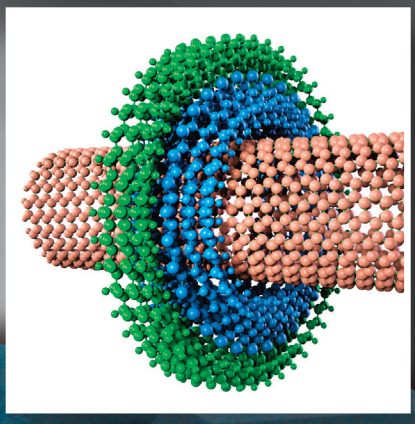
Tribology Series

Principles and Applications of Tribology

Second Edition



Bharat Bhushan

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PRINCIPLES AND APPLICATIONS OF TRIBOLOGY

Tribology Series

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SECOND EDITION

Bharat Bhushan

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The Ohio State University
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To my wife Sudha, my son Ankur and my daughter Noopur

Contents

About the Author

Dr Bharat Bhushan received an MS in mechanical engineering from the Massachusetts Institute of Technology in 1971, an MS in mechanics and a PhD in mechanical engineering from the University of Colorado at Boulder in 1973 and 1976, respectively, an MBA 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 Honoris Causa from the National Academy of Sciences at Gomel, Belarus, in 2000 and University of Kragujevac, Serbia, in 2011. He is a registered professional engineer.

He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the College of Engineering, and the Director of the Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics (NLB^2) at the Ohio State University, Columbus, Ohio. His research interests include fundamental studies with a focus on scanning probe techniques in the interdisciplinary areas of bio/nanotribology, bio/nanomechanics and bio/nanomaterials characterization and applications to bio/nanotechnology, and biomimetics. He is an internationally recognized expert on bio/nanotribology and bio/nanomechanics using scanning probe microscopy, and is one of the most prolific authors on the subject. He is considered by some a pioneer of the tribology and mechanics of magnetic storage devices. He has authored 8 scientific books, 90+ handbook chapters, 700+ scientific papers (h-index – 57+; ISI Highly Cited in Materials Science, since 2007; ISI Top 5% Cited Authors for Journals in Chemistry since 2011), and 60+ technical reports. He has also edited 50+ books and holds 17 US and foreign patents. He is co-editor of the Springer NanoScience and Technology Series and co-editor of *Microsystem Technologies*. He has given more than 400 invited presentations on 6 continents and more than 200 keynote/plenary addresses at major international conferences.

Dr Bhushan is an accomplished organizer. He organized the 1st Symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the 1st 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 during 1993–1998. 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 two dozen awards for his contributions to science and technology

from professional societies, industry, and US government agencies. He is also the recipient of various international fellowships including the Alexander von Humboldt Research Prize for Senior Scientists, the Max Planck Foundation Research Award for Outstanding Foreign 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 Ukraine, an honorary member of the Society of Tribologists of Belarus, a fellow of ASME, IEEE, STLE, and the New York Academy of Sciences, and a member of ASEE, Sigma Xi and Tau Beta Pi.

Dr Bhushan has previously worked for Mechanical Technology Inc., Latham, NY; SKF Industries Inc., King of Prussia, PA; IBM, Tucson, AZ; and IBM Almaden Research Center, San Jose, CA. He has held visiting professorships at the University of California at Berkeley, the University of Cambridge, UK, the Technical University Vienna, Austria, the University of Paris, Orsay, ETH Zurich, and EPFL Lausanne. He is currently a visiting professor at KFUPM, Saudi Arabia, the Harbin Institute, China, the University of Kragujevac, Serbia, and the University of Southampton, UK.

Foreword

The concept of tribology was announced in 1966 in a report by the UK Department of Education and Science. It encompasses the interdisciplinary science and technology of interacting surfaces in relative motion and associated subjects and practices. It includes parts of physics, chemistry, solid mechanics, fluid mechanics, heat transfer, materials science, lubricant rheology, reliability and performance.

