession of various sections and chapters is expected to be useful in helping both students and experts pursuing the area of tribology of advanced materials to gradually build up knowledge

of the fundamentals and, subsequently, to understand the most recent advances. In particular, this book has the following major important features: (1) the fundamental science of tribology is presented, thus allowing the book to be used as a textbook for teaching, academic, or research purposes; (2) a broad range of materials is covered, such as advanced tough ceramics, high-temperature ceramics, biomaterials, and nanoceramics, to illustrate how the materials science aspect can be realized while analyzing the tribological results; and (3) the book will appeal to a large number of active researchers from various disciplines of metallurgy and materials science, ceramics, and mechanical engineering.

This book is an outcome of several years of teaching undergraduate and post-graduate courses in the area of tribology of materials, advanced ceramics, composite materials, and biomaterials, and other related fundamental courses in materials science, which were offered to students of the Indian Institute of Technology (IIT) Kanpur, India, as well as at the Faculty of Mechanical Engineering at the University of Ljubljana, Slovenia. More important, the research results of many of the post-graduate students from our groups are also summarized in some chapters. B. Basu would like to specifically acknowledge some of his past and present students, B. V. Manoj Kumar, G. B. Raju, Shekhar Nath, P. Suresh Babu, Amartya Mukhopadhyay, K. Madhav Reddy, Animesh Choubey, M. Surender, S. Bajaj, N. Sinha, Tufan Kumar Guha, P. Maji, Rohit Khanna, Subhodip Bodhak, Srimanta Das Bakshi, D. Sarkar, Manisha Taneja, Ravi Kumar, A. Tewari, T. Venkateswaran, U. Raghunandan, Divya Jain, Nitish Kumar, Amit S. Sharma, Ashutosh K. Dubey, Alok Kumar, Sushma Kalmodia, Shilpee Jain, Neha Gupta, Indu Bajpai, Garima Tripathi, Prafulla K. Mallik, Anup Patel, Rajeev Kumar, and Atiar R. Molla. The dedication of these students to understanding the tribological properties of a range of ceramics and composites is reflected in the research work summarized in many of the chapters of this book. With gratitude, B. Basu appreciates the past and present research collaboration with a number of researchers and academicians, including Drs. Omer Van Der Biest, Jozef Vleugels, R. K. Bordia, G. Sundararajan, S. K. Mishra, A. K. Suri, R. Mitra, I. Manna, A. Basumallick, J. Ramkumar, B. Subramonian, Manoj Gupta, K. C. Hari Kumar, R. G. Vitchev, Hasan Mondal, Ferhat Kara, Nurcan Kalis Ackibas, P. Gilman, S. C. Koria, R. K. Dube, M. Karanjai, D. Roy, M. C. Chu, S. J. Cho, Doh-Yeon Kim, Jo Wook, and S. Kang. The encouragement and collaboration with two of his colleagues, the late Prof. R. Balasubramaniam and the late Prof. V. S. R. Murty, is also remembered. B. Basu also expresses sincere thanks to his long-term friend and mentor, Dr. Jaydeep Sarkar, for his constant encouragement during the writing of this book. B. Basu also remembers the constant inspiration of a number of colleagues and former teachers, including Profs./Drs. S. Ranganathan, K. Chattopadhyay, Sanjay K. Biswas, Ashutosh Sharma, N. K. Mukhopadhyay, Indranil Manna, D. Basu, Anoop K. Mukhopadhyay, Brian Lawn, M. V. Swain, M. Hoffman, Vikram Jayaram, Goutam Biswas, D. Mazumdar, Dipankar Banerjee, Atul Chokshi, and B. S. Murty.

