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Tribology Needs for Future Space and Aeronautical Systems

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ABSTRACT

Future aeronautical and space missions will push tribology technology beyond its current capability. The objective of this paper is to discuss the current state of the art of tribology as it is applied to advanced aircraft and spacecraft. This report will discuss materials lubrication mechanisms, factors affecting lubrication, current and future tribological problem areas, potential new lubrication techniques, and perceived technology requirements that need to be met in order to solve these tribology technology problems.

INTRODUCTION

In the past, the friction, wear, and lubrication (tribology) needs of aircraft and spacecraft appeared to be well within the state of the art. Hydrodynamic and elastohydrodynamic regimes of liquid lubrication are (and have been for some time) very well-defined and mature technologies. In addition, the other regime of liquid lubrication, boundary lubrication, although still more of an art than a science, has been adequately developed to meet most current lubrication needs. Temperature extremes (beyond the capabilities of lubricants) have been controlled by either heating or cooling the liquid lubricant to keep it within its operating temperature range. In situations where liquids could not provide lubrication, solids have been employed. Solid lubricants have finite lives and generally higher friction coefficients, and a certain amount of wear takes place; however, they have been used selectively where liquid lubricant use was not feasible or desirable. Thus, the lubrication of mechanical components in the past has not been a problem.

The lubrication of future advanced aircraft and spacecraft may not be quite as tractable, however. These craft will operate at higher temperatures in order to obtain improved efficiencies and performance levels. Currently, liquid lubricants can function at temperatures up to about 260 °C before breaking down. Solid lubricants can function up to about 1200 °C, but generally, friction coefficients and wear rates are higher than with liquid lubricants. In addition, solid lubricants have finite lifetimes, and like liquid boundary lubricants, their success often depends on the method by which they are employed or the individual applying them.

In addition to the high-temperature problems of the future, there are many low-temperature problems in the space propulsion systems in use today (Refs. 4, 17, 18, 31, 63-65, 90, 91, 103-105, 135). The solid lubricants used to lubricate the liquid oxygen turbopumps in the space shuttle, for example, do not meet the desired performance goal. To ensure success, the pumps have to be torn down and fitted with new bearings after every launch. Other systems that could experience lubrication problems at low temperatures are aircraft flying at high altitudes ($\sim$ -40 °C), actuators and sensors that must be cooled to cryogenic temperatures, and surface vehicles or general mechanical equipment operating on the Moon or Mars ($\sim$ -170 °C).

Endurance, wear, and reliability are directly related to how well mechanical components are lubricated. Future space missions will include mechanical components that will have to operate reliably for up to 30 years in low Earth orbit (LEO). The space exploration initiative (SEI) will also require equipment that will operate reliably for many years. Lubrication of vehicles, mining and power-generation equipment, and any other equipment associated with surface habitation may be a considerable problem on the Moon and Mars. Some of the challenges in these environments include thermal cycling of the lubricants, contamination by the lubricants, degradation due to atomic oxygen and radiation, the ability to supply enough lubricant to the contact areas to prevent starvation, and contamination or abrasion by dust.

This report will discuss the general state of the art of space and aeronautics tribology, the current and future technology problems, and perceived needs for future missions.

MECHANISMS OF LUBRICATION

Liquid Lubrication

There are four defined regimes of liquid lubrication: hydrodynamic, elastohydrodynamic, boundary, and mixed. These regimes are directly proportional to the oil viscosity (Z) and to the relative velocity (V) and inversely proportional to the load (L). Figure 1, known as the Stribeck-Hersey curve (Refs. 56, 61, 122), depicts these regimes in terms of friction coefficient as a function of viscosity, velocity, and load (ZV/L).

The first regime is known as hydrodynamic lubrication. It is characterized by a complete separation of the surfaces by a fluid film that flows through the contact region. In addition to fluid viscosity, load, and velocity, the geometry of the contact can also play an important role in the development of hydrodynamic films. When hydrodynamic lubrication takes place, the oil viscosity is high, the velocity is high, and the load is low. Typically, the thickness (h) of the lubricant film separating the surfaces is greater than 0.25 μm (10^{-5} in.). Basically, this regime of lubrication is governed by the rheology of the liquid, and no wear of the surfaces takes place.

