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Solid Lubrication Fundamentals and Applications

Introduction and Background

Kazuhisa Miyoshi
Lewis Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Lewis Research Center

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Chapter 1
Introduction and Background

1.1 Definition and Scope of Tribology

Tribology is defined as "the science and technology of interacting surfaces in relative motion, and of associated subjects and practices" [1.1]. This term was introduced and defined in a report by a group set up by the British Department of Education and Science [1.2]. Tribology, having its origin in the Greek word "τριβος," meaning rubbing or attrition, deals with force transference between surfaces moving relative to each other. This discipline includes such subjects as lubrication, adhesion, friction, and wear of engineering surfaces with a view to understanding surface interactions in detail (Fig. 1.1) and then prescribes improvements in given applications.

The technical function of numerous engineering systems, such as machines, instruments, and vehicles, depends on processes of motion. According to its basic physical definition the term "motion" denotes the change in the position of an object with time. Many processes in nature and technology depend on the motion and the dynamic behavior of solids, liquids, and gases (Table 1.1 and [1.3, 1.4]). For example, bearings and gears permit smooth, low-friction rotary or linear movement between two surfaces (Fig. 1.2). Bearings employ either sliding or rolling action and gears have both sliding and rolling action. In these cases a strong attempt is made to provide enough lubrication to keep the bearing and gear teeth surfaces separated by a film of solid lubricant, oil, or other lubricant such as grease. The absence of physical contact provides most bearings and gears with long service lives.

Tribology is a discipline that traditionally belongs to mechanical engineering. However, with the recent push toward higher speeds, loads, and operating temperatures, longer term life, lighter weight and smaller size, and harsh environments in mechanical, mechatronic, and biomechanical systems, the field of tribology is becoming more and more interdisciplinary, embracing physics, chemistry, metallurgy, biology, and engineering.

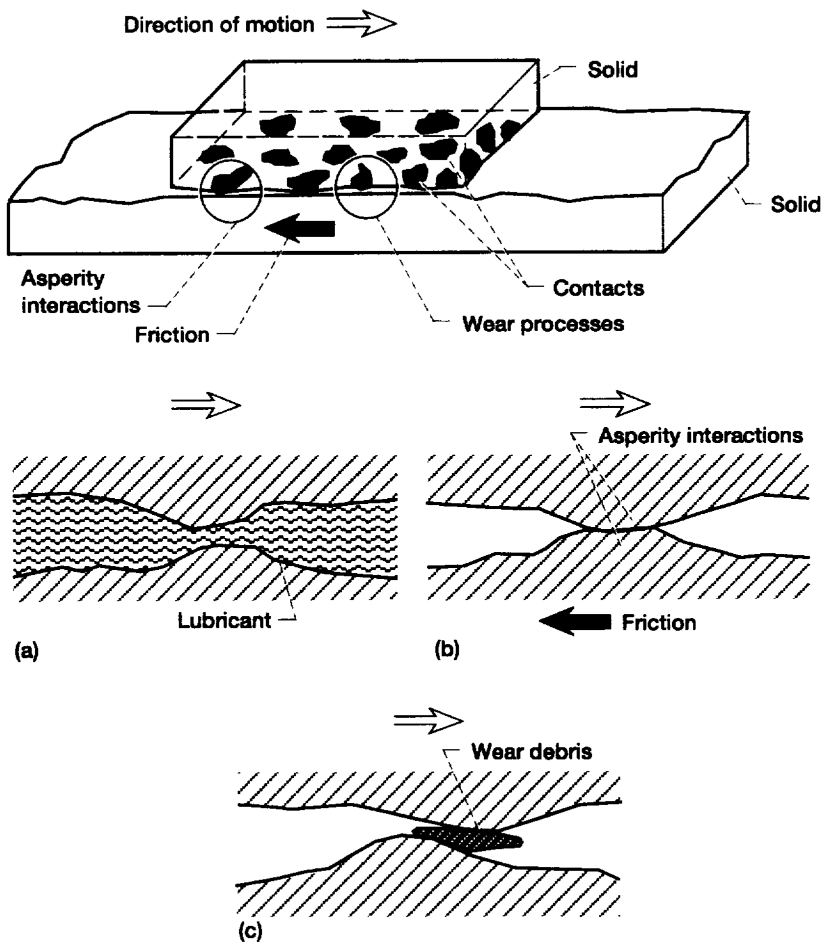


Figure 1.1.—Definition of tribology. (a) Lubrication. (b) Adhesive bonding. (c) Wear.

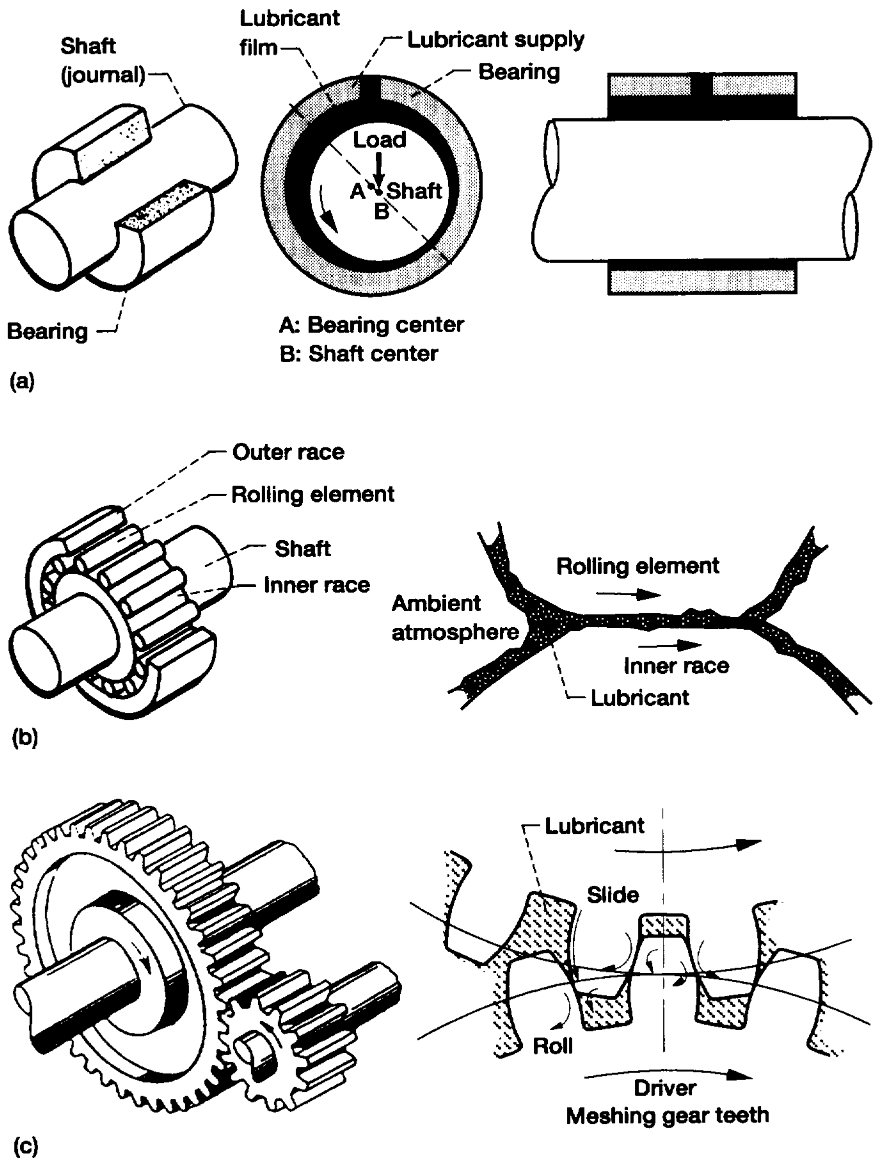
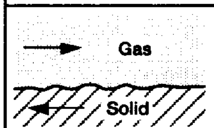
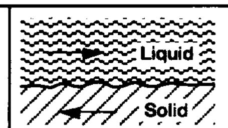
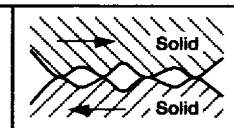