M. Kalin acknowledges cooperation related to tribology of ceramics from J. Vižintin and F. Kopač from his group at the Faculty of Mechanical Engineering, and S. Novak and G. Dražič from the Jožef Stefan Institute in Ljubljana, Slovenia. M. Kalin would like to acknowledge help from M. Polajnar and J. Kogovšek for

assistance in final technical revisions of this book. He would also like to express particular thanks to S. Jahanmir (MiTi Heart Corp, USA) and K. Kato (Tohoku University, Japan) for their mentoring, scientific, and personal advice during their joint work at the Ceramics Department at the National Institute of Standards and Technology (NIST, Gaithersburg, MD), and Tohoku University (Japan), respectively, as well as for the remarkable support and kind friendship over many years.

The authors would like to thank Drs. Ian Hutchings, Said Jahanmir, Koji Kato, and Karl-Heinz Zum Gahr for writing the comments on and forewords to this book.

The authors would like to take this opportunity to acknowledge the financial support, of various governmental agencies of India, including the Indian Space Research Organisation (ISRO), Department of Atomic Energy (DAE), Department of Biotechnology (DBT), Defense Research and Development Organization (DRDO), Council of Scientific and Industrial Research (CSIR), Department of Science and Technology (DST), UK-India Education and Research Initiative (UKIERI), and Indo-US Science and Technology Forum (IUSSTF) in the last two decades, which facilitated research in the area of tribology of advanced materials at IIT Kanpur. B. Basu also expresses gratitude to Mr. N. M. Dube and his colleagues at DUCOM, Bangalore, for designing and fabricating custom-made fretting and high-speed cryogenic tribotesters. B. Basu expressed sincere thanks to Mr. Divakar Tiwari and his present students (Amit, Ashutosh, Anup, Neha, Indu, Shilpee, and Alok) for their untiring efforts and effective assistance during various stages of the manuscript preparation. We would also like to thank IIT Kanpur for extending financial and other support during the writing this book. The continuous financial support from the Ministry of Higher Education, Science and Technology of Slovenia, as well as the Slovenian Research Agency, over the years is also greatly appreciated. Finally, we would like to acknowledge the continuous support extended by our parents, in-laws, and family members, Pritha and Prithvijit and Janja and Matija, during the course of the writing of this book.

IIT Kanpur, India, and IISc, Bangalore, India — Bikramjit Basu
Ljubljana, Slovenia — Mitjan Kalin
July 2011

FOREWORD

Engineering ceramics form a diverse and important class of materials, with a wide range of properties and applications, from rolling bearings to dental implants, and from high-performance cutting tools to artificial hip joints. In these applications and many more, the tribological behavior of the ceramic is paramount, but the properties by which the material is specified are often "standard" and easily measured ones such as density, hardness, Young's modulus, modulus of rupture, and perhaps fracture toughness. As we now know from extensive research, these properties are often poor predictors of tribological performance. Better understanding of the behavior of ceramics in tribological applications, and of the detailed influence of microstructural features such as porosity, phase, and grain size distributions, as well as the tribochemical processes that occur at the material's surface, will benefit all manufacturers and users of these materials and will enable their properties and value to be optimized. A deep appreciation of materials science and engineering, coupled with both the chemical and mechanical influences which act on the ceramic in use, is needed to understand the wear and friction of these materials.

Fracture, plastic flow, and tribochemical processes can all play key roles in the wear and friction of ceramics. It can be argued that their tribological behavior is even more complex than that of metals. This book, which focuses on the subject from a materials science perspective, forms a valuable contribution to the literature on the tribology of engineering ceramics and their composites, and the authors are to be congratulated on its comprehensive scope.

