

# **HANDBOOK OF HARD COATINGS**

## **Deposition Technologies, Properties and Applications**

Edited by

**Rointan F. Bunshah**

University of California, Los Angeles  
Los Angeles, California

**NOYES PUBLICATIONS**  
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## *IN MEMORIAM*



**Professor Rointan F. (Ron) Bunshah**  
*1927–1999*

It is with great sadness that we note the death of Professor Rointan (Ron) F. Bunshah. Ron passed away on October 24, 1999 after a long, gallant and quiet battle with leukemia. This book constitutes his final project and will stand as a memorial to his career and his many accomplishments over the years. This book is also one of many dozens of books in the Materials Science and Process Technology Series, originally from Noyes Publications, and now William Andrew Publishing, that Ron helped originate and manage as Series Editor for many, many years.

Ron's career started over fifty years ago with his B.S. degree in 1948 from the Banares Hindu University in India. After moving to the United States, he received his M.S. and D.Sc. degrees in 1951 and 1952, respectively, from the Carnegie Institute of Technology in Pittsburgh. He remained at Carnegie until 1954 as a research metallurgist and instructor. He then joined New York University as an Adjunct Professor and Research Scientist. Six years later, he moved to the Lawrence Radiation Laboratory in Livermore, CA as a Senior Metallurgist. His last appointment, in 1968, was to the University of California at Los Angeles, as a Professor in the Department of Materials Science which is in the School of Engineering and Applied Science. He took "early" retirement from UCLA in 1991, but returned soon thereafter for another seven years, continuing to teach and lead active research projects until the fall of 1998.

While at UCLA, Professor Bunshah was a distinguished senior faculty member who took an active part in the University. He was presented with the

Distinguished Teaching Award of the Engineering Graduate Student Association in 1971, and directly supervised twenty-eight M.S. and ten Ph.D. students as well as mentoring over twenty post-doctoral researchers. His laboratory and his work on vacuum metallurgy and thin films were internationally recognized as among the best in the world.

Ron's technical contributions covered a wide range, not only with metals and alloys, but also in the realm of semiconductors, dielectrics, and diamond coatings. His work covered the materials themselves as well as novel fabrication and deposition techniques and technologies. The most important of these technologies is known as Activated Reactive Evaporation (ARE), which combined evaporative deposition with a reactive plasma activation or modification of the depositing films. This novel technology allowed researchers to alter the kinetics of an evaporative deposition in ways which had been impossible, and led to new discoveries in materials and processing. His research output was documented in nearly three-hundred publications, a number of edited books, and innumerable invited talks and presentations at conferences.

Professor Bunshah was also very generous in devoting a significant fraction of his professional time to his colleges outside of UCLA. Much of this focused on the American Vacuum Society, of which he was President in the early 1960's. He was instrumental in two key accomplishments with the AVS: the formation of the Vacuum Metallurgy Division in 1960, and the initiation of the International Conference on Metallurgical Coatings (ICMC) in 1973. He served as the first Chair of the Vacuum Metallurgy Division, and was Chair of the ICMC for at least the first ten years of its operation. In recognition of this founding role, the ICMC initiated in 1983 an "R.F. Bunshah" award, which is given in his honor each year for the best paper at the Conference.

Ron received many honors during his career. From the AVS, he was awarded the Gaede-Langmuir prize, AVS Fellow, and AVS Honorary Member. At the ICMC Conference in 1998, I had the honor of presenting him with the Founder's Award, recognizing his singular devotion to organizing and running the Conference. Other honors included the First Life Member of the Indian Vacuum Society, Life Membership in the Indian Institute for Metals, the Distinguished Alumnus Award of the Benares Hindu University, and Fellowship in the American Society for Metals. He was on the editorial board of many journals, including Applied Surface Science, Surface Technology, Coatings Science and Technology, Thin Solid Films, Research and Development, and International Research/Development.