Figure 1.2.—Plain bearings, rolling-element bearings, and gears. (a) Plain bearings based on sliding action. (b) Rolling-element bearings based on rolling action. (c) Gears based on rolling and sliding action.

TABLE 1.1.—TYPES OF SURFACE MOTION AND RELATED SUBJECTS

Related subject	Schematic representation of contact and motion		
			
Lubrication	Gas or air film	Fluid film	Solid film
Resistance to motion	Gas or air friction	Viscous friction	Solid friction
Damage mechanism	Erosion; corrosion	Cavitation erosion; corrosion	Wear; erosion
Technical systems	Gas turbine; wind turbine	Hydraulic turbine	Seals; clutches; brakes; wheel and rail; tires

1.2 Social and Economic Impact of Tribology

The subject of tribology is identified as one of great importance; yet largely because of its multidisciplinary nature, it has received insufficient attention. As a direct result mechanical engineering design is retarded, and many tens of billions of dollars have unnecessarily been lost each year through friction, wear, related breakdowns, wasted energy, etc. These costs are the direct costs of friction and wear. Consideration must also be given to the indirect costs, such as loss of production, product liabilities, failure to accomplish a significant mission, or standby maintenance costs.

Table 1.2 presents some classical estimates of economic losses due to tribology and savings through tribology. The final report of the National Commission on Materials Policy to the Congress of the United States (as reported by Ballard in 1974) stated that "material losses due to tribology (friction and wear) cost the U.S. economy \$100 billion per year, with a material component of this loss of about \$20 billion. At that time Rabinowicz also estimated the total U.S. cost of wear to be \$100 billion per year [1.5]. In 1978 the National Bureau of Standards (presently, the National Institute of Standards and Technology) estimated \$70 billion for corrosion and \$20 billion for wear [1.6]. Peterson estimated that the wear cost for naval aircraft and ships per year is approximately two-thirds the fuel cost [1.7]. These figures indicate that the cost of tribological losses is large and should be reduced by national efforts.

Jost, of the United Kingdom, suggested that with research efforts it is comparatively easy and inexpensive to save up to 20% of tribological losses. For example, for the United States the calculated savings would have been \$12 billion to \$16 billion per year in 1974 [1.8]. It is not surprising that estimates of financial savings for the United States in 1977 are significantly larger, and range from \$16

TABLE 1.2.—ECONOMIC IMPACTS OF TRIBOLOGY
[Data from Jost [1.2].]

(a) Economic losses in United States due to inadequate tribology

Loss	Cost, $billion
Material[a]	100
Total wear[b]	100
Corrosion[c]	70
Wear[c]	20
Wear per year[d]	(e)

(b) Estimated savings reasonably obtainable by U.S. industry through tribology [1.8]

Reduction in–	Total savings, $billion[f]
Energy consumption through lower friction Manpower Lubricant costs Maintenance and replacement costs Breakdown losses Investment costs due to higher utilization, greater mechanical efficiency, and longer machinery life	12 to 16

[a]National Commission on Materials Policy to U.S. Congress as reported by Ballard, 1974.
[b][1.5].
[c][1.6].
[d][1.4].
[e]2/3 of fuel cost.
[f]1974 dollars.

billion to more than $40 billion per year [1.9, 1.10]. It is now believed that proper attention to tribology, especially in education, research, and application, could lead to economic savings of between 1.3 and 1.6% of the gross national product (GNP) [1.8]. Thus, tribology impacts strongly on the national economy and on the lifestyles of most people. Wear contributes to short product lives and friction contributes to energy consumption. As material and energy shortages develop, there will be greater demand for longer product lives, increased wear resistance, and reduction in energy consumption through lubrication and accordingly lower friction.

The most effective way to reduce friction and wear is to separate the two sliding surfaces by means of a lubricating film (third body), such as a film of solid lubricant, oil, grease, or gas. Elements of machines, such as bearings (plain, rolling element, slides, guides, and ways), gears, cylinders, flexible couplings, chains, cams and cam followers, and wire ropes, have fitted or formed surfaces that move with respect to each other by sliding, rolling, approaching and receding, or combinations of these motions. Therefore, these elements are lubricated to prevent or reduce the actual contact between surfaces. Moving surfaces of machine elements are lubricated by interposing and maintaining films that minimize actual contact between the surfaces and that shear easily so that the frictional force opposing surface motion is low. If actual contact between surfaces occurs, high frictional forces leading to high temperatures and wear will result.

