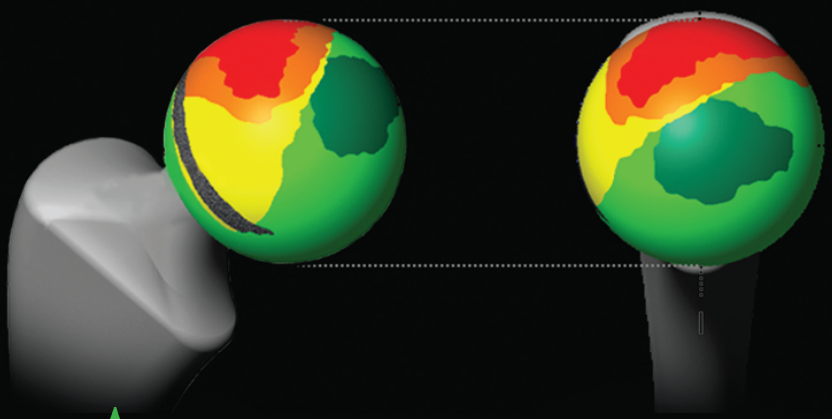
Giuseppe Pezzotti



Advanced Materials for Joint Implants

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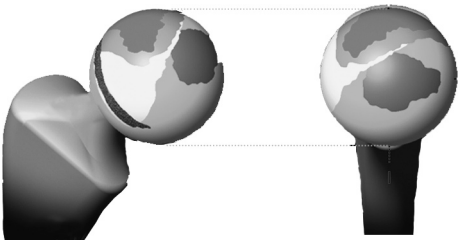

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To the young samurai, Iori

Reviews

"This book presents the most updated and basic knowledge about the biomechanics of artificial hip and knee joints from the macroscopic to the molecular scale. It covers advanced biomaterials, including alumina and zirconia ceramics and their composites and ultra-high-molecular-weight polyethylene. The latest developments in methods of characterizing these biomaterials are also explained at the outset so that readers get updated with new analytical techniques. The book will help young doctors and researchers to better understand the past failure patterns, and it proposes innovative ideas in the field of joint arthroplasty, thus giving fundamental hints for realistic breakthroughs in the time to come."

Prof. Nobuhiko Sugano, MD, PhD
Osaka University Graduate School of Medicine, Japan

"This book is an excellent review of the ceramic and polymeric materials that constitute advanced orthopaedic prosthetic materials. After an introduction, a chapter is devoted to characterisation techniques, which is exceptionally well written and, like all the chapters, is very well referenced with sufficient illustrations to highlight the basis of the technique. The following chapters deal with alumina, zirconia, alumina–zirconia composites and, most important, ultra-high-molecular-weight polyethelene (UHMWPE). The detail the author devotes to these different systems considering their intrinsic properties, factors that determine the strength, toughness and wear behaviour and, in the case of zirconia, the polymorphic transformations is impressive. The author highlights the critical need for more research on the properties of and means for reliably improving UHMWPE. This is a substantial and excellent text and should be on the bookshelf of every orthopaedic surgeon and medical library. I am unaware of any other text that matches the thoroughness of this contribution."

Prof. Michael Swain, PhD
University of Otago, New Zealand

"This book is the most comprehensive and informative source of information on implants for orthopaedic prostheses yet available. It draws on Prof. Pezzotti's extensive knowledge covering fracture mechanics of ceramics and environmentally induced chemical changes of ceramics and their subsequent interactions. It also includes Prof. Pezzotti's excellent insights into the chemical and structural characterisation of materials. The importance of bringing these factors together to understand the issues associated with biomedical implants is key and has never been properly addressed to date. I am sure this publication would be of great interest to surgeons, students, prostheses designers and scientists."

Prof. Mark Hoffman, PhD
The University of New South Wales, Australia

"This book, written by one of the most recognized authors in the field, represents an outstanding review of state-of-the-art and future trends concerning materials for joint prosthesis applications. With more than one thousand references, the book covers the fields of ceramic and polymer materials, with emphasis on their characterization from the nano- to the macro-scale, microstructure-properties relations and lifetime. It gives clear features of what the future could be in this important societal area. This is an excellent reference for university teachers and a source of inspiration for students and engineers."

Prof. Jérôme Chevalier, PhD
University of Lyon—INSA Lyon, France

"This book is an invaluable guide to the physical and chemical features of bioceramics as applied to implants for joint replacement. Improving the longevity of implants on active, aging population is a priority, and the beneficial cross-talk between material scientists, biologists and clinicians should reflect a thorough knowledge of novel materials. The advanced analytical methods described here unveil significant insights into the intimate structure and properties of bioceramics and offer a powerful tool to all scientists and clinicians who are involved in this promising field of translational research."

Prof. Nicola Baldini, MD, PhD
University of Bologna, Italy

"Readers will definitely enjoy the fruits of dazzling progress in biomaterials science and spectroscopic technology vividly described in this book by Prof. Giuseppe Pezzotti. The deep scientific knowledge reported in it will further promote new studies for scientists as well as for clinicians working in the field of joint arthroplasty. This book could effectively contribute to the future developments of next-generation products responding to the increasing expectations of patients and orthopaedic surgeons. In addition, I have great expectations that the introduced novel spectroscopic approaches could provide the final deterministic evaluation tool needed for screening individual joint implants before being delivered to the surgery room, a process which is definitely needed for strengthening and completing the regulatory procedures of new products made by the PMDA in Japan and the FDA in the United States."

