INTRODUCTION TO

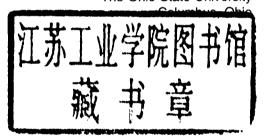
# TRIBOLOGY

BHARAT BHUSHAN

# INTRODUCTION TO TRIBOLOGY

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### **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

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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

President, International Tribology Council Angel Lodge Laboratories & Works London, UK

# **PREFACE**

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, and 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, 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 the 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. This book is a condensed version of the comprehensive book titled Principles and Applications of Tribology, first published by John Wiley in 1999. 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 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 in 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 PowerPoint presentation of the entire book on an IBM-compatible computer for the course offered during a quarter or semester duration is available

from the author. A solution manual is also available from the author. Both the PowerPoint presentation and the solution manual will be shipped to those who are using the book as a textbook for a class with 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 learned a great deal 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 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, with the guidance of Dr Tibor Tallian. I benefited immensely 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 myself 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 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 forbearing 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.

Bharat Bhushan

Powell. Ohio

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## INTRODUCTION

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 translationary 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 (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 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 rules 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

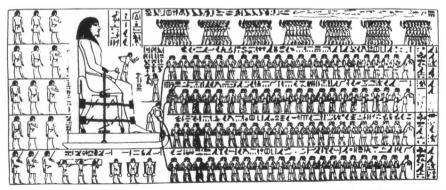


Fig. 1.1.1 Egyptians using lubricant to aid movement of colossus, El-Bersheh, Circa 1880 BC.