Without lubrication most machines would run for only a short time. With inadequate lubrication excessive wear is usually the most serious consequence, since a point will be reached, usually after a short period of operation, when the machine elements cannot function and the machine must be taken out of service and repaired. Repair costs (material and labor) may be high, but lost production or lost machine availability may be by far the greatest cost. With inadequate lubrication, even before elements fail, frictional forces between surfaces may be so great that drive motors will be overloaded or frictional power losses will be excessive. Finally, with inadequate lubrication machines will not run smoothly and quietly.

1.3 Historical Perspective of Tribology and Solid Lubricants

Historical factors have influenced the development of tribology, in particular solid lubricants. This brief perspective will help the reader understand the present state of the science and technology in this field. A detailed history of tribology, including lubricants and lubrication, can be found in the literature (e.g., [1.11, 1.12]).

We live in a solid world. The earth itself is solid; the stones and sands on its surface are solid; people and their tools and their machines are solid. These solids are in contact with each other. Whenever two solids touch each other so that forces of action and reaction are brought into play, the solids may be said to undergo a surface interaction [1.13]. Naturally, the history of tribology spans a period similar to that of recorded history. Important tribological developments occurred in prehistoric and early historic times.

The first civilization recorded in the history of humanity developed in the fourth millennium B.C., probably about 3500 B.C., in a territory known as Sumer adjacent to the Persian Gulf at the southern end of Mesopotamia (see the earlier chapters of [1.11]. Somewhat later, Egyptian civilization flourished. Five recorded accomplishments of the Sumerian and Egyptian civilizations (3500 B.C. to 30 B.C.) are of great tribological significance:

1. Drills employing alternating rotary motion and simple bearings were developed for making fire and drilling holes.
2. The potter's wheel, employing simple pivot bearings made from wood or stone, was produced to facilitate the throwing of clay at relatively high rotational speeds.
3. The wheeled vehicle appeared.
4. Heavy stone statues and building blocks were transported on sledges.
5. Lubricants were used in a number of applications involving rotation and translation.

Lubricants were mainly of vegetable or animal origin. A most interesting story related to the early use of lubricants comes from the building of the pyramids in the third millennium B.C. Hydrated calcium sulphate (gypsum) was used to form the thin bed of viscid mortar. The mortar acted as a lubricant to facilitate accurate setting of the huge blocks of stone. Clearly, tribology and the use of lubricants date back to the first recorded civilization. Since this early beginning lubrication and the production of lubricating media have grown to be one of the largest industries in the world, yet from one-third to one-half of all the energy produced still is lost through friction.

Although the slippery feel and appearance of graphite has been known for centuries, its use as a solid lubricant probably dates back to the Middle Ages. Graphite is also known as black lead and plumbago. It was long confused with similar-appearing minerals, particularly molybdenite, and was not classified as a separate mineral until 1556. In 1779 it was proved to be carbon when it was oxidized to carbon dioxide. About 1564 the Borrowdale graphite mines in England began producing graphite for pencils. These early pencils were made by encasing slabs of cut graphite in slotted wooden dowels. The name "graphite" did not come into being until 1789, when Werner drew it from the Greek word "graphein," which means to write. The ore molybdenite was known to the early Greeks. It has often been confused with graphite and with lead. The name is derived from the Greek word meaning lead.

Traditional animal and vegetable sources satisfied the ever-increasing demand for lubricants throughout the Industrial Revolution. Table 1.3 lists a selection of the lubricants most commonly employed during the Industrial Revolution.

It is commonly thought that solid lubricants are a relatively recent phenomenon, but their use in the lubrication of heavy, slow-moving machinery was well established during the Industrial Revolution. One of the first patents, issued in 1812, describes the use of graphite, pork lard, beef suet, mutton suet, tallow, oil, goose grease, or any kind of grease or greasy substance as lubricants. Also, instructions were given on the methods of application and amounts of the composition to be used in bearings, steam-engine piston rods, and the stone spindles of

TABLE 1.3.—LUBRICANTS OF INDUSTRIAL REVOLUTION AND THEIR APPLICATIONS

(a) Liquid lubricants

Lubricant	Application
Animal:	
Sperm oil	Lightly loaded spindles and general machinery as an excellent lubricant
Whale oil	Rare use as a lubricant
Fish oils	Little or occasional use in machinery
Lard oil	Wide use as an excellent lubricant
Neat's-foot oil	Low-temperature applications
Tallow oil	Some use as a good lubricant
Vegetable:	
Olive oil	By far the most common vegetable oil; heavy duty; fully equal to sperm oil
Rape-seed oil	Wide application
Palm oil	Limited use as a lubricant; a constitutent of a special lubricant formulation
Coconut oil	Limited application
Ground-nut oil	Similar application to olive oil
Castor oil	Use in severely loaded machinery
Mineral oil[a]	Quite small; insignificant

(b) Solid (dry) lubricants

Graphite, or plumbago	Use in heavy, slow-moving machinery
Soapstone, or talc	Lightly loaded machinery; silk looms
Molybdenum disulfide	Rotating axles

[a]By distillation or other forms or refining from crude oil, shale, coal, or wells.

mills. The first extensive technical investigation was by Rennie, who, in 1829, measured coefficients of friction with various solid materials as lubricants. In the 1800's a variety of solid lubricants were used in metal-working applications.

Molybdenum is widely distributed over the Earth's crust in the form of molybdenite. The largest commercial source of the mineral is in Climax, Colorado, where it is mined from granite containing the ore in a finely divided state. Molybdenum disulfide (MoS_2) has a metallic luster and is blue-gray to black. Early pioneers traveling through the Climax area used pulverized rock to lubricate the wheels on their Conestoga wagons. This probably was one of the first uses of MoS_2 as a solid lubricant in the United States.

The selection of liquid lubricants changed dramatically in the mid-nineteenth century when the first oil well was drilled in Titusville, Pennsylvania, in 1859. Mineral oils, which had previously been available only in relatively small volumes by distillation from shale, emerged in large quantities from flowing and pumping wells to form the major source of lubricants. The 1850's witnessed a far-reaching transition in the origin of lubricants and the start of a petroleum industry that was to support and be vital to industrial expansion in the nineteenth and twentieth centuries. The technology of lubrication advanced rapidly.