For nonconformal concentrated contacts, where loads are high enough to cause elastic deformation of the surfaces but velocity and viscosity are not large enough to produce film thicknesses greater than 0.25 μm (10^{-5} in.), the second lubrication regime comes into effect. This regime is known as elastohydrodynamic lubrication (EHL). The thickness of the lubricant film in this regime is 0.025 to 2.5 μm (10^{-6} to 10^{-4} in.).

As the thickness of the oil film decreases to values below 0.0025 μm (10^{-7} in.), the boundary lubrication regime comes into play. In this regime, asperity contact between the sliding surfaces takes place, and the lubrication process becomes the shear of chemical compounds on the surface. This regime is dependent on the oil lubricant additives producing compounds on the surface that have the ability to shear and provide lubrication. Boundary lubrication is highly complex, involving surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics. The transition between elastohydrodynamic and boundary lubrication is not sharp; between them is a region called the mixed lubrication regime wherein there is some elastohydrodynamic and some boundary lubrication.

Usually, during hydrodynamic and elastohydrodynamic lubrication no wear takes place because there is no contact between the sliding surfaces. But during mixed and boundary lubrication there is contact, so some wear does take place. Chemical additives must be put into oils to alleviate this process. But as load increases, the reaction films become less effective, and eventually severe wear and ensuing failure with seizure can take place. Figure 2 (Ref. 61) illustrates the wear processes that can take place, as a function of load.

Solid Lubrication

Solid lubrication is essentially the same as boundary lubrication (in liquid lubrication), except that there is no liquid carrier to resupply a solid material (such as a chemical reactant) to the surfaces to produce a lubricating solid film. Instead, a solid film must be applied to the sliding surfaces before sliding commences, and this film must last for the life of the component. An alternative to using a film is to make a part of the bearing (e.g., the bearing cage) out of a solid lubricant or a solid lubricant composite. The cage (or other selected part) will then supply solid lubricant to the interfaces by a transfer mechanism.

When films or coatings are used for lubrication, either of two basic lubricating mechanisms are at work (Refs. 39-41). Before the proper lubricant can be chosen, one should know which mechanism is operating. In the first mechanism, the film itself is capable of supporting the load, and the wear process is one in which the film is gradually worn away. Figure 3 shows a photomicrograph of a wear track on a polyimide-bonded graphite fluoride film after 15 000 cycles of sliding against a metallic pin under a 9.8 N load. The photomicrograph illustrates that the film asperities are capable of supporting this particular load. Thus, the wear process for this film is one of a gradual wearing away of the film until the metallic substrate is reached. Studies have shown that the film's rate of wear by this mechanism is determined by the load and by the area of contact with the metallic slider. For more information see Ref. 41.

Not all films are capable of supporting the load, but they can still provide lubrication by the second mechanism: shear of a very thin film of lubricant (usually less than 2 μm thick) at the surface of the substrate. If the original film is thicker than 2 μm, it is very quickly worn away (either it plastically deforms or brittlely fractures) and a secondary film can then form from wear debris and/or material that has not been worn away. Sometimes if the film is too thick or the geometry is not correct, the secondary film will not form at all. A thin film has a greater chance of forming a very thin shear film than does a thick film because there is less chance of wear particles escaping the contact area during film deformation (known as run-in). In addition, when the shear mechanism is in operation, the film applied to a rough surface tends to endure longer because a better bond is achieved and the roughness provides a reservoir for solid lubricant material (Ref. 40).

Cross-sectional diagrams of the wear area on a bonded, solid lubricant film after 1, 30, and 60 kilocycles of sliding are shown in Fig. 4. This figure illustrates the two different types of macroscopic lubricating mechanisms. Note that the vertical magnification is 50 times the horizontal magnification to emphasize the wear process.

FACTORS AFFECTING LUBRICATION

Liquid Lubrication Factors

There are many factors that influence the lubrication process of oils besides viscosity, velocity, and load. Probably the most influential parameter is temperature. Temperature affects the viscosity of oil and, eventually, causes the oil to vaporize at some high temperature or become too thick to flow freely at some low temperature.