Although the name tribology is new, the constituent parts of tribology – encompassing friction and wear – are as old as history. The economic aspects of tribology are significant. Investigations by a number of countries arrived at figures of savings of 1.0% to 1.4% of the GNP, obtainable by the application of tribological principles, often for proportionally minimal expenditure in Research and Development.

Being an interdisciplinary area, the important aspects of tribology have been difficult to cover in a single book of interest to readers ranging from students to active researchers in academia and industry.

To prepare such a wide-ranging book on tribology, Professor Bhushan has harnessed his knowledge and experience gained in several industries and universities. He has set out to cover not only the fundamentals of friction, wear and lubrication, friction and wear test methods and industrial applications, but also includes a chapter on the field of micro/nanotribology, which may be of special interest in the light of the emergence of proximal probes and computational techniques for simulating tip–surface interactions and interface properties.

Professor Bharat Bhushan's comprehensive book is intended to serve both as a textbook for university courses as well as a reference for researchers. It is a timely addition to the literature on tribology, and I hope that it will stimulate and further the interest of tribology and be found useful by the international scientific and industrial community.

Professor H. Peter Jost
President, International Tribology Council
Angel Lodge Laboratories & Works
London, UK
July, 1998

Series Preface

The first edition of *Principles and Applications of Tribology* was published in 2002. The second edition promises to deliver much more than the earlier version. In the past few decades, since the concept of "tribology" was introduced by Peter Jost in 1966, the industry has gone through dramatic changes. These changes were dictated by demands for new, more reliable products and to improve the quality of life. To fulfill these demands, new technologies and products have emerged. In the field of tribology, improved materials and surface treatments were developed, new lubricants were introduced and new insights into the mechanisms of contacting surfaces were gained. Nowadays, humanity is facing new challenges such as sustainability, climate change and gradual degradation of the environment. Tribology, like any other field of science, is continuously developing to stay at the forefront of the emerging technologies.

This book provides a comprehensive account of the field of tribology. The text starts with the physical and chemical characteristics of surfaces and surface contacts. It then describes the basic principles of friction, wear and lubrication mechanisms. An attractive feature of this book is its wide scope. The book content extends far beyond the more traditional approach of some tribological books that concentrate mainly on lubricants and lubrication mechanisms. In this book, the newer areas of nanotribology, green tribology and biomimetics are covered. There is even a short discussion on the experimental methods used in tribology. A long chapter is devoted to industrial components and applications relevant to tribology. Tribological constraints on new technologies such as MEMS and microfabrication are introduced. This approach demonstrates that the field of tribology is evolving and adapting to remain relevant to modern industry.

Not so long ago, tribologists were running experiments on tribometers trying to understand the mechanisms of wear and friction at a macro level. Today, they run complex experiments, aided by computer simulations, which permit insights to be gained into what is happening during contact at the molecular or atomic level. In the past few decades, a substantial knowledge base on various aspects of tribology has been built. As tribology is an interdisciplinary area of science, knowledge from chemistry, physics, material science, engineering, computational science and many others is required to provide an understanding of the phenomena that occur. The book reflects that by providing a comprehensive coverage of this important topic. It is recommended for undergraduate and postgraduate students and also for practicing engineers.

Gwidon Stachowiak
University of Western Australia

Preface to Second Edition

Tribology is an important interdisciplinary field. It involves design of components with static and dynamic contacts for the required performance and reliability. The second edition of Principles and Applications of Tribology has been revised to reflect the developments in the field over the past decade.

Modern tools and techniques as well as computational modeling have allowed systematic investigations of interfacial phenomena down to atomic scales. These developments have furthered the field of nanotribology and nanomechanics and our understanding of the interface of science and technology.