During the mid-1930's petroleum oils were improved through the use of additives, which increased their load-carrying ability, lubricating properties, corrosive protection, and thermal oxidation stability. A trend also developed that required moving parts to operate at higher and higher temperatures. Because petroleum oils could not adequately do the job at these high temperatures, synthetic lubricant materials were introduced. Temperatures now encountered in supersonic aircraft, spacecraft, and certain industrial applications are beyond the useful range of even the synthetic lubricants. This trend to the operation of bearing surfaces at higher temperatures and low pressures has led to the development and use of solid lubricants to attain the necessary lubrication. Solid lubricants have at least one very desirable feature—they do not evaporate under the aforementioned conditions.

A solid lubricant can generally be defined as a material that provides lubrication, under essentially dry conditions, to two surfaces moving relative to each other. The most common dry solid lubricants are graphite, MoS_2, tungsten disulfide (WS_2), and polytetrafluorethylene. The use of bonded, solid lubricant materials is relatively new. The first U.S. patent for a bonded material (phosphoric-acid-bonded graphite film) was issued in the mid-1940's. Several hundred patents for solid lubricating materials and binders have been issued so far. The use of molybdenum disulfide as a lubricating solid also began in the 1940's, and MoS_2 is now used in more applications than any other lubricating solid.

On April 6, 1938, Plunkett was investigating the results of a failed experiment involving refrigeration gases when he found a white, waxy substance. The material, polytetrafluoroethylene (PTFE), commonly known as Teflon, has proved inert to virtually all chemicals. It also is one of the most slippery dry materials known.

The study and application of solid lubricants, as they are now known, is a relatively new field. No systematic study of these materials was begun until long after they were introduced in the aircraft industry. In the 1950's, with the development of the jet engine, a number of research laboratories began a systematic study of solid lubrication for high temperatures. Most of the work was directed toward defining the required characteristics of solid lubricants. In the 1960's space lubrication needs prompted increased research into solid lubrication with emphasis on the role of atmosphere. Ways of using solid lubricants were explored. By the early 1970's, when many of the problems had been resolved and their limitations defined, most of the research stopped.

Recently, however, a number of new applications have arisen that have prompted renewed interest. These applications are piston rings for low-heat-rejection engines, lubricating cages for advanced gas turbines, gears and bearings for long-term service in space mechanisms, cages for turbopump bearings operating in liquid hydrogen and oxygen, lightweight gear and bearing systems, and low-cost bearing systems for automobiles and industrial machinery. The new requirements are primarily long-term life and broad-temperature-range capability. New solid lubricants are needed that meet these requirements.

Lastly, although the importance of friction and resistance to motion has no doubt been recognized throughout the ages, a full appreciation of the significance of tribology in a technological society is a recent phenomenon.

1.4 Description of Solid and Liquid Lubrication

Lubricating films are classified as three types: solid films, fluid films, and thin films (Table 1.4). They are described briefly here, but more details can be found in the literature (e.g., [1.14–1.16]).

1.4.1 Solid Films

A solid lubricant is defined as "any material used as a thin film or a powder on a surface to provide protection from damage during relative movement and to reduce friction and wear." Solid lubrication is achieved by self-lubricating solids or by imposing a solid material having low shear strength and high wear resistance between the interacting surfaces in relative motion. The solid material may be a dispersion in oils and greases, a loose powder, or a coating.

Solid lubricants are used when liquid lubricants do not meet the advanced requirements of modern technology. They are less expensive than oil and grease lubrication systems for many applications. Solid lubricants also reduce weight, simplify lubrication, and improve materials and processes. Figure 1.3 and Table 1.5 [1.17, 1.18] list applications needed to meet critical operating conditions for which fluid lubricants are ineffective or undesirable. Changes in critical evironmental conditions, such as pressure, temperature, and radiation, affect lubricant efficiency. Further, in the cost-conscious automotive industry, solid lubricants are replacing oils and greases in many applications and helping to make highly efficient automobiles possible.

Oils or greases cannot be used in many applications because of the difficulty in applying them, sealing problems, weight, or other factors, such as environmental conditions. Solid lubricants may be preferred to liquid or gas films for several reasons. In high-vacuum environments, in space-vacuum environments, or in food-processing machines, a liquid lubricant would evaporate and contaminate the product, such as optical and electronic equipment or food. At high temperatures liquid lubricants decompose or oxidize; suitable solid lubricants can extend the operating temperatures of sliding systems beyond 250 or 300 °C while maintaining relatively low coefficients of friction. At cryogenic temperatures liquid lubricants are highly viscous and are not effective. Under radiation or corrosive environments liquid lubricants decompose or will be contaminated.

TABLE 1.4.—LUBRICATING FILMS

(a) Types

Type	Lubricating films
Solid films	Lamellar film (MoS_2; graphite) Nonmetallic film (titanium dioxide, calcium fluoride, glasses, lead oxide, zinc oxide, and tin oxide) Soft metallic film (lead, gold, silver, indium, and zinc) Lamellar carbon compound film (graphite; graphite fluoride) Diamond and diamondlike carbon (diamond; i-carbon; a-carbon: hydrogen; carbon nitride; boron nitride Fats, soap, wax (stearic acid) Polymers (PTFE, nylon, polyethylene)
Fluid films	Hydrodynamic film: Thick hydrodynamic film Elastohydrodynamic film Hydrostatic film Squeeze film
Thin films	Mixed lubricating film Boundary lubricating film

(b) Terms and definitions

Term	Definition
Solid film	Solid films are more or less permanently bonded onto the moving surfaces.
Fluid film	Fluid films are thick enough that during normal operation they completely separate surfaces moving relative to each other.
•Hydrodynamic film	Hydrodynamic films are formed by motion of lubricated surfaces through a convergent zone such that sufficient pressure is developed in the film to maintain separation of the surfaces.
•Hydrostatic film	Hydrostatic films are formed by pumping fluid under pressure between surfaces that may or may not be moving with respect to each other.
•Squeeze film	Squeeze films are formed by movement of lubricated surfaces toward each other.
Thin film	Thin films are not thick enough to maintain complete separation of the surfaces all the time.

