Understanding Materials Science

Second Edition

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Rolf E. Hummel

University of Florida

Understanding Materials Science

History • Properties •
Applications

Second Edition

Springer

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Library of Congress Cataloging-in-Publication Data

Hummel, Rolf E., 1934–

Understanding materials science / Rolf E. Hummel.—2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-387-20939-5 (alk. paper)

1. Materials science. I. Title.

TA401.6.A1H86 2004

620.1'1—dc22

2004041693

ISBN 0-387-20939-5

Printed on acid-free paper.

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Printed in the United States of America. (MP/HAM)

9 8 7 6 5 4 3 2 1

SPIN 10960202

Springer-Verlag is a part of *Springer Science Business Media*

springeronline.com

Understanding the history of materials means understanding the history of mankind and civilization.

Preface to Second Edition

My concept for this book, namely to show the connection between the technical and the cultural, economic, ecological, and societal aspects of materials science seems to have been realized judging from the enthusiastic reception of readers coming not only from the hard sciences, but also from the humanities and medicine. Indeed, the first printing sold out less than two years after publication, which made reprinting necessary and gave me the opportunity to make some changes and additions. The comments of many students who took a course based on this book and by colleagues from all over the world confirmed my hunch that many individuals would be interested not only in the physical and technological aspects of materials but also in how materials and the goods which were made of them shaped the development of mankind. By relating history and technology in this text many students were disabused of the idea that “most everything was invented in the past hundred years” (and in the USA).

When contemplating a second edition, I withstood the temptation to substantially expand the book by including major new topics and a more detailed treatment of several subjects. If substantial in-depth treatment of a given topic is wanted, reference should be made to one of the many encyclopedic materials science books that have two or three times more pages. One should realize, however, that the contents of these larger books cannot be covered in a customary three-credit semester course. This necessitates that each teacher select those topics which he/she deems to be most important, that is, with which he/she is most familiar. I have chosen to restrict the presented material and the depth of its treatment to that which is realistically digestible in an introductory course in materials science without overburdening the students with too much detail. Clearly, this text is not meant to be encyclopedic, but instead aims to whet the appetite of its readers and to inspire them to further explore the proper-

ties and applications of metals, alloys, ceramics, plastics, and electronic materials by means of easily understandable explanations and entertaining historical facts. It is also intended to raise the readers' awareness of their obligations to society as practicing engineers and scientists.

What has been changed compared to the first edition? Naturally, there is always room for improvement. Accordingly, a large number of additions, corrections, and clarifications have been made on almost each page. Furthermore, the treatment of "high-tech ceramics" has been substantially expanded (mostly at the suggestions of my colleagues) by including topics such as silicon nitride ceramics, transformation-toughened zirconia, alumina, ultra-hard ceramics, and bioceramics. A separate section on composite materials has been added, including fiber-reinforced composites, particular composites, and laminar composites. A section on advanced fabrics seemed to be of interest to the readers. Most of all, however, Chapter 18 (Economic and Environmental Considerations) has been rewritten and expanded in many places by updating the statistical information on prices of materials, production figures, world reserves, consumption (particularly oil), recycling (particularly plastics, paper, household batteries, electronic scrap, automobiles), the possible use of "bio-diesel" (rape plant oil), waste prevention, lead-free solder, energy savings through recycling, efficient design, and stability of materials. The iron and steel production statistics were updated in Chapter 7, and new figures on gold production and consumption were included in Chapter 17. Finally, considerations on new trends such as "nanomaterials by severe plastic deformation," a rendition of Moore's law, and more philosophical remarks on the expected ethical behavior of engineers have been incorporated into Chapter 19.

A few readers have suggested that I should provide the complete solutions for the homework problems. I am against this. The exercises should be challenges (some more, some less). Giving the detailed solution of the problems (rather than just the numerical results) would tempt many students not to work the problems and in turn would deprive them of an important learning experience and the satisfaction of having succeeded through perseverance. I can assure the readers, however, from my own experience that all problems are solvable.

Those readers who like interactive communication and animated visualizations by using the computer are directed to the post scriptum of the Preface to the First Edition that follows.

My thanks go to many of my students who, through their kind words of praise and their challenging questions, helped me to

clarify many points. My colleagues, such as Professor Emeritus Gerold (MPI Stuttgart/Germany), Professor Emeritus Petzow (MPI Stuttgart/Germany), Professor Emeritus Hensch (Imperial College London), and Professors Ebrahimi, Sigmund, and Mecholsky (University of Florida) helped with valuable suggestions which are much appreciated.

Rolf E. Hummel
Gainesville, FL
June 2004

Preface to the First Edition

It is a challenging endeavor to trace the properties and the development of materials in the light of the history of civilization. Materials such as metals, alloys, ceramics, glass, fibers, and so on have been used by mankind for millennia. Actually, materials have shaped entire civilizations. They have been considered of such importance that historians and other scholars have named certain ancient periods after the material which was predominantly utilized at that respective time. Examples are the Stone Age, the Bronze Age, and the Iron Age. As time progressed the materials became increasingly sophisticated. Their properties were successively altered by man to suit ever-changing needs. We cannot but regard with utmost respect the accomplishments of men and women who lived millennia ago and who were capable of smelting, shaping, and improving the properties of materials.

