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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 translational 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



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

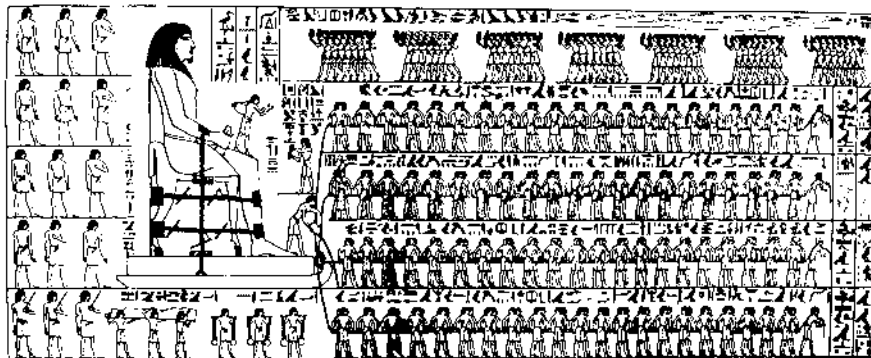


Figure 1.1.2 Egyptians using lubricant to aid movement of a colossus, El-Bersheh, circa 1880 BC.

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 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 (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 appears 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 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, aircrafts, 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). In 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 touched by 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 asperities. Consequently, the importance of investigating a single asperity contact in studies of the fundamental

Macrotribology	Micro/nanotribology
Large Mass Heavy Load	Small Mass (μg) Light Load (μg to mg)
↓ Wear (Inevitable)	↓ No Wear (Few atomic layers)
Bulk Material	Surface (few atomic layers)

Figure 1.3.1 Comparisons between macrotribology and micro/nanotribology.

tribological and mechanical properties of surfaces has long been 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, have allowed systematic investigations of interfacial problems with high resolution as well as ways and means of 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 *et al.*, 1995; Bhushan, 1997, 1999, 2001b, 2010a, 2011). 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 Figure 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.

Micro/nanotribological studies are needed to develop a fundamental understanding of interfacial phenomena on a small scale and to study interfacial phenomena in micro- and nano structures used in magnetic storage systems, micro/nanoelectromechanical systems (MEMS/NEMS) and other industrial applications. The components used in microstructures 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/nano components are highly dependent on the surface interactions (few atomic layers). These structures are generally lubricated with molecularly thin films. Microtribological and nanotribological techniques are ideal ways to study the friction and wear processes of micro- and nanostructures. Although micro/nanotribological studies are critical to study microstructures and nanostructures, these studies are also valuable in the 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 *et al.*, 1995; Bhushan, 1997, 1999). To give a historical perspective of the field, the scanning tunneling microscope (STM) developed by Doctors Gerd Binnig and Heinrich Rohrer and their

colleagues in 1981 at the IBM Zurich Research Laboratory, the 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 the STM, in 1985, Binnig *et al.* (1986, 1987) developed an atomic force microscope (AFM) to measure ultras-small forces (less than 1 μN) present between the AFM tip surface and the sample surface. AFMs can be used in the measurement of all engineering surfaces which may be either electrically conducting or insulating. AFM has become a popular surface profiler for topographic measurements on the microscale 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 the microscale and nanoscale. AFMs are also used for the studies of adhesion, scratching, wear, lubrication, surface temperatures, and for the measurement 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, 2001b, 2011). Such simulations provide insights into the 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

The friction, wear and the lubrication behavior of interfaces are very dependent upon the surface material, the shape of mating surfaces and the operating environment. A surface film may change the physical and chemical properties of the first few atomic layers of material through interaction with the environment. The structure and properties of solids are discussed in Chapter 2, followed by solid surface characterization in Chapter 3. Chapter 3 includes a discussion of the nature of surfaces, the physico-chemical characteristics of solid surfaces, the statistical analysis of surface roughness, and the 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, thus, various friction mechanisms, the physical and chemical properties that control friction, and the 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 the 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 the various regimes of lubrication, the theories of hydrostatic, hydrodynamic and elasto-hydrodynamic lubrication and various designs of bearings. In Chapter 10, mechanisms of boundary lubrication, the 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 the state of the art and their applications are described and relevant data are presented. In Chapter 12, the 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 standard tribological components, microcomponents, material processing and industrial applications are presented. In Chapter 15, the fields of green tribology and biomimetics are introduced and various examples in each field are presented.

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