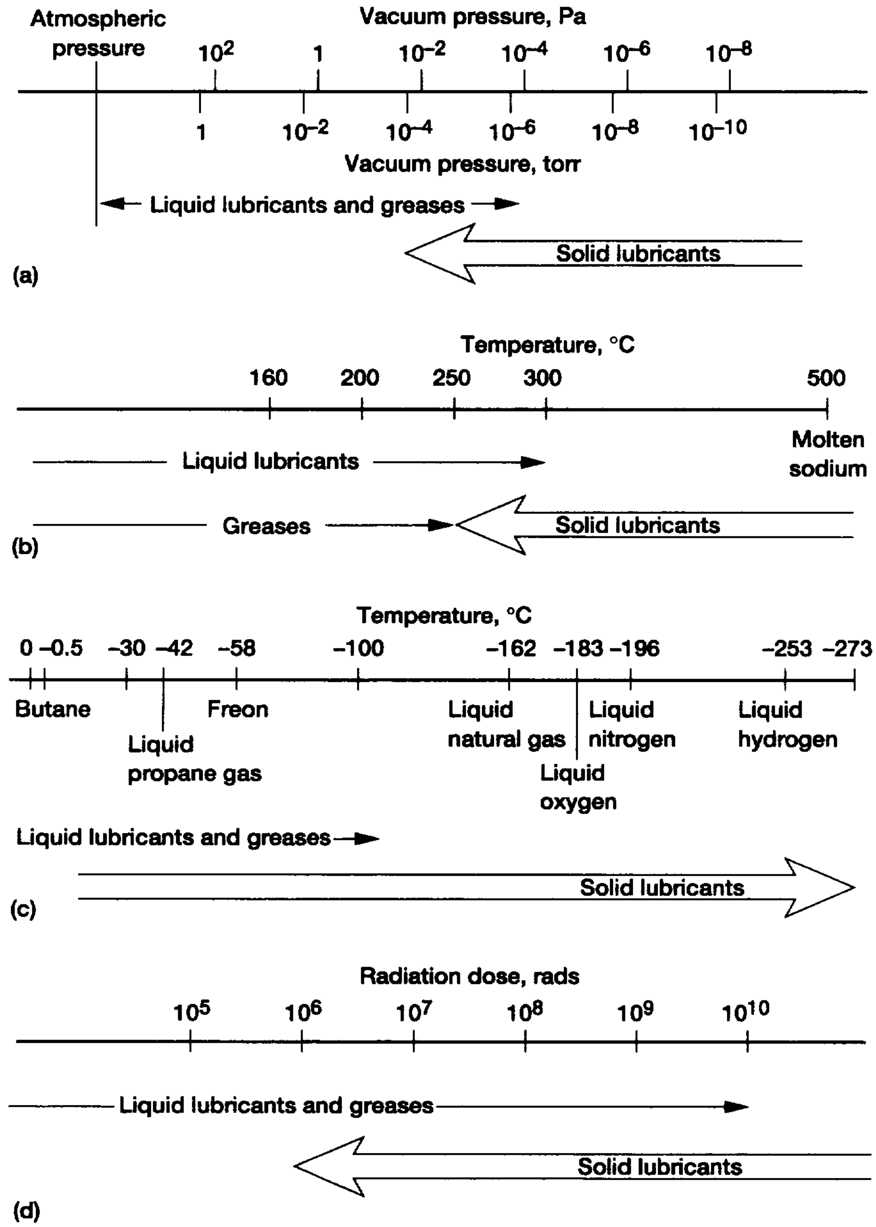


Figure 1.3.—Ranges of application of solid lubricants in (a) high vacuum, (b) high temperature, (c) cryogenic temperature, and (d) radiation environments.

TABLE 1.5.—APPLICATION OF SOLID LUBRICANTS

(a) Areas where fluid lubricants are undesirable

Requirement	Applications
Avoid contaminating product or environment	Food-processing machines Optical equipment Space telescopes Metal-working equipment Surface-mount equipment Tape recorders Microscopes and cameras Textile equipment Paper-processing machines Business machines Automobiles Medical and dental equipment Spectroscopes
Maintain servicing or lubrication in inaccessible or unlikely areas	Aircraft Space vehicles Satellites Aerospace mechanisms Nuclear reactors Consumer durables
Resist abrasion in dirt-laden environments	Aircraft Space vehicles (rovers) Automobiles Agricultural and mining equipment Off-road vehicles and equipment Construction equipment Textile equipment
Provide prolonged storage or stationary service	Aircraft equipment Railway equipment Missile components Nuclear reactors Telescope mounts Heavy plants, buildings, and bridges Furnaces

Further, in the weight-conscious aerospace industry, solid lubricants lead to substantial weight savings relative to the use of liquid lubricants. The elimination (or limited use) of liquid lubricants and their replacement by solid lubricants affect aircraft or spacecraft weight and therefore have a dramatic impact on mission extent and craft maneuverability. Under high vacuums, high temperatures, cryogenic temperatures, radiation, or space or corrosive environments, solid lubrication may be the only feasible system.

TABLE 1.5.—Continued

(b) Areas where fluid lubricants are ineffective

Environment		Applications
High vacuum	Room temperature or cryogenic temperatures	Vacuum products Space mechanisms Satellites Space telescope mounts Space platforms Space antennae
	Clean room	Semiconductor manufacturing equipment
	High temperature	X-ray tubes X-ray equipment Furnaces
High temperatures	Air atmosphere	Furnaces Metal-working equipment Compressors
	Molten metals (sodium, zinc, etc.)	Nuclear reactors Molten metal plating equipment
Cryogenic temperatures		Space mechanisms Satellites Space vehicles Space propulsion systems Space telescope mounts Space platforms Space antennae Turbopumps Liquid nitrogen pumps Butane pumps Freon pumps Liquid natural gas pumps Liquid propane pumps Refrigeration plants

Numerous solid lubricants, such as permanently bonded lubricating films, have been developed to reduce friction and wear in applications of this type where fluid lubricants are ineffective and undesirable. The simplest kind of solid lubricating film is formed when a low-friction solid lubricant, such as MoS_2, is suspended in a carrier and applied to the surface like a normal lubricant. The carrier may be a volatile solvent, a grease, or any of several other types of material. After the carrier is squeezed out or evaporates from the surfaces, a layer of MoS_2 provides lubrication.

TABLE 1.5.—Concluded.

