MODERN TRIBOLOGY HANDBOOK

Volume One

Principles of Tribology

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MODERN TRIBOLOGY HANDBOOK

Volume Two

Materials Coatings,
and Industrial Applications

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Editor-in-Chief

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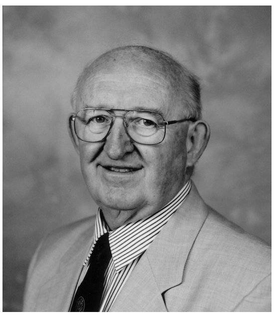
Foreword



The very size of this *Modern Tribology Handbo*ok reflects the extent to which the subject has developed since the word *tribology* was introduced in 1966. While much progress has been recorded in recent decades and several research workers, some of whom are authors of chapters in these volumes, have revealed new facets of the subject and generated valuable data, it is as well to remember that the major users of tribological knowledge are the engineers who design, manufacture, and operate machinery. The general engineer who finds much value in handbooks will welcome the addition of this new compendium of tribological knowledge and data. It is important that the reader and user of this handbook be aware of the well-tried approaches to the measurement of friction and wear and the difficulties sometimes encountered in the interpretation of the results. Throughout the long history of tribology, engineers have sought simple guidance on the magnitude of dominant quantities affecting the performance and life of machinery. Engineers in many fields frequently require estimates of the magnitudes of the friction and wear likely to be experienced by different combinations of materials sliding or rolling together in various environments. The presentation of practical information in the form of data banks for friction and wear based upon current knowledge and experience will thus be warmly welcomed. The frustration experienced by practicing engineers when seeking guidance from expert tribologists on representative values of such quantities is legendary!

The basic concepts of contact, friction, wear, and lubrication have been embellished in impressive style by recent analytical and experimental approaches to these subjects, and the outcome is thoroughly reviewed in the initial and major section of the handbook dealing with macrotribology. Impressive studies have greatly enhanced our understanding of the physical and chemical nature of surfaces during the latter half of the 20th century, and the subject which underpins many aspects of tribology thus attracts special attention. Some of the topics, such as wear maps and elastohydrodynamic lubrication, are almost as new as the term *tribology* itself.

Effective lubrication remains the ideal way of controlling friction and wear in most mechanical systems. The science and technology of generating fluid-film lubrication to protect tribological components is now firmly established. However, studies of macrotribology have been supplemented by remarkable investigations of micro-, nano-, and even molecular tribology in recent times. This is illustrated by studies of the physical and chemical properties of surfaces; the contact and adhesion between solids; the effects of surface modifications and coatings upon friction and wear; lubricant rheology; very thin elastohydrodynamic lubricating films; and the nature of boundary and mixed lubrication. This alone justifies the substantial and welcome section of the handbook devoted to micro- and nanotribology. While most of the work is devoted to experimental studies, one chapter is devoted to the fascinating subject of molecular dynamics simulations in this field.

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Both the conventional and the newer tribological materials are considered in the third section of the handbook. This provides a timely opportunity for the reader to extend his or her knowledge of the advantages and limitations of ceramics, diamond, diamond-like carbon and related films, and a wide range of coating composites.

The last major section of the handbook is devoted to industrial components and systems. Familiar components which have typically enjoyed a century or more of development, such as slider bearings, rolling element bearings, gears, and seals are all considered, alongside components and systems encountered in road, rail, marine, and space vehicles. The special tribological problems faced in earth-moving and manufacturing equipment attract individual attention.

It is refreshing to see newer applications of tribology included in the handbook. The term biotribology was introduced in 1973 to embrace the application of tribology to biological and particularly medical situations. While the success of joint replacement tends to dominate this field, since it represents a remarkable and dominant feature of orthopedic surgery, there are also an increasing number of examples of the successful transfer of tribological knowledge to the biological field. It is, however, the impact of information technology on society that has promoted major progress in tribology in recent times. The role of tribology has undoubtedly been central to the successful development of magnetic storage and retrieval systems. Spectacular achievements have been recorded in relation to computers, printers, cameras, and scanners, and the reader will welcome the chapters devoted to these developments.