The advances in micro/nanofabrication processes have led to the development of micro/nanoelectromechanical systems (MEMS/NEMS) used in various electro/mechanical, chemical, optical, and biological applications. These devices are expected to have a major impact on our lives, comparable to that of semiconductor technology, information technology, or cellular or molecular biology.

Chapters on nanotribology and introduction to nanotechnology (MEMS/NEMS) have been totally rewritten. A major addition to this new edition is the chapter on ecological or green tribology. The tribological aspects of ecological balance and of environmental and biological impacts, including tribological components, materials and surfaces that mimic nature (biomimetic surfaces) and the control of friction and wear that is important for alternative energy production, make up a novel and growing area of science and technology.

The author hopes that the second edition will be a useful addition to interface science and technology. Thanks are due to Megan BeVier for typing the manuscript.

Power point presentation of the entire book for a semester course is available from the author. Solution manual is also available from the author. Both Power point presentation and the solution manual will be shipped to those who are using the book as textbook for a class of minimum of 6 students.

Professor Bharat Bhushan
Powell, Ohio
May, 2012

Preface to First Edition

Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices. Its popular English language equivalent is friction, wear and lubrication or lubrication science. The nature and consequence of the interactions that take place at the interface control its friction, wear and lubrication behavior. During these interactions, forces are transmitted, mechanical energy is converted, physical and chemical nature, including the surface topography of the interacting materials, are altered. Understanding the nature of these interactions and solving the technological problems associated with the interfacial phenomena constitute the essence of tribology.

Sliding and rolling surfaces represent the key to much of our technological society. Understanding of tribological principles is essential for the successful design of machine elements. When two nominally flat surfaces are placed in contact, surface roughness causes contact to occur at discrete contact spots and interfacial adhesion occurs. Friction is the resistance to motion that is experienced whenever one solid body moves over another. Wear is the surface damage or removal of material from one or both of two solid surfaces in a moving contact. Materials, coatings and surface treatments are used to control friction and wear. One of the most effective means of controlling friction and wear is by proper lubrication which provides smooth running and satisfactory life for machine elements. Lubricants can be liquid, solid, or gas. The role of surface roughness, the mechanisms of adhesion, friction and wear, and physical and chemical interactions between the lubricant and the interacting surfaces must be understood for optimum performance and reliability. The importance of friction and wear control cannot be overemphasized for economic reasons and long-term reliability. The savings can be substantial, and these savings can be obtained without the deployment of investment.

The recent emergence and proliferation of proximal probes, in particular,tip-based microscopies (the scanning tunneling microscope and the atomic force microscope) and the surface force apparatus, and of computational techniques for simulating tip–surface interactions and interfacial properties, have allowed systematic investigations of interfacial problems with high resolution, as well as ways and means for modifying and manipulating nanoscale structures. 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, which pertains to experimental and theoretical investigations of interfacial processes on scales ranging from the atomic and molecular to the microscale. Micro/nanotribological studies are valuable for a

fundamental understanding of interfacial phenomena to provide a bridge between science and engineering.

There is a concern that some of today's engineering and applied science students may not be learning enough about the fundamentals of tribology. No single, widely-accepted textbook exists for a comprehensive course on tribology. Books to date are generally based on the authors' own expertise in narrow aspects of tribology. A broad-based textbook is needed. The purpose of this book is to present the principles of tribology and the tribological understanding of most common industrial applications. The book is based on the author's broad experience in research and teaching in the area of tribology, mechanics and materials science for more than thirty years. Emphasis is on the contemporary knowledge of tribology, and includes the emerging field of micro/nanotribology. The book integrates the knowledge of tribology from mechanical engineering, mechanics and a materials science points of view. Organization of the book is straightforward. The first part of the book starts with the principles of tribology and prepares the students to understand the tribology of industrial applications. The principles of tribology follow with materials, coatings and surface treatments for tribology. Chapter 15 describes the tribological components and applications.