(b) Areas where fluid lubricants are ineffective

Radiation (gamma rays, fast neutrons, x rays, beta rays, etc.)	Nuclear reactors Space mechanisms Satellites Space vehicles Space platforms Space antennae
Corrosive gases (chlorine, etc.)	Semiconductor manufacturing equipment
High pressures or loads	Metal-working equipment Bridge supports Plant supports Building supports
Fretting corrosion (general)	Aircraft engines Turbines Landing gear Automobiles

Solid lubricants are also bonded to rubbing surfaces with various types of resin, which cure to form strongly adhering coatings with good frictional properties. In some plastic bearings the solid lubricant is sometimes incorporated into the plastic. During operation some of the solid lubricant may be transferred to form a lubricating coating on the mating surface.

In addition to MoS_2, PTFE, polyethylene, and a number of other materials are used to form solid films. Sometimes, combinations of several materials, each contributing specific properties to the film, are used.

Because of recent innovations in the physical and chemical vapor deposition processes, solid lubricating materials, such as MoS_2, WS_2, diamond, and PTFE films, are grown economically on ceramics, polymers, and metals and used as solid lubricating films.

1.4.2 Fluid Films

Fluid film lubrication is the most desirable form of lubrication, since during normal operation the films are thick enough to completely separate the load-carrying surfaces. Thus, friction is at a practical minimum, being due only to shearing of the liquid lubricant films; and wear does not occur, since there is essentially no mechanical contact. Fluid films are formed in three ways: hydrodynamically, hydrostatically, and by squeezing (Table 1.4(b)).

Hydrodynamic films.—The most effective way to separate two sliding surfaces by means of a fluid and to reduce friction and wear is known as hydrodynamic lubrication. It provides coefficients of friction on the order of 0.003, or less, depending on the sliding velocity, load, and fluid viscosity. It eliminates wear entirely, since the solids do not touch or collide with each other. Gyroscope bearings are one example where the ideal conditions of hydrodynamic lubrication are substantially achieved. Two types of hydrodynamic film lubrication are now recognized: thick hydrodynamic films and elastohydrodynamic films (Table 1.4(a)).

Plain journal bearings and tilting-pad or tapered-land thrust bearings (Figs. 1.2(a) and 1.4) have thick hydrodynamic films, usually more than 25 μm thick. In applications the loads are low enough, and the areas over which the loads are distributed are large enough, that the load-carrying area does not deform enough to significantly alter that area. Load-carrying surfaces of this type are often referred to as "conforming," although it is obvious that in tapered-land thrust bearings, for example, the surfaces do not conform in the normal concept of the word. However, the term is a convenient opposite for the term "nonconforming," which quite accurately describes the types of surface where elastohydrodynamic films are formed.

The surfaces of the balls in a ball bearing theoretically make contact with the raceways at points; the rollers in a roller bearing make contact with the raceways along lines; and meshing gear teeth also make contact along lines (e.g., Figs. 1.2(b) and (c)). These types of surface are nonconforming. Under the pressures applied to these elements by the lubricating film, however, the metals deform

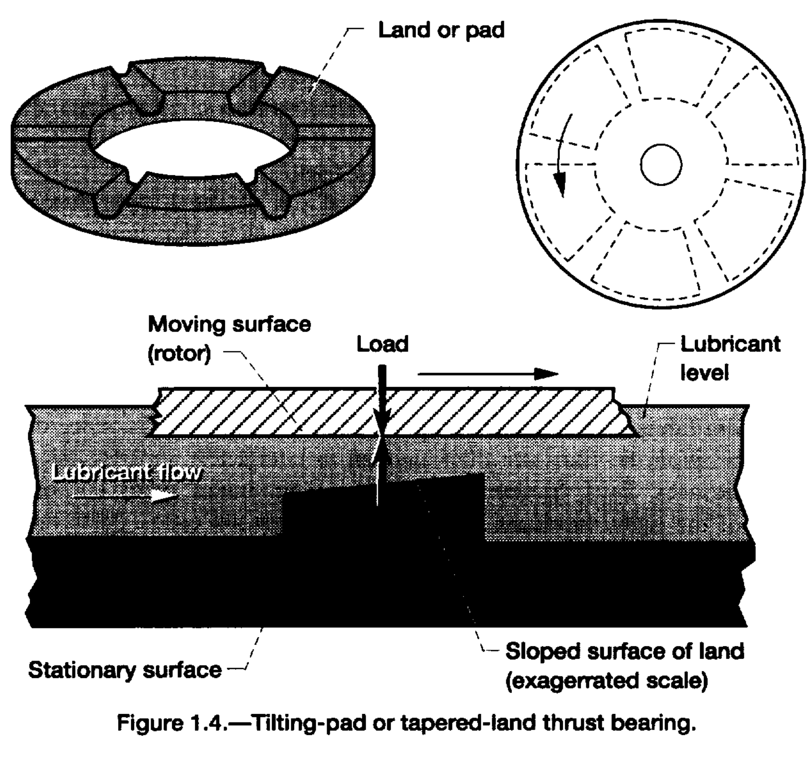


Figure 1.4.—Tilting-pad or tapered-land thrust bearing.

elastically, expanding the theoretical points or lines of contact into discrete areas. Since a convergent zone exists immediately before these areas of contact, a lubricant will be drawn into the contact area and can form a hydrodynamic film. This type of film is referred to as an "elastohydrodynamic film." The "elasto" part of the term refers to the fact that elastic surface deformation must occur before the film can be formed. This type of lubrication is elastohydrodynamic lubrication (EHL), a condition of lubrication in which the friction and film thickness between two surfaces in relative motion are determined by the elastic properties of the surfaces in combination with the viscous properties of the lubricant. The viscous properties include variation of viscosity with pressure, temperature, and shear rate. EHL films are very thin, on the order of 0.25 to 1.25 μm thick. However, even with these thin films, complete separation of the contacting surfaces can be obtained.

Any material that will flow at the shear stresses available in the system may be used for fluid film lubrication. In most applications petroleum-derived lubricating oils are used. There are some applications for greases. Some materials not usually considered to be lubricants, such as liquid metals, water, and gases, are also used. For example, magnetic recording is accomplished by relative motion between a magnetic medium and a magnetic head (Fig. 1.5); under steady operating conditions a load-carrying hydrodynamic gas (air) film is formed [1.19].