Prof. Kengo Yamamoto, MD, PhD
Tokyo Medical University, Japan

About the Author

Giuseppe Pezzotti is a full professor (tenure) at the Ceramic Physics Laboratory of the Kyoto Institute of Technology, Japan, since 2000. He graduated *summa cum laude* in mechanical engineering from Rome University "La Sapienza", Italy, in 1984 and holds two doctoral degrees in engineering and in medical sciences, both obtained in Japan, the country where he has steadily lived for 25 years. From 2002 to 2012, Prof. Pezzotti served as the director of the Research Institute for Nanoscience at Kyoto Institute of Technology. Since 2005, he is an adjunct professor at the Department of Orthopaedic Research of Loma Linda University, Loma Linda, CA. Since 2009, he has held an invited professorship at the Department of Medical Engineering of Osaka University and since 2010 has been visiting professor at the Department of Molecular Cell Physiology of Kyoto Prefectural University of Medicine. Prof. Pezzotti has published around 550 scientific papers and 10 book chapters and holds 8 patents, including a world patent regarding nanoscale stress microscopy in the scanning electron microscope. The spectroscopic methods and algorithms developed by Prof. Pezzotti have been so far transferred to more than 20 major industries around the world. Among other numerous awards and prizes, he was twice recipient of Official Gratitude Awards from the Chinese Embassy in Tokyo. In 2010, he was chosen as one of the 80 most successful Expatriate Italians in the World by the Ministry of Foreign Affairs of Italy. He received the 2011 "150 Years of Italian Science in the World" award on occasion of the 150th anniversary of the Italian Republic. In 2013, he became a member of the Academy of Science of Bologna Institute in appreciation of his advanced studies linking quantum mechanics to medical sciences.

Contents

Preface

Just around ten years ago, when I occasionally met Prof. Ian C. Clarke at a meeting of the American Ceramic Society, I had not even imagined that I would author a book on biomaterials ten years later. At that time, I was deeply involved with some basic issues related to the grain boundary structure and the viscosity of polycrystalline ceramics and was definitely more concerned with the effect of temperature rather than the biological environment. Besides the charismatic leadership of Prof. Clarke, who guided me through the new scientific path, I could obtain fundamental strength from what initially seemed like the clarification of a scientific curiosity rather than a useful discovery: the stress dependence of the cathodoluminescence emission from oxygen vacancy sites in ceramic oxides. The more I investigated this effect, the more I wondered about the bold and intrinsic non-stoichiometric nature of ceramic surfaces, as well as the related vacancy site multiplication or annihilation in the biological environment. I also realized that this somewhat obvious piezospectroscopic effect could have a profound impact on the existing biomaterials science and represent a first clue toward a quantitative molecular-scale approach to the tribological evaluation of modern artificial joints.

This book is the culmination of ten years of research that I have mainly undertaken to develop a consistent and feasible procedure for the quantitative assessment of ceramic surfaces in joint implants on the molecular scale. Many experiments, including Raman assessments not only of ceramic but also of polyethylene bearings, were originally carried out to support and complement the cathodoluminescence approach, although they now represent a substantial part of this book. Honestly, I had never expected it would take so long to actually finish this book, but investing such a large amount of time on this topic was the fruit of a necessary decision, since I gradually came to realize that technical papers scattered across journals, no matter how many they be, could never successfully communicate the entireness of my findings. Yet, I hope that the ideas presented in this book will sometimes come to

permeate biomaterials science, with the newly shown spectroscopic methodologies eventually becoming a standard. I feel happy about the idea that through the logical structure built in this book, the joy and the excitement I obtained from my little discoveries could be shared with those courageous readers who had the patience to go through it.

Giuseppe Pezzotti

Kyoto, July 2013

Acknowledgments

The author offers his most grateful thanks to Prof. Ian C. Clarke, PhD, at Loma Linda University, CA, for picking him out of a crowd of physicists and engineers, introducing him to the field of joint arthroplasty, and teaching him how to concurrently manage basic research and industrial outcomes. Partnerships with Prof. Nobuhiko Sugano, MD, PhD, at Osaka University Medical School, and Prof. Kengo Yamamoto, MD, PhD, at Tokyo Medical University, greatly accelerated research on biomedical implants and linked it to actual medical needs; for all this, the author conveys them his deep gratefulness. Professor Masahiro Hasegawa, MD, PhD, at the Graduate School of Medicine of Mie University, and Dr. Masaaki Matsubara, MD, PhD, at Nissan Tamagawa Hospital, Tokyo, are acknowledged for sharing their precious retrievals and new samples and for constructively discussing the related research outcomes. Many valuable contributions and constructive criticisms were received from Prof. Jérôme Chevalier, PhD, at INSA-Lyon MATEIS, CNRS, Prof. Mike Swain, PhD, at Otago University, and Prof. Mark Hoffman, PhD, at the University of New South Wales. Their favorable opinions on this research were vital to getting this book published. Special appreciations are due to Prof. Mark Rainforth, PhD, at the University of Sheffield, for his inspiring high-resolution microscopy work on worn ceramic surfaces. The author is deeply indebted to his former students and present co-workers, Wenliang Zhu, Dr. Eng.; Andrea Leto, Dr. Eng.; Yasuhito Takahashi, Dr. Eng.; Leonardo Puppulin, Dr. Eng., and Kyoju Fukatsu, Dr. Eng., for their fundamental contributions during the development of the Raman and cathodoluminescence algorithms for stress, molecular orientation, and oxygen off-stoichiometry analyses, for their patient proofreading of several chapters of this book, and for their kind help in the preparation of its figures. This book would not have been possible without the research contributions of all the Japanese and foreign students and researchers who have belonged in the past and those who presently

work at the Ceramic Physics Laboratory of Kyoto Institute of Technology in Japan. Sincere gratitude is finally given to Ms. Manami Tanaka for her stoic help with nasty administration issues at Kyoto Institute of Technology, thus pledging me with the freedom and the concentration to write this book.