The book is intended for three types of readers: (1) senior undergraduate and graduate students of tribology and design; (2) research workers who are active or intend to become active in this field; and (3) practicing engineers who have encountered a tribology problem and hope to solve it as expeditiously as possible. The book should serve as an excellent text for one or two semester graduate courses in tribology as well as for a senior level undergraduate course of mechanical engineering, materials science or applied physics. For a first or one semester course on introduction to tribology and industrial applications the following sections may be included: Chapter 1, 3.1, 3.2, 3.3, 3.4.1, 3.4.2.4, 3.4.2.6, 3.4.3.2, 3.4.7, 3.4.8, 3.5, 4.1, 4.2.1, 4.2.3, 4.3.1.2, 4.3.3, 4.4, 5.1, 5.2, 5.4, 6.1, 6.2.1 to 6.2.6, 6.3, condensed 6.4, 6.5, 7.1, 7.2.1, 7.2.3, 7.3.1, 7.4, 8.1, 8.2, 8.3, condensed 8.4, 8.5, 9.1, 9.2, 9.3.1, 9.3.2.5, 9.5.2, 9.6.1, 9.6.2, 9.6.3, 9.7, 10.1, 10.2, 10.5, 11.1, 11.3, 11.5, 12.2, 12.3.1, 12.4, and 14.2. For a second semester course on materials, friction and wear of materials, and industrial applications, the following sections may be included: Chapter 2, short reviews of the following sections: 3.3, 3.4.1, 3.4.2.6, 3.4.3.2, 4.2.3.1, 4.2.3.2, 4.2.3.4, 4.3.1.2 and 6.2, 6.4, 6.5, short reviews of 8.2 and 8.3, 8.4, 8.5, 8.A, 8.B, 8.C, 9.1, 9.2, Chapter 10, Chapter 12, Chapter 13, and Chapter 14.

I wish to thank all of my former and present colleagues and students who have contributed to my learning of tribology. I was introduced to the field of tribology via a graduate course in Tribology in Fall 1970 by Profs. Brandon G. Rightmyer and Ernest Rabinowicz at Massachusetts Institute of Technology. I learnt a great deal from Prof. Nathan H. Cook, my M.S. thesis supervisor. My real learning started at R& D Division of Mechanical Technology Inc., Latham, New York, under the guidance of Dr. Donald F. Wilcock, Dr. Jed A. Walowit and Mr. Stanley Gray, and at Technology Services Division of SKF Industries Inc., King of Prussia, Pennsylvania, under the guidance of Dr. Tibor Tallian. I benefited immensely from the help of many colleagues at the General Products Division of IBM Corporation, Tucson, Arizona, and at the Almaden Research Center of IBM Corporate Research Division, San Jose, California. Dr. Kailash C. Joshi helped me in establishing myself at IBM Tucson and Dr. Barry H. Schechtman mentored me at IBM Almaden, San Jose, and helped me immensely. Prof. Bernard H. Hamrock at The Ohio State University has provided nice companionship. Since 1991, I have presented many graduate and undergraduate tribology courses at The Ohio

State University as well as many on-site short tribology courses in the U.S. and overseas. The book is based on the class notes used for various courses taught by me.

My special thanks go to my wife Sudha, my son Ankur and my daughter Noopur, who have been very forebearing during the years when I spent long days and nights in conducting the research and keeping up with the literature and preparation of this book. They provided the lubrication necessary to minimize friction and wear at home. Kathy Tucker patiently typed and retyped the manuscript for this book.

Professor Bharat Bhushan
Powell, Ohio
June, 1998

1

Introduction

In this introductory chapter, the definition and history of tribology and their industrial significance are described, followed by the origins and significance of an emerging field of micro/nanotribology. The last section presents the organization of the book.

