INTRODUCTION TO TRIBOLOGY

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INTRODUCTION TO TRIBOLOGY

SECOND EDITION

Bharat Bhushan

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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 Honouris 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 of bio/nanotribology and bio/nanomechanics using scanning probe microscopy, and is one of the most prolific authors. 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 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, 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), 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 professorship 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 enunciated in 1966 in a report of 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 GNPs, 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 the knowledge and experience gained by him 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

This Second Edition of the successful *Introduction to Tribology* published in 1999 promises to deliver much more than its earlier version. Over the last 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 for improving the quality of life. To fulfill these demands, new technologies have emerged. Much has changed in many areas of science over the last decade and the tribology is not an exception. Improved materials and surface treatments were developed, novel 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. There are also concerns about providing enough food and clean water to the human population and issues associated with supplying enough energy to allow people to pursue a civilized life. Tribology makes vital contribution to the resolution of these problems. As is any other field of science, tribology is continuously evolving to stay at the forefront of the emerging technologies.

As tribology is an interdisciplinary area of science, knowledge from chemistry, physics, material science, engineering, computational science, and many others is required to allow for the understanding of the tribological phenomena. This book provides a comprehensive account of the field of tribology and this edition includes the latest developments in the understanding and interpretation of friction, wear, and lubrication. It introduces tribology at the nano- and micro-level, i.e. nanotribology, tribology in MEMS and magnetic surface storage devices. This approach demonstrates to the reader that tribology continuously evolves and adapts and remains relevant to the modern industry. This is a much-welcomed edition to the tribology book series as tribology provides badly needed answers to many problems. The book is recommended for both under- and postgraduate students and engineers.

Gwidon Stachowiak
University of Western Australia

Preface to the Second Edition

Tribology is an important interdisciplinary field. It involves the design of components with static and dynamic contacts for a required performance and reliability. The second edition of the book is thoroughly updated. Notable additions include an updated chapter on nanotribology, introduction to nanotechnology (MEMS/NEMS), and a new chapter on green tribology and biomimetics.

Modern tools and techniques as well as computational modeling have allowed systematic investigations of interfacial phenomena down to atomic scales. These developments have led to the development of the field of nanotribology and nanomechanics. These studies are needed to develop a fundamental 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.

Ecological, or green, tribology is a relatively new field. It is defined as the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts. This includes tribological components and materials and surfaces that mimic nature (biomimetic surfaces) and the control of friction and wear that is important for alternative energy production.

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

A Power Point presentation of the entire book for a semester course is available from the author. A 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 a textbook for a class of a minimum of six students.

Professor Bharat Bhushan
Powell, Ohio
May, 2012

Preface to the 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, the physical and the chemical nature, including 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. An 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, 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 in gaining 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 their authors' own expertise in narrow aspects of tribology. A broad-based textbook is needed. This book is a condensed version of the comprehensive book titled *Principles and Applications of Tribology* published by Wiley first in 1999. The purpose of this book is to present the principles of tribology and the tribological understanding of the 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 30 years. The emphasis is on contemporary knowledge of tribology, and includes the emerging field of micro/nanotribology. The book integrates the knowledge of tribology from mechanical engineering, mechanics, and materials science points of view. The organization of the book is straightforward. The first part of the book starts with the principles of tribology and prepares students to understand the tribology of industrial applications. The principles of tribology follow with the emerging field of micro/nanotribology. The last chapter describes the tribological components and applications.

The book should serve as an excellent text for a one semester graduate course in tribology as well as for a senior level undergraduate course of mechanical engineering, materials science, or applied physics. The book is also intended for use by research workers who are active or intend to become active in this field, and practicing engineers who have encountered a tribology problem and hope to solve it as expeditiously as possible.

A Power Point presentation of the entire book for a semester course is available from the author. A 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 a minimum of six students.

