

PRINCIPLES AND  
APPLICATIONS OF  
TRIBOLOGY



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# PRINCIPLES AND APPLICATIONS OF TRIBOLOGY

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To my wife Sudha, my son Ankur and my daughter Noopur



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# FOREWORD

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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 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.

Prof. H. Peter Jost

*Angel Lodge Laboratories & Works  
London, UK  
July 1998*

---

# PREFACE

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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 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, 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, has 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 micro-scale. Micro/nanotribological studies are valuable in 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 in tribology. Books to date are generally based on 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 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. The last chapter describes the tribological components and applications.

The book is intended for three types of readers: senior undergraduate and graduate students of tribology and design, 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. 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 material may be included: Chapter 1, Sections 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, 6.2.1–6.2.6, 6.3, condensed Section 6.4, Sections 6.5, 7.1, 7.2.1, 7.2.3, 7.3.1, 7.4, 8.1, 8.2, 8.3, condensed Section 8.4, Sections 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 material may be included: Chapter 2, short reviews of 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, Sections 6.4, 6.5, short reviews

of Sections 8.2 and 8.3, Sections 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 from Profs. Brandon G. Rightmyer and Ernest Rabinowicz at Massachusetts Institute of Technology. I learnt a lot from Prof. Nathan H. Cook, my MS thesis supervisor. My real learning started at 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 J. 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 US 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. Kathy Tucker patiently typed and retyped the manuscript for this book.

Bharat Bhushan

*Powell, Ohio  
June 1998*



## INTRODUCTION

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In this introductory chapter, the definition and history of tribology and their industrial significance are described, followed by origins and significance of an emerging field of micro/nanotribology. In the last section, 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 translational motion. The transportation of large stone building blocks and monuments required the know-how of frictional devices and lubricants, such as water-lubricated sleds. Figure 1.1.1 illustrates the use of a sledge to transport a heavy statue by 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 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  $172 \times 800$  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 glory of 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 days 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 laws governing the motion of a rectangular block sliding over a flat surface. He introduced, for the first time, the concept of 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 laws of friction after he studied dry sliding between two flat surfaces (Amontons, 1699). First, the friction force

**Fig. 1.1.1** Egyptians using lubricant to aid movement of colossus, El-Bersheh, Circa 1880 BC.

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 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 as 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 were 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 developed little until the mid-twentieth century. Ragnar Holm made one of the earliest substantial contributions to the study of wear (Holm, 1946).

The industrial revolution (1750–1850 AD) is recognized as a 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 led to promotion of manufacturing skills. 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, 1992, 1996; Bhushan and Gupta, 1997).

## 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 6% 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), the United Kingdom could save approximately 500 million pounds per annum, and the United States could save in excess of 16 billion dollars per annum by better tribological practices. 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.

### **1.3 ORIGINS AND SIGNIFICANCE OF MICRO/NANOTRIBOLOGY**

At most interfaces of technological relevance, contact occurs at numerous asperities. Consequently, the importance of investigating a single asperity contact in studies of the fundamental tribological and mechanical properties of surfaces has been long recognized. The recent emergence and proliferation of proximal probes, in particular tip-based microscopies (the scanning tunneling microscope and the atomic force microscope) 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 nanoscale structures. These advances have led to the development of the new field of microtribology, nanotribology, molecular tribology, or atomic-scale tribology (Bhushan, 1997, 1999; Bhushan et al., 1995). This field is concerned with experimental and theoretical investigations of processes ranging from atomic and molecular scales to microscales, occurring during adhesion, friction, wear, and thin-film lubrication at sliding surfaces.

The differences between the conventional or macrotribology and micro/nanotribology are contrasted in Fig. 1.3.1. In macrotribology, tests are conducted on components with relatively large mass under heavily loaded conditions. In these tests, wear is inevitable and the bulk properties of mating components dominate the tribological performance. In micro/nanotribology, measurements are made on components, at least one of the mating components, with relatively small mass under lightly loaded conditions. In this situation, negligible wear occurs and the surface properties dominate the tribological performance.

**Fig. 1.3.1** Comparisons between macrotribology and micro/nanotribology.

The micro/nanotribological studies are needed to develop fundamental understanding of interfacial phenomena on a small scale and to study interfacial phenomena in micro- and nanostructures used in magnetic storage systems, microelectromechanical systems (MEMS) and other industrial applications. The components used in micro- and nanostructures are very light (on the order of few micrograms) and operate under very light loads (on the order of a few micrograms to a few milligrams). As a result, friction and wear (on a nanoscale) of lightly loaded micro/nanocomponents are highly dependent on the surface interactions (few atomic layers). These structures are generally lubricated with molecularly thin films. Micro- and nanotribological techniques are ideal to study the friction and wear processes of micro- and nanostructures. Although micro/nanotribological studies are critical to study micro- and nanostructures, these studies are also valuable in fundamental understanding of interfacial phenomena in macrostructures to provide a bridge between science and engineering.