1.1 Definition and History of Tribology

The word tribology was first reported in a landmark report by Jost (1966). The word is derived from the Greek word *tribos*, meaning rubbing, so the literal translation would be "the science of rubbing." Its popular English language equivalent is friction and wear or lubrication science, alternatively used. The latter term is hardly all-inclusive. Dictionaries define tribology as the science and technology of interacting surfaces in relative motion and of related subjects and practices. Tribology is the art of applying operational analysis to problems of great economic significance, namely, reliability, maintenance, and wear of technical equipment, ranging from spacecraft to household appliances. Surface interactions in a tribological interface are highly complex, and their understanding requires knowledge of various disciplines, including physics, chemistry, applied mathematics, solid mechanics, fluid mechanics, thermodynamics, heat transfer, materials science, rheology, lubrication, machine design, performance, and reliability.

It is only the name tribology that is relatively new, because interest in the constituent parts of tribology is older than recorded history (Dowson, 1998). It is known that drills made during the Paleolithic period for drilling holes or producing fire were fitted with bearings made from antlers or bones, and potters' wheels or stones for grinding cereals, etc., clearly had a requirement for some form of bearings (Davidson, 1957). A ball thrust bearing dated about AD 40 was found in Lake Nimi near Rome.

Records show the use of wheels from 3500 BC, which illustrates our ancestors' concern with reducing friction in translationary motion. Figure 1.1.1 shows a two-wheeled harvest cart with studded wheels, circa 1338 AD. The transportation of large stone building blocks and monuments required the know-how of frictional devices and lubricants, such as water-lubricated sleds. Figure 1.1.2 illustrates the use of a sledge to transport a heavy statue by the

Principles and Applications of Tribology, Second Edition. Bharat Bhushan.

Figure 1.1.1 Drawing of two-wheeled harvest cart with studded wheels. Luttrell Psalter (folio 173v), circa 1338 AD.

Egyptians, circa 1880 BC (Layard, 1853). In this transportation, 172 slaves are being used to drag a large statue weighing about 600 kN along a wooden track. One man, standing on the sledge supporting the statue, is seen pouring a liquid (most likely water) into the path of motion; perhaps he was one of the earliest lubrication engineers. Dowson (1998) has estimated that each man exerted a pull of about 800 N. On this basis, the total effort, which must at least equal the friction force, becomes 172×800 N. Thus, the coefficient of friction is about 0.23. A tomb in Egypt that was dated as from several thousand years BC provides the evidence of use of lubricants. A chariot in this tomb still contained some of the original animal-fat lubricant in its wheel bearings.

During and after the Roman Empire, military engineers rose to prominence by devising both war machinery and methods of fortification, using tribological principles. It was the Renaissance engineer–artist Leonardo da Vinci (1452–1519), celebrated in his day for his genius in military construction as well as for his painting and sculpture, who first postulated a

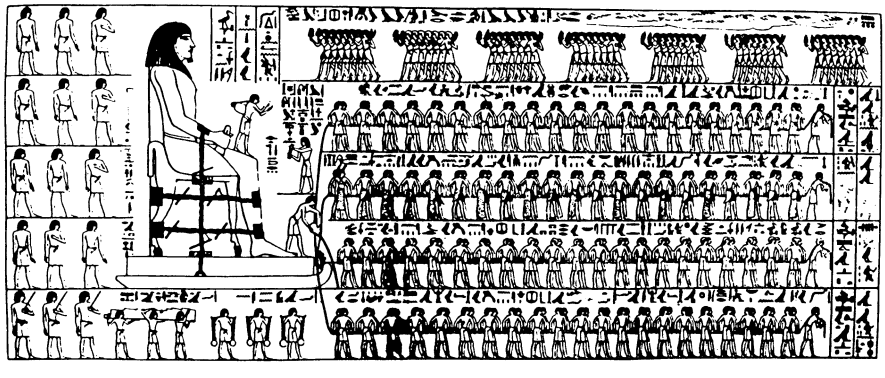

Figure 1.1.2 Egyptians using lubricant to aid movement of a colossus, El-Bersheh, circa 1880 BC.