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 from Profs. Brandon G. Rightmyer and Ernest Rabinowicz at Massachusetts Institute of Technology. I learnt a great deal from Prof. Nathan H. Cook, my MS thesis supervisor. My real learning started at the R& D Division of Mechanical Technology Inc., Latham, New York with the guidance from 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 with the guidance from Dr Tibor Tallian. I immensely benefited from many colleagues at General Products Division of IBM Corporation, Tucson, Arizona and at Almaden Research Center of IBM Corporate Research Division, San Jose, California. Dr Kailash C. Joshi helped me in establishing 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 a nice companionship. Since 1991, I have offered many graduate and undergraduate tribology courses at The Ohio State University as well as many on-site short tribology courses in the United States 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 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.

Professor Bharat Bhushan
Powell, Ohio
August, 2001

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. In the last section the organization of the book is presented.

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

Introduction to 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.

by the 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 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 scientific approach to friction. Da Vinci deduced the rules governing the motion of a rectangular

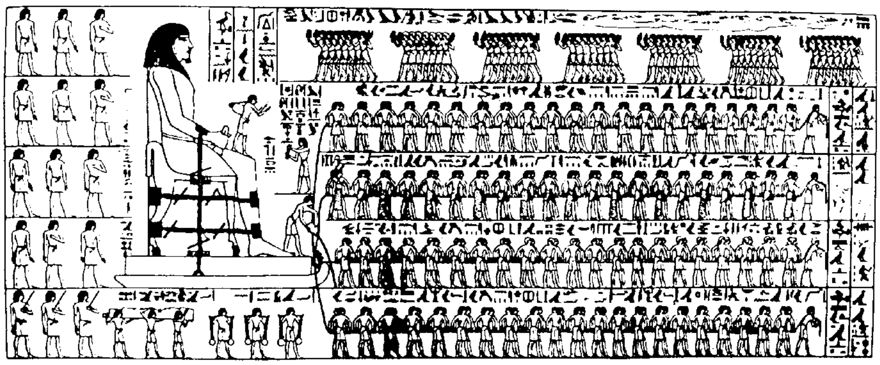

Figure 1.1.2 Egyptians using lubricant to aid movement of colossus, El-Bersheh, circa 1880 BC.

block sliding over a flat surface. He introduced the concept of the coefficient of friction as the ratio of the friction force to normal load. His work had no historical influence, however, because his notebooks remained unpublished for hundreds of years. In 1699, the French physicist Guillaume Amontons rediscovered the rules of friction after he studied dry sliding between two flat surfaces (Amontons, 1699). First the friction force that resists sliding at an interface is directly proportional to the normal load. Second the amount of friction force does not depend on the apparent area of contact. These observations were verified by the French physicist Charles-Augustin Coulomb (better known for his work on electrostatics [Coulomb, 1785]). He added a third law that the friction force is independent of velocity once motion starts. He also made a clear distinction between static friction and kinetic friction.

Many other developments occurred during the 1500s, particularly in the use of improved bearing materials. In 1684, Robert Hooke suggested the combination of steel shafts and bell-metal bushes would be preferable to wood shod with iron for wheel bearings. Further developments were associated with the growth of industrialization in the latter part of the eighteenth century. Early developments in the petroleum industry started in Scotland, Canada, and the United States in the 1850s (Parish, 1935; Dowson, 1998).

Though essential laws of viscous flow were postulated by Sir Isaac Newton in 1668, scientific understanding of lubricated bearing operations did not occur until the end of the nineteenth century. Indeed, the beginning of our understanding of the principle of hydrodynamic lubrication was made possible by the experimental studies of Beauchamp Tower (1884) and the theoretical interpretations of Osborne Reynolds (1886) and related work by N.P. Petroff (1883). Since then, developments in hydrodynamic bearing theory and practice have been extremely rapid in meeting the demand for reliable bearings in new machinery.

Wear is a much younger subject than friction and bearing development, and it was initiated on a largely empirical basis. Scientific studies of wear scarcely developed until the mid-twentieth century. Ragnar Holm made one of the earliest substantial contributions to the study of wear (Holm, 1946).