The Jost Report[1] of 1966 emphasized that losses associated with the shutdown of machinery disabled by the failure of tribological components represented a troublesome economic millstone around the necks of machinery and manufacturing systems. Since that time, maintenance of machinery has changed considerably, with emphasis moving away, in many cases, from routine inspection and component replacement to more effective procedures. It is therefore fitting that the closing chapter of the handbook should be devoted to machinery diagnosis and prognosis. It is now well recognized that the tribologist and maintenance engineer must work closely together in monitoring the health of machinery and the performance of tribological components that might so easily compromise the well-being of our industrial society.

The Editor-in-Chief and his team are to be warmly congratulated in bringing together this extensive, timely, and useful *Modern Tribology Handbook*.

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Reference

1. Department of Education and Science, 1966, Lubrication (Tribology) Education and Research, A Report on the Present Position and Industry's Needs, HMSO, London.

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Preface

Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices. The nature and consequences of the interactions that take place at the moving interface control its friction, wear, and lubrication behavior. Understanding the nature of these interactions and solving the technological problems associated with the interfacial phenomena constitute the essence of tribology. The field of tribology incorporates a number of disciplines, including mechanical engineering, materials science, mechanics, surface chemistry, surface physics and a multitude of subjects, such as surface characterization, friction, wear, lubrication, bearing materials, lubricants, and the selection and design of lubrication systems, and it forms a vital element of engineering.

The importance of friction and wear control cannot be overemphasized for economic reasons and long-term reliability. It is important that all designers of mechanical systems use appropriate means to reduce friction and wear, through the proper selection of bearings and the selection of appropriate lubricants and materials for all interacting surfaces. It is equally important that those involved with manufacturing understand the tribological origins of unwanted friction, excessive wear, and lubrication failure in their equipment. The lack of consideration of tribological fundamentals in design and manufacturing is responsible for vast economic losses, including shortened life, excessive equipment downtime, and large expenditures of energy.

The recent emergence and proliferation of proximal probes (in particular tip-based microscopies and the surface force apparatus) and of computational techniques for simulating tip-surface interactions and interfacial properties has allowed systematic investigations of interfacial problems with high resolution as well as ways and means for modifying and manipulating nanostructures. These advances provide the impetus for research aimed at developing a fundamental understanding of the nature and consequences of the interactions between materials on the atomic scale, and they guide the rational design of material for technological applications. In short, they have led to the appearance of the new field of micro/nanotribology.

There are also new applications which require detailed understanding of the tribological processes on macro- and microscales. Since the early 1980s, tribology of magnetic storage systems has become one of the important parts of tribology. Microelectromechanical Systems (MEMS) have begun to appear in the marketplace which present new tribological challenges. Tribology of processing systems such as copiers, printers, scanners, and cameras is important, although it has not received much attention. Along with the new industrial applications, there has been development of new materials, coatings, and treatments, such as synthetic diamond, true diamond, diamond-like carbon films, and chemically grafted films, to name a few.

It is clear that the general field of tribology has grown rapidly during the past 50 years or so. Conventional tribology is well established, but micro/nanotribology is evolving and is expected to take center stage for the next decade. New materials are needed, and their development requires fundamental understanding of tribological processes. Furthermore, new industrial applications continue to evolve with their unique challenges. Much of the new tribological information has not made it into the hands

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that need to use it. Very few tribology handbooks exist, and these are dated. They have focused on conventional tribology, traditional materials, and already-matured industrial applications. The objective of this handbook is to cover modern tribology with an emphasis on all industrial applications. A large number of leading tribologists from around the world have contributed chapters dealing with all aspects of the subject. The appeal of the subject is expected to be very broad, including researchers and practicing engineers and scientists.