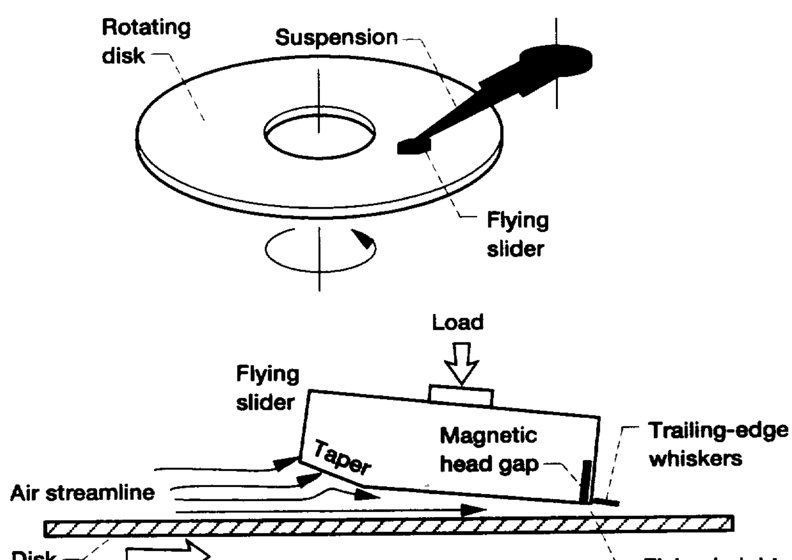


Figure 1.5.—Hydrodynamic gas (air) film lubrication in magnetic hard-disk drive system.

Ideal conditions of hydrodynamic lubrication can rarely be maintained in practice. Starting, stopping, misalignment, heavy loads, and other service conditions can cause the fluid film to be squeezed out or allow the surface asperity to break through the film, so that the two solids are pressed into contact with one another. Even in modern high-end computer tape and disk drives, there is physical contact between the medium and the head during starting and stopping. Ideal hydrodynamic lubrication then ends, and boundary lubrication, or lubrication by solids, begins.

Hydrostatic films.—In hydrostatic film lubrication the pressure in the fluid film that lifts and supports the load is provided from an external source. Thus, relative motion between opposing surfaces is not required to create and maintain the fluid film. The principle is used in plain and flat bearings of various types, where it offers low friction at very low speeds or when there is no relative motion; more accurate centering of a journal in its bearing; and freedom from stick-slip effects.

Figure 1.6 illustrates the simplest type of hydrostatic bearing. Oil under pressure is supplied to the recess or pocket. If the supply pressure is sufficient, the load will be lifted and floated on a fluid film. The total force developed by the pressure in the pocket and across the lands will be such that the total upward force is equal to the applied load. The clearance space and the oil film thickness will be such that all the oil supplied to the bearing can flow through the clearance spaces under the pressure conditions prevailing.

Squeeze films.—As the applied pressure on an oil increases, its viscosity increases. This fact contributes to the formation of what are called squeeze films [1.14].

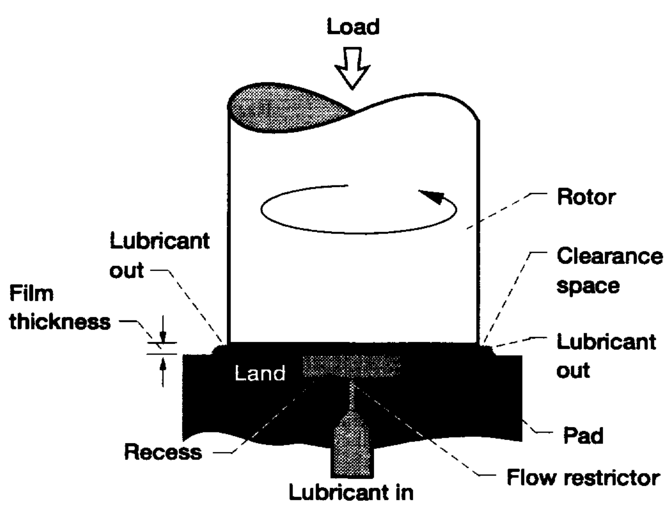


Figure 1.6.—Simple hydrostatic thrust bearing.

Figure 1.7(a) shows the principle of the squeeze film, where application of a load causes plate A to move toward stationary plate B. As pressure develops in the oil layer, the oil starts to flow away from the area. However, the increase in pressure also increases the oil viscosity, so that the oil cannot escape as rapidly and a heavy load can be supported for a short time. Sooner or later, if load continues to be applied, all the oil will flow or be forced from between the surfaces and metal-to-metal contact will occur, but for short periods such a lubricating film can support very heavy loads.

One application where squeeze films are formed is in piston pin bushings (Fig. 1.7(b)). At the left the load is downward on the pin and the squeeze film develops at the bottom. Before the film is squeezed so thin that contact can occur, the load reverses (right view) and the squeeze film develops at the top. The

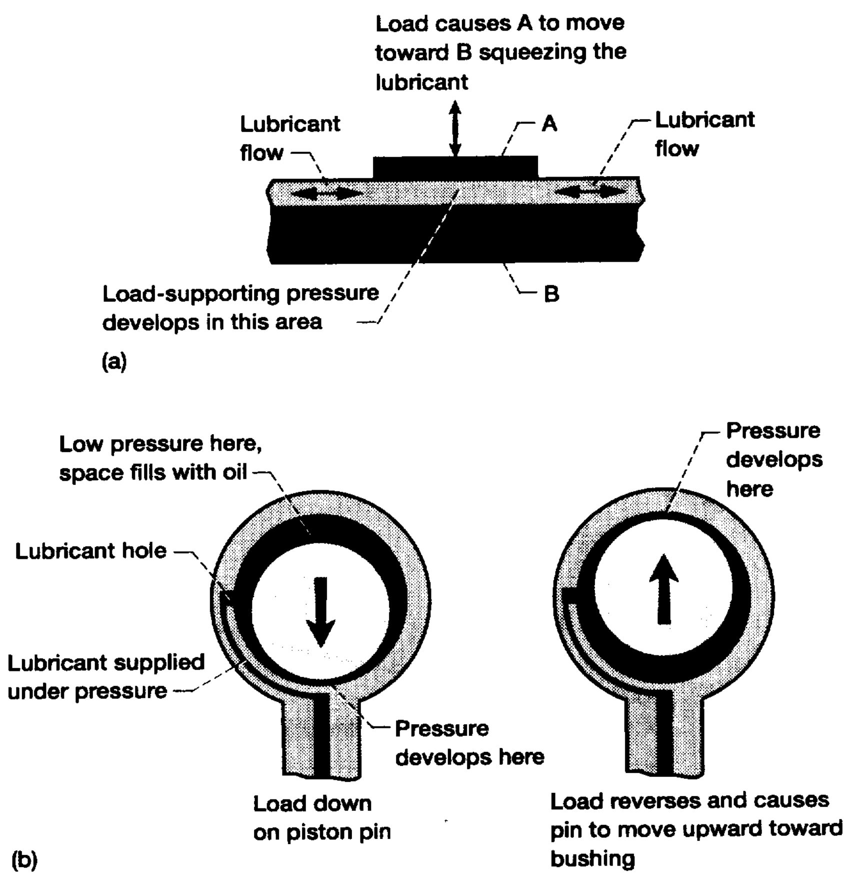


Figure 1.7.—Squeeze film bearing. (a) Squeeze film principle. (b) Squeeze film in piston pin bushing.