The scanning tunneling microscope, the atomic force and friction force microscopes and the surface force apparatus are widely used for micro/nanotribological studies (Bhushan, 1997, 1999; Bhushan et al., 1995). To give a historical perspective of the field, the scanning tunneling microscope (STM) developed by Drs Gerd Binnig and Heinrich Rohrer and their colleagues in 1981 at the IBM Zurich Research Laboratory, Forschungslabor, is the first instrument capable of directly obtaining three-dimensional (3D) images of solid surfaces with atomic resolution (Binnig et al., 1982). STMs can only be used to study surfaces which are electrically conductive to some degree. Based on their design of STM, in 1985, Binnig et al. developed an atomic force microscope (AFM) to measure ultrasmall forces (less than  $1\ \mu\text{N}$ ) present between the AFM tip surface and the sample surface, Binnig et al. (1986, 1987). AFMs can be used for measurement of all engineering surfaces which may be either electrically conducting or insulating. AFM has become a popular surface profiler for topographic measurements on micro- to nanoscale. AFMs modified to measure both normal and friction forces, generally called friction force microscopes (FFMs) or lateral force microscopes (LFMs), are used to

measure friction on micro- and nanoscales. AFMs are also used for studies of adhesion, scratching, wear, lubrication, surface temperatures, and for measurements of elastic/plastic mechanical properties (such as indentation hardness and modulus of elasticity). Surface force apparatuses (SFAs), first developed in 1969, are used to study both static and dynamic properties of the molecularly thin liquid films sandwiched between two molecularly smooth surfaces (Tabor and Winterton, 1969; Bhushan, 1999).

Meanwhile, significant progress in understanding the fundamental nature of bonding and interactions in materials, combined with advances in computer-based modeling and simulation methods, have allowed theoretical studies of complex interfacial phenomena with high resolution in space and time (Bhushan, 1999). Such simulations provide insights into atomic-scale energetics, structure, dynamics, thermodynamics, transport and rheological aspects of tribological processes. Furthermore, these theoretical approaches guide the interpretation of experimental data and the design of new experiments, and enable the prediction of new phenomena based on atomistic principles.

#### **1.4 ORGANIZATION OF THE BOOK**

Friction, wear, and lubrication behavior of interfaces is greatly dependent upon the surface material, shape of mating surfaces and operating environment. A surface film may change the physical and chemical properties of the first few atomic layers of material through interaction with environment. Structure and properties of solids are discussed in Chapter 2 followed by solid surface characterization in Chapter 3. Chapter 3 includes discussion on nature of surfaces, physico-chemical characteristics of solid surfaces, statistical analysis of surface roughness, and methods of characterization of solid surfaces. Chapter 4 is devoted to the elastic and plastic real area of contacts that occur when two solid surfaces are placed in contact. Statistical and numerical analyses and measurement techniques are presented. Chapter 5 covers various adhesion mechanisms in dry and wet conditions. Various analytical and numerical models to predict liquid mediated adhesion are described. When the two surfaces in contact slide or roll against each other friction is encountered; various friction mechanisms, physical and chemical properties that control friction, and typical friction data of materials are discussed in Chapter 6. Chapter 7 is devoted to the interface temperatures generated from the dissipation of the frictional energy input. Analysis and measurement techniques for interface temperatures and the impact of temperature rise on an interface performance are discussed.

Repeated sliding or rolling results in wear. In Chapter 8, various wear mechanisms, types of particles present in wear debris, and representative data for various materials of engineering interest are presented. Chapter 9 reviews various regimes of lubrication, the theories of hydrostatic, hydrodynamic and elastohydrodynamic lubrication and various designs of bearings. In

Chapter 10, mechanisms of boundary lubrication, description of various liquid lubricants and additives and greases are presented. In Chapter 11, various experimental techniques and molecular dynamics computer simulation techniques used for micro/nanotribological studies and state of the art and their applications are described and relevant data are presented. In Chapter 12, design methodology and typical test geometries for friction and wear test methods are described.

In Chapter 13, bulk materials, coatings and surface treatments used for tribological applications are described. Coating deposition and surface treatment techniques are also described. In Chapter 14, descriptions, relevant wear mechanisms and commonly used materials for common tribological components, microcomponents, material processing and industrial applications are presented.

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