Another factor is oxidation. Oils tend to oxidize, so oxidation inhibitors must be added. Other chemicals are added for other reasons. Sometimes oils possess chemicals that cause corrosion of metallic surfaces. Conversely, in some cases the metallic surfaces themselves can initiate the chemical breakdown or polymerization of oils (especially fluorocarbon oils, Refs. 30, 137). Oils can attack seals, causing them to shrink or swell, and sometimes oils can foam, causing lubricant starvation. Thus, chemicals must be added to oils not only to make them better boundary lubricants but also to make them effective. Table 1 lists the type and purpose of the most commonly used additives. For more information on the theory of lubrication and types of additives needed in oils see Ref. 13.

Solid Lubrication Factors

There are also many factors or conditions that affect solid lubricant performance. A wear rate or a friction coefficient cannot be specified without knowing the conditions under which the lubricant will be operating. The types of factors that affect solid lubricant performance are listed in Table 2. Depending on the particular solid lubricant employed, a change in the value of just one of these parameters can cause a change in the value of the friction coefficient, wear rate, or endurance life that might be expected. Note that low friction does not necessarily correlate to low wear or long life.

Some metals, such as AISI 300 series stainless steel or titanium, are intrinsically hard to lubricate. A solid lubricant applied to these materials may fail immediately, but this does not classify the solid lubricant as a bad lubricating material. It just means that it will not lubricate this particular material. The solid lubricant and the metal it lubricates are a system; ideally the type of materials to be lubricated should be chosen just as carefully as the solid lubricant. However, in many instances the metal to be lubricated is selected without regard to how well a solid lubricant will work with that particular metal. When this occurs, the designer must find the best solid lubricant for that particular metal, which may not be the optimum lubricant-metal system for the intended application.

Contact stress is an important parameter to consider when solids are used as lubricants. Concentrated contacts that occur during lubrication involve high stresses; thus, in general, hard metals can be lubricated by solid lubricant films to produce lower wear and longer endurance lives than softer metals. An example of a commonly used bearing steel that has been successfully used for many aeronautic and space applications is AISI 440C, which has a Rockwell-C hardness of 60. Geometry of sliding or rolling components can also influence the contact stress that the solid lubricant experiences. If the stresses are too high, the solid lubricant can brittlely fracture or plastically flow out of the contact area, and lubricant life will be short. In addition, incorrect geometry can inhibit a solid lubricant film from entering the contact area or forming transfer films.

Generally a solid lubricant film should not be applied to both surfaces because the objective is to produce a thin film that shears within the contact region. If both sliding surfaces are coated with the same film, there is a tendency to have high adhesion and massive transfer back and forth between the surfaces, and thus, high film wear. By applying the film to only one surface, the noncoated surface will gradually preferentially orient a thin layer on the solid lubricant coating. The oriented thin layer will then transfer a film to the noncoated surface; this process will provide for low wear and friction. Applying the solid lubricant film to the right surface is important. In general, the lubricant film should be applied to the surface that distributes the stress over the largest contact area and that will supply the largest amount of lubricant to the sliding surfaces. For example, it would be better to apply a solid lubricant film to a cylinder wall rather than a piston ring.

The substrate surface roughness was mentioned previously. Since most bonded solid lubricant films will not adequately bond to very smooth surfaces, the substrate surface needs to be roughened in some manner to ensure a good bond. In addition to bonding better, this roughened surface serves as a reservoir for the lubricant. Such roughening can be done mechanically or chemically (Refs. 13, 40). The surface sliding against the solid lubricant should be very smooth, however, to prevent abrasive wear of the solid lubricant (Ref. 44).

Friction creates heat during the sliding process, and thus temperature and sliding velocity usually go hand in hand—the higher the velocity, the higher the temperature. Sometimes higher temperatures are beneficial to a solid lubricant's performance, but in most cases higher temperatures decrease the life of a solid lubricant film. As a rule friction, wear, and endurance are highly dependent on temperature, so this factor must be controlled. As the temperature of the film is affected by speed, so also are the rheological properties of the film, especially the flow properties of polymer films. Thus, if the speed is too fast, the film can brittlely fracture instead of plastically flowing.