bearing oscillates with respect to the pin, but this motion probably does not contribute much to film formation by hydrodynamic action. Nevertheless, bearings of this type have high load-carrying capacity.

Effect of viscosity, speed, and load.—The oil film (wedge) formed in a hydrodynamic bearing is a function of speed, load, and oil viscosity. Under fluid film conditions an increase in viscosity or speed increases the oil film thickness and the coefficient of friction; an increase in load decreases them. It is now generally accepted that the coefficient of friction μ can be shown by a curve such as that in Fig. 1.8. The coefficient of friction is plotted as a function of a single dimensionless factor, viscosity times velocity divided by load [1.3, 1.14]. A similar type of curve could be developed experimentally for any fluid film bearing. The curve is also called the Stribeck curve. The accurate experimental measurements of Stribeck from 1900 to 1920 served as a basis for the theoretical work of many researchers in establishing the theory of hydrodynamically lubricated bearings.

In Fig. 1.8 three main lubrication regimes may be distinguished:

1. Fluid film lubrication (thick hydrodynamic lubrication, elastohydrodynamic lubrication, etc.) exists in the zone to the right of c.
2. Mixed film lubrication or partial elastohydrodynamic lubrication (EHL) exists in the portion of the curve between a and c, including the minimum value of μ to the dimensionless value indicated by b.

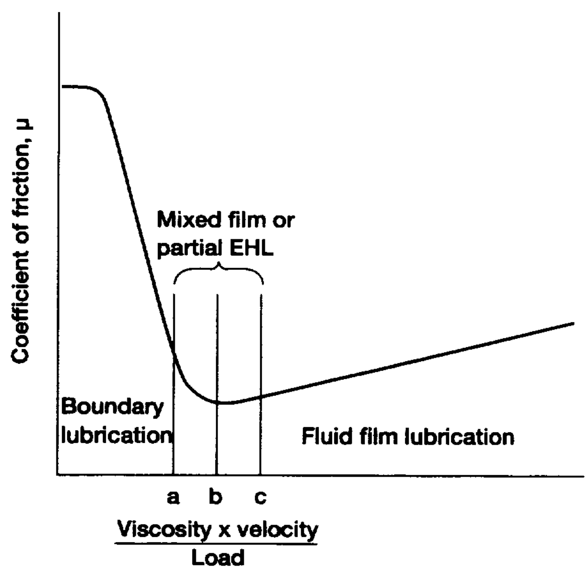


Figure 1.8.—Variation in coefficient of friction with viscosity, velocity, and load for fluid-lubricated sliding bearing (the Stribeck curve).

3. Boundary lubrication exists to the left of a, where conditions are such that a full fluid film cannot be formed, some friction and wear commonly occur, and very high coefficients of friction may be reached.

Mixed film lubrication and boundary lubrication are discussed next.

1.4.3 Thin Films

A copious, continuous supply of liquid lubricant is necessary to maintain fluid films. In many cases it is not practical or possible to provide such an amount of lubricant to machine elements. In other cases, as for example during starting of a hydrodynamic film bearing, loads and speeds are such that fluid films cannot be maintained. Under these conditions lubrication is by what are called thin films.

When surfaces run together under thin film conditions, enough oil is often present so that part of the load is carried by fluid films and part is carried by contact between the surfaces. This condition is often called mixed film lubrication. With less oil present, or with higher loads, a point is reached where fluid oil plays little or no part. This condition is often called boundary lubrication, the condition of lubrication in which the friction and wear between two surfaces in relative motion are determined by the properties of the surfaces and by the properties of the lubricant other than bulk viscosity. Many circumstances that are referred to as "boundary lubrication" are in fact elastohydrodynamic.

When rubbing (sliding) contact is made between the surface peaks, known as asperities, a number of actions take place, as shown in Fig. 1.9, which represents a highly magnified contact area of two surfaces:

1. At locations a in Fig. 1.9, sliding surfaces completely separate and thick films are formed. Friction there is due only to shearing of the liquid lubricant films.
2. There is heavy rubbing at location b, as surface films are sheared, and elastic or plastic deformation occurs. Real (in contrast to apparent) areas of contact are extremely small and unit stresses are very high.

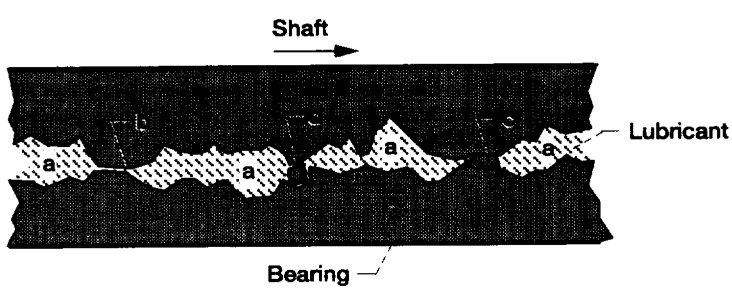


Figure 1.9.—Actions involved in boundary lubrication.

3. As some areas at location c are rubbed or sheared, the clean surfaces weld together. The minute welds break as motion continues. But depending on their strength, the welds may break at another section so that metal is transferred from one member to the other.
4. The harder shaft material plows through the softer bearing material at location d, breaking off wear particles and creating new roughnesses.

These actions account for friction and wear in boundary lubrication.

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Kazuhisa Miyoshi

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This chapter presents an introduction and historical background to the field of tribology, especially solid lubrication and lubricants and sets them in the perspective of techniques and materials in lubrication. Also, solid and liquid lubrication films are defined and described.

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