In the West, the Industrial Revolution (AD 1750–1850) is recognized as the period of rapid and impressive development of the machinery of production. The use of steam power and the subsequent development of the railways in the 1830s, automobiles in the early 1900s and aircraft in the 1940s led to the need for reliable machine components. Since the beginning of the twentieth century, from enormous industrial growth leading to demand for better tribology, knowledge in all areas of tribology has expanded tremendously (Holm, 1946; Bowden and Tabor, 1950, 1964; Bhushan, 1996, 2001a; Bhushan and Gupta, 1997; Nosonovsky and Bhushan, 2012).

1.2 Industrial Significance of Tribology

Tribology is crucial to modern machinery which uses sliding and rolling surfaces. Examples of productive friction are brakes, clutches, driving wheels on trains and automobiles, bolts, and nuts. Examples of productive wear are writing with a pencil, machining, polishing, and shaving. Examples of unproductive friction and wear are internal combustion and aircraft engines, gears, cams, bearings, and seals.

According to some estimates, losses resulting from ignorance of tribology amount in the United States to about 4% of its gross national product (or about $200 billion dollars per year in 1966), and approximately one-third of the world's energy resources in present use appear as friction in one form or another. Thus, the importance of friction reduction and wear control cannot be overemphasized for economic reasons and long-term reliability. According to Jost (1966, 1976), savings of about 1% of gross national product of an industrial nation can be realized by better tribological practices. According to recent studies, expected savings are expected to be of the order of 50 times the research costs. The savings are both substantial and significant, and these savings can be obtained without the deployment of large capital investment.

The purpose of research in tribology is understandably the minimization and elimination of losses resulting from friction and wear at all levels of technology where the rubbing of surfaces is involved. Research in tribology leads to greater plant efficiency, better performance, fewer breakdowns, and significant savings.

Since the 1800s, tribology has been important in numerous industrial applications requiring relative motion, for example, railroads, automobiles, aircraft, and the manufacturing process of machine components. Some of the tribological machine components used in these applications include bearings, seals, gears, and metal cutting (Bhushan, 2001a). Since the 1980s, other applications have included magnetic storage devices, and micro/nanoelectromechanical systems (MEMS/NEMS) as well as biomedical and beauty care products (Bhushan, 1996, 1998, 1999, 2000, 2001a, 2001b, 2010a, 2010b, 2011, 2012b). Since the 2000s, bioinspired structures and materials, some of which are eco-friendly, have been developed and exploited for various applications (Nosonovsky and Bhushan, 2008, 2012; Bhushan, 2012a).

Tribology is not only important to heavy industry, it also affects our day-to-day life. For example, writing is a tribological process. Writing is accomplished by the controlled transfer of lead (pencil) or ink (pen) to the paper. During writing with a pencil there should be good adhesion between the lead and the paper so that a small quantity of lead transfers to the paper and the lead should have adequate toughness/hardness so that it does not fracture/break. The objective when shaving is to remove hair from the body as efficiently as possible with minimum discomfort to the skin. Shaving cream is used as a lubricant to minimize friction between the razor and the skin. Friction is helpful during walking and driving. Without adequate friction, we would slip and a car would skid! Tribology is also important in sports. For example, a low friction between the skis and the ice is desirable during skiing. Fabric fibers should have low friction when touching human skin.

Body joints need to be lubricated for low friction and low wear to avoid osteoarthritis and joint replacement. The surface layer of cartilage present in the joint provides the bearing surface and is lubricated with a joint fluid consisting of lubricin, hyaluronic acid (HA) and lipid. Hair conditioner coats hair in order to repair hair damage and lubricate it. It contains silicone and fatty alcohols. Low friction and adhesion provide a smooth feel in wet and dry environments, reduce friction between hair fibers during shaking and bouncing, and provide easy combing and styling. Skin creams and lotions are used to reduce friction between the fingers and body skin. Saliva and other mucous biofluids lubricate and facilitate the transport of food and soft liquids through the body. The saliva in the mouth interacts with food and influences the taste–mouth feel.

1.3 Origins and Significance of Micro/Nanotribology

At most interfaces of technological relevance, contact occurs at numerous levels of asperity. Consequently, the importance of investigating a single asperity contact in studies of the