The handbook is divided into four sections. The first section, on Macrotribology, covers the fundamentals of conventional tribology. It consists of 15 chapters on topics including surface physics, surface roughness, solid contact mechanics, adhesion, friction, contact temperatures, wear, lubrication and liquid lubricants, friction and wear measurement techniques, design of friction and wear tests, and friction and wear data bank. The second section on Micro/Nanotribology covers the fundamentals of the emerging field of micro/nanotribology. It consists of studies using surface force apparatus, scanning probe microscopy, and molecular dynamic simulations. These studies complement our tribological understanding on the macroscale. The third section on Solid Tribological Materials and Coatings covers the materials; hard, wear-resistant, and solid lubricant coatings; and surface treatments used in tribological applications as well as coating evaluation techniques. The fourth and last section on Tribology of Industrial Components and Systems covers a large range of industrial applications. This section starts out with the most common tribological components followed by tribology of various industrial applications from the "old" and "new" economy. A Glossary of Terms in Tribology is added, which should be of general interest.

We embarked on this project in October 1998, and we worked very hard to get all the chapters to the publisher in a record time of a little over 1 year. I wish to sincerely thank the authors for offering to write comprehensive chapters on a tight schedule. This is generally an added responsibility in the hectic work schedules of most researchers today. I also wish to thank the section editors who worked hard to solicit the most competent authors. They are listed in the handbook. I depended on a large number of reviewers who provided critical reviews, in many cases, of more than one chapter in a short time. They are listed in the handbook as well. I also would like to thank Mr. Sriram Sundararajan, a Ph.D. student in my lab, who patiently assisted in the handling of the chapters.

I hope the readers of this handbook find it useful.

Bharat Bhushan
Editor
September 2000

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The Editor

Dr. Bharat Bhushan received an M.S. in mechanical engineering from the Massachusetts Institute of Technology in 1971, an M.S. in mechanics and a Ph.D. in mechanical engineering from the University of Colorado at Boulder in 1973 and 1976, respectively, an M.B.A. from Rensselaer Polytechnic Institute at Troy, NY, in 1980, Doctor Technicae from the University of Trondheim at Trondheim, Norway, in 1990, a Doctor of Technical Sciences from the Warsaw University of Technology at Warsaw, Poland, in 1996, and Doctor Honouris Causa from the Metal–Polymer Research Institute of the National Academy of Sciences at Gomel, Belarus. He is a registered professional engineer (mechanical). He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the Department of Mechanical Engineering as well as the Director of the Computer Microtribology and Contamination Laboratory at the Ohio State University, Columbus. He is an internationally recognized expert in tribology on the macro- to nanoscales, and is one of the field's most prolific authors. He is considered by some a pioneer in the tribology and mechanics of magnetic storage devices and a leading researcher in the field of micro/nanotribology using single probe microscopy. He has authored 5 technical books, 23 handbook chapters, more than 400 technical papers in reviewed journals, and more than 60 technical reports. He has edited more than 25 books, and holds 10 U.S. patents. He is founding editor-in-chief of the *World Scientific Advances in Information Storage Systems Series*, the *CRC Press Mechanics and Materials Science Series*, and the *Journal of Information Storage and Processing Systems*. He has given more than 200 invited presentations on five continents and more than 50 keynote/plenary addresses at major international conferences.

He organized the first symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the first international symposium on Advances in Information Storage Systems in 1990, both of which are now held annually. He is the founder of an ASME Information Storage and Processing Systems Division founded in 1993 and served as the founding chair from 1993 through 1998. His biography has been listed in over two dozen *Who's Who* books including *Who's Who in the World*, and he has received more than a dozen awards for his contributions to science and technology from professional societies, industry, and U.S. government agencies. Dr. Bhushan is also the recipient of various international fellowships including the Alexander von Humboldt Research Prize for Senior Scientists and the Fulbright Senior Scholar Award. He is a foreign member of the International Academy of Engineering (Russia), the Byelorussian Academy of Engineering and Technology, and the Academy of Triboengineering of the Ukraine, an honorary member of the Society of Tribologists of Belarus, a fellow of ASME and the New York Academy of Sciences, a senior member of IEEE, and a member of STLE, ASEE, Sigma Xi, and Tau Beta Pi.

Dr. Bhushan has previously worked for Automotive Specialists, Denver, CO; the R & D Division of Mechanical Technology Inc., Latham, NY; the Technology Services Division of SKF Industries Inc., King of Prussia, PA; the General Products Division Laboratory of IBM Corporation, Tucson, AZ; and the Almaden Research Center of IBM Corporation, San Jose, CA.

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