Prof. Ian Hutchings

Cambridge, UK

FOREWORD

Microstructures of structural ceramics and their composites have been developed during the last decades mainly for applications under static and dynamic mechanical, thermal, or corrosive loads. Among others, the aim was to improve fracture toughness to overcome the inherent brittleness and increase the reliability of ceramic components in high-loaded applications by optimizing microstructural features, such as size and shape of grains or reinforcing phases, as well as processing technologies. However, to use the potential of ceramic materials in components under high tribological loading, materials microstructures have to be adjusted based on a competent knowledge of tribological mechanisms involved and the structureñproperty relationships. Using case studies, this book contributes to Ýlling the gap in our understanding of the effects of structures of ceramic materials on tribological behavior. Beginning with fundamental aspects of structure and properties of ceramic materials as well as an introduction to tribology, it covers the tribological behavior of a wide range of materials from structural ceramics through bioceramics, biocomposites, and nanocomposites to cermets. This book can be very useful for newcomers, such as students, in the Ýeld of ceramics and tribology, as well as for readers with an interest in utilizing the high potential of ceramic materials in tribological applications.

Prof. Karl-Heinz Zum Gahr

Karlsruhe Institute of Technology (KIT), Germany

ABOUT THE AUTHORS

Bikramjit Basu, PhD

Associate Professor, Department of Materials Science and Engineering, Indian Institute of Technology, Kanpur, India; E-mail: bikram@iitk.ac.in; currently at Materials Research Center, Indian Institute of Science, Bangalore, India

Dr. Bikramjit Basu is currently an Associate Professor at the Indian Institute of Science, Bangalore, and is on leave from the Indian Institute of Technology (IIT), Kanpur, India. Bikramjit obtained his undergraduate and postgraduate degrees, both in Metallurgical Engineering, from the National Institute of Technology (NIT), Durgapur, and the Indian Institute of Science, Bangalore, in 1995 and 1997, respectively. He earned his PhD in Ceramics at Katholieke Universiteit Leuven, Belgium, in March 2001. He returned to India to join IIT Kanpur in November 2001 as Assistant Professor after a brief postdoctoral research experience at the University of California, Santa Barbara. He held visiting positions at the University of Warwick (U.K.), Seoul National University (South Korea), and University Polytechnic Catalonia (Spain).

Dr. Basu has authored or co-authored more than 140 peer-reviewed research papers with 20 papers in the *Journal of American Ceramic Society*. He is the principal editor of the book *Advanced Biomaterials: Fundamentals, Processing and Applications* (John Wiley & Sons Inc., in association with American Ceramic Society), which was published in September 2009. He is on the editorial boards of five international journals and serves as a reviewer of more than 20 SCI journals in the area of ceramics and biomaterials. He has edited a number of special issues of various journals, including *Journal of Materials Science*, *International Journal of Applied Ceramics Technology*, and *Journal of Biomedical Materials Research: Part B*.

At IIT Kanpur, Dr. Basu established a vibrant research program in the area of tribology, structural ceramics, and biomaterials. His research spans the interdisciplinary areas of ceramics, tribology, and biomaterials. In developing interdisciplinary research programs in tribology and ceramics, he has collaborated with the

materials scientists of the International Advanced Research Center for Powder Metallurgy and New Materials (ARCI), Defense Metallurgical Research Laboratory (DMRL), National Metallurgical Laboratory (NML), Central Glass and Ceramics Research Institute (CGCRI), Indian Space Research Organization (ISRO), and Bhabha Atomic Research Center (BARC).

In the area of tribology, he has made significant contributions in establishing the correlation between wear micromechanisms and material properties for a large number of ceramics/composites, including toughened ceramics, such as yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), Ti_3SiC_2, sialon**,** and other materials, such as (W,Ti)C-Co, TiB_2-based ceramics**,** and TiCN-Ni-XC(X=Nb/W/Ta/Hf). Using a self-designed high**-**speed cryo-tribometer, Dr. Basu and his co-workers performed a critical set of experiments to understand friction and wear mechanisms of high**-**purity metals and ceramic bearings. Such a study has relevance for space applications. His research mostly focused on developing microstructure-based understanding of wear mechanisms for various ultra-fine grained ceramics, nanocomposites, and biomaterials, as well as critically analyzing wear resistance properties in the light of the mechanics-based models. His fundamental contribution is the development of analytical models to predict the tribochemical and tribomechanical wear of ceramics.