His colleges within the ICMC community, the AVS, UCLA, and the numerous students and collaborators, will now miss his leadership, his insight, and his active drive to develop new deposition techniques and coatings, along with his friendship which, for many, goes back several decades. We extend our deepest sympathy to his wife, Zoreh, and his family.

Stephen Rossnagel  
Yorktown Heights, NY

June, 2000

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# Preface

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This volume covers a wide range of topics relating to the fabrication, characterization, and application of what we know as *hard coatings*. This book project dates back many years to a proposed collaboration with Professor Dr. Christian Weissmantel, who suggested a coedited volume with Professor Bunshah. Unfortunately, Professor Weissmantel passed away and it was many years before the project could be started.

The contributors to this volume represent the senior workers in this field over the past twenty years, and their names will be well known to those working in the field. It is a distinctly international list, representing the countries and labs that have been at the forefront of hard coatings work. It should be noted that many, if not all, of these authors are regular participants in the annual International Conference on Metallurgical Coatings and Thin Films (ICMTF), a conference founded by Professor Bunshah more than twenty-five years ago, and still vibrant and growing each year.

The volume is roughly organized into three areas: fabrication, characterization, and applications. The first chapter is a general introduction to the field of hard coatings and wear-resistant surfaces by Professor Bunshah. In this brief chapter, Bunshah describes some of the earliest work with these materials, and then defines some of the terms used throughout the volume. This chapter is followed by two general chapters on deposition technology. The first is also by Bunshah, and covers the traditional vacuum-based thin-film techniques such as evaporation, sputter deposition, and chemical vapor deposition. This chapter is quite useful in giving the reader a wide overview of these topics along with the references and resources for more detailed explanations. The second deposition chapter (Ch. 3) by Professor Knotek describes alternate techniques used for thermal spraying of hard coatings

at high rates over large areas. These techniques and technologies are very applicable to the commercial uses of hard coatings.

The fourth through sixth chapters introduce the science of characterizing and measuring hard coatings or films. The first chapter in this section, by Professors Hultman (Linköping, Sweden) and Sundgren (Chalmers, Sweden), is a very detailed and systematic overview of the relationships between the physical properties of these films and composites, and the underlying structure of the material. These two professors are without peer in the world for their fundamental contributions to the science of hard coatings and multilayers, and the chapter is a good introduction to the field. The second characterization chapter, by Bull (Newcastle, UK) and Rickerby (Harwell, UK), explores some of the practical characterization techniques used to evaluate hard materials. These include techniques for hardness measurement, adhesion, and stress. The third characterization chapter, by Bhushan and Gupta (Ohio State University), takes this a step farther, examining the tribological properties of films. This includes hardness and adhesion, as well as the measurement of friction and wear. These latter topics are key to the applications of hard materials, which are generally used to protect underlying softer materials.

The seventh and eighth chapters describe applications, and are broken into two areas: coatings used for cutting tools, and coatings used for non-cutting applications. In each case, the key advantage of hard coatings is that they can be used to increase the quality and lifetime of tools of various types. These chapters describe just some of the many applications. The ninth chapter covers a range of materials somewhat different from the conventional hard coatings, which are often nitrides or oxides (of metals). This chapter explores cubic boron nitride and diamond-like films, and covers deposition, characterization, and application in the single chapter. This materials set has some very unique properties and the field is still rapidly evolving.

Finally, Professor Bunshah provides a summary chapter with comments on each of the areas in the volume. In addition, he makes some suggestions and predictions for future work and applications. In many ways, this chapter is most valuable because it sums up a lifetime of experience and wisdom, and puts some perspective on the field.

As mentioned in the Memoriam, this project is the last volume in the rather prodigious output of Professor Bunshah. It is fitting, though, that this volume has come together shortly after his death and it serves as a testament to his contributions over the many years.

Stephen Rossnagel  
Yorktown Heights, NY  
June, 2000

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