Typical courses on world history expose students mainly to the description of major wars, the time span important rulers have reigned, and to the formation, expansion and downfall of world empires. Very little is generally said about the people who lived and toiled in ancient times and about the evolution of civilizations. This book traces the utilization, properties, and production techniques of materials from the Stone Age via the Bronze Age and the Iron Age up to modern times. It explains the physical properties of common materials as well as those of “exotic materials” such as superalloys, high-tech ceramics, optical materials, electronic materials, and plastics. Likewise, natural and artificial fibers and the technique of porcelain- and glass-making are covered. Moreover, this book provides a thorough introduction into the science and engineering of materials, covering all essential features that one would expect to find in a horizontally integrated introductory text for materials science. Specifically, the book presents the mechanical, electrical, magnetic, optical,

and thermal properties of all materials including textiles, fibers, paper, cement, and wood in a balanced and easily understandable way. This book is not an encyclopedia of materials science. Indeed, it is limited in its depth so that the content can be conveniently taught in a one-semester (15-week), three-credit-hour course. Nevertheless, the topics are considered to be essential for introducing engineers and other interested readers to the fascinating field of materials science.

Plenty of applied problems are given at the end of the technical chapters. The solutions for them are listed in the Appendix. The presentation follows an unusual sequence, starting with a description of the properties of the first materials utilized by man, such as stone, fiber, and copper. Subsequently, the differences between these materials are explained by considering their atomistic structure, the binding forces between the atoms, and their crystallography. A description of the Bronze Age is followed by the treatment of alloys and various strengthening mechanisms which are achieved when multiple constituents are blended to compounds. The properties of iron and steel are explained only after an extensive history of iron and steel making has been presented. In Part II, the electronic properties of materials are covered from a historical, as well as from a scientific, point of view. Eventually, in Part III the historic development and the properties of ceramics, glass, fibers and plastics as we understand them today are presented. The book concludes with a chapter on economics, world resources, recycling practices, and ecology of materials utilization. Finally, an outlook speculating on what materials might be utilized 50 years from now is given. Color reproductions of relevant art work and artifacts are included in an insert to show the reader how materials science is interwoven with the development of civilization.

This book is mainly written for engineering, physics, and materials science students who seek an easily understandable and enjoyable introduction to the properties of materials and the laws of physics and chemistry which govern them. These students (and their professors) will find the mixture of history, societal issues, and science quite appealing for a better understanding of the context in which materials were developed. I hope, however, that this book also finds its way into the hands of the general readership which is interested in the history of mankind and civilization as it relates to the use and development of materials. I trust that these readers will not stop at the end of the historical chapters, but instead will continue in their reading. They will discover that the technical sections are equally fascinating since they provide an understanding of the present-day appliances and tech-

nical devices which they use on a daily basis. In other words, I hope that a sizeable readership also comes from the humanities. Last, but not least, future archaeo-metallurgists should find the presentation quite appealing and stimulating.

A book of this broad spectrum needs, understandably, the advice of many specialists who are knowledgeable in their respective fields. It is my sincere desire to thank all individuals who in one way or another advised me after I wrote the first draft of the manuscript. One individual above all stands out particularly: Dr. Volkmar Gerold, Professor Emeritus of the University of Stuttgart and the Max-Planck-Institut for Materials Research who read the manuscript more than once and saw to it that each definition and each fact can stand up to the most rigid scrutiny. My sincere thanks go to him for the countless hours he spent on this project.

Other colleagues (most of them from the University of Florida) have read and advised me on specific chapters. Among them, Dr. R.T. DeHoff (diffusion and general metallurgy), Dr. A. Brennan (polymers), and Dr. E.D. Verink (corrosion) are particularly thanked. Further, Drs. C. Batich and E. Douglas (polymers), Drs. D. Clark, J. Mecholsky, and D. Whitney (ceramics), Dr. C. Beatty (recycling), Dr. J.D. Livingston (MIT; magnetism), Dr. C. Pastore (Philadelphia College of Textiles and Science; fibers), Mr. E. Cohen (Orlando, FL) and Mr. R.G. Barlowe (U.S. Department of Agriculture, World Agricultural Outlook Board) need to be gratefully mentioned. Ms. Tita Ramirez cheerfully typed the manuscript with great skill and diligence. Finally, Dr. M. Ludwig carried on my research work at those times when my mind was completely absorbed by the present writings. To all of them my heartfelt thanks.

Rolf E. Hummel
Gainesville, FL
April 1998

P.S. For those readers who want to deepen their understanding in selected technical topics covered in this book and who have a propensity to the modern trend of playing with the computer, I recommend considering a computer software entitled "*Materials Science: A Multimedia Approach*" by J.C. Russ (PWS Publishing Comp. Boston/Ma; <http://www.pws.com>). This CD-ROM provides animated visualizations of physical principles and interactive sample problems.

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PART I

MECHANICAL PROPERTIES OF MATERIALS