In recognition of his contributions to the field of ceramics, tribology, and biomaterials, Dr. Basu received noteworthy awards from the Indian Ceramic Society (2003), Indian National Academy of Engineering (2004), and Indian National Science Academy (2005), and was awarded the "Metallurgist of the Year" (2010), by the Ministry of Steels, Government of India. He is the first Indian from India to receive the prestigious "Coble Award for Young Scholars" from the American Ceramic Society in 2008. In 2010, he received the NASI (National Academy of Science, India)–SCOPUS Young Scientist award.

Dr. Mitjan Kalin

Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia; E-mail: mitjan.kalin@fs.uni-lj.si

Since obtaining his PhD in 1999 (University of Ljubljana, Slovenia), Dr. Kalin has focused primarily on the research of wear and friction mechanisms for advanced materials, such as ceramics and coatings, as well as on boundary lubrication, tribochemistry, and nanotribology. In the last 10 years, he has led about 15 single-investigator, bilateral, and multilateral projects, more than half of which were international. He has contributed to about 120 conference proceedings and 70 peer-reviewed papers. He has published eight chapters in interna-

tional books, as well as eight full-text student-course *scripta*. He is a co-editor of the book *Tribology of Mechanical Systems: A Guide to Present and Future Technologies* (ASME Press, 2004). He has delivered over 30 invited lectures and talks at conferences, institutes, universities, and technology-driven companies worldwide. He has also presented about 80 reports and studies made for industrial partners in the area of maintenance, wear, and lubrication. He is author or co-author of eight patents, two of them U.S. patents. Dr. Kalin has received three awards from the Faculty of Mechanical Engineering for scientific and research work, and two awards from the Slovenian Society for Tribology for international recognition. He is also a recipient of the prestigious Burt L. Newkirk Award (ASME, 2006) and the Slovenian state Zois award (2006) for important scientific achievements.

Dr. Kalin is a reviewer for over 30 international peer-reviewed journals in various fields of engineering, material science, physics, chemistry, and nanotechnology. Since 2006, he has been Associate Editor of the *ASME Journal of Tribology*. He is also a member of the editorial boards of the *Journal of Industrial Lubrication and Tribology*, *Emerald* (2004–), *Advances in Tribology*, *Hindawi* (2009–), and *ISRN Mechanical Engineering*, *Hindawi* (2010–), and a member of the publishing council of the SV-JME *Journal of Mechanical Engineering* (2007–). He has been Guest Editor of several special issues of *Tribology International* (Elsevier) and *Lubrication Science* (Wiley). He has also been recently appointed Editor of *Lubrication Science* (Wiley, 2012–). He also reviews various proposals for Wiley, ASME Press, and Springer, over 30 SCI peer-reviewed journals in tribology and several related fields, as well as many proposals for national and international research agencies, such as the European Commission and the European Research Foundation. He is a secretary and member of the Executive Committee (1997–) of the Slovenian Society for Tribology, and one of its founding members. He also serves as an executive board member (2006–) of the Slovenian Society for Materials. He is also an active member of the Society of Tribologists and Lubrication Engineers (STLE); since 2001 he has served in various positions in the Ceramics and Composites Committee, and in 2004 he was elected as president of this committee. He has been a member of organizing, international, and/or advisory boards at many international conferences, and in 2009 acted as a chair of the Engineering Conferences International (ECI) conference "Advances in Boundary Lubrication and Surface Boundary Films" (Seville, Spain, 2009).

He is currently full professor (2010–) and Head of the Chair for Tribology, Technical Diagnostics, and Maintenance (2011–) at the University of Ljubljana, Slovenia. He has also done postdoctoral work at NIST, the Catholic University (Leuven, Belgium), Tohoku University (Japan), and the University of Pisa (Italy). Currently, he holds the position of Vice-Dean for Research and International Affairs at the Faculty of Mechanical Engineering at the University of Ljubljana on his second term.