The environment to which a solid lubricant is exposed can also markedly affect a solid lubricant's tribological properties. The relative humidity of air, which varies from 20 percent in winter to 80 percent in summer, can have such an effect, but inert atmospheres like argon or vacuum can have an even greater effect. Since solid lubricant performance varies depending on the environment, one must be cognizant of such effects when selecting a solid lubricant.

Most solid lubricant films do not function well in a liquid environment, whether it be water or oil. Even the minuscule amount of oil deposited by an inquiring finger can drastically affect tribological properties and reduce endurance life. Cleanliness with respect to dust and dirt are also extremely important. A small, hard particle can imbed itself in a film and severely abrade the counterface.

CURRENT AND FUTURE TRIBOLOGICAL PROBLEM AREAS

Aeronautics

For more than 30 years the development of liquid lubricants capable of operating at bulk temperatures up to and beyond 500 °F (Ref. 9) has been a goal. Unfortunately, to date, not much progress has been made. A few lubricants have shown promise, but for the most part, only incremental success has been achieved. Some new synthetic lubricants have been developed (Refs. 9, 27-29, 78, 79), but new problems have accompanied their development and still there is no commercially available lubricant that will operate at bulk temperatures higher than 500 °F.

The aeronautical propulsion industry's plans for developing new aircraft for the next century will require engines that can operate at higher and higher temperatures, since being able to operate jet engines at higher temperatures would enable greater efficiency and thrust. Programs are being planned to develop high-temperature materials for combustors, turbines, nozzles, and such, but very little effort is being exerted to develop new liquids or alternative means to lubricate mechanical components. The U.S. Department of Defense is doing some work, but very little is being done in the civilian sector. More work needs to be done not only on liquid lubricants but also on developing gas (fluid film) bearings and magnetic bearings for aeronautical use.

The main problem with solid lubricants is that they have a finite life, and there is no way to replenish a film once it has worn away. Also friction coefficients are somewhat higher than those obtained with liquid lubricants. However, they are capable of operating at higher or lower temperatures than liquids, though they generally will not lubricate uniformly over a wide temperature range. Solid lubricants have been developed that will provide a degree of lubrication up to 2000 °F (Refs. 109, 112-115), but they do not have low friction coefficients (generally they are >0.2), and they can be abrasive if not properly prepared. Future aeronautical applications will require solid lubricants with longer lives, lower friction coefficients, and the ability to operate over wider temperature ranges.

New solid lubricant formulations that will provide greater endurance need to be developed. In addition, a means of resupplying a solid lubricant to the contact zone needs to be developed. Currently, most solids are applied to rolling element bearings that have been developed for liquids; there is a need to develop rolling element bearings that incorporate the properties of solids, not liquids. However, as in liquid boundary lubrication, there is a lack of fundamental understanding of how these materials lubricate; more research needs to be applied in this direction.

Space

Kannel and Dufrane (Ref. 62) studied the tribological problems that have occurred in the past and that are projected to occur in future space missions. Figure 5 (Ref. 62) is a qualitative chart which illustrates that, despite significant advances in tribology, the demands on tribology for future space missions will grow faster than the solutions.

Lubrication problems in space depend on the particular application. Since excess weight is a problem for satellites, large reservoirs of liquid lubricant and the resultant pumping systems (as used in aeronautical systems) are not appropriate. Instead, rolling element bearings are lubricated with small liquid reservoirs and/or porous cages, or sometimes greases are employed. Since most of the bearings used on satellites are lightly preloaded, the stresses on the oils are not great, and because the bearings operate predominantly in the elastohydrodynamic regime, they have had fairly good success over the years. However, a loss of lubricant through vaporization, creep, and the like has caused some bearings to fail before their mission was complete.

In an attempt to reduce vaporization (and also contamination), new synthetic lubricants such as the perfluorinated polyether (PFPE) lubricants, which have very low evaporation rates (Ref. 30), have been employed. These lubricants also have a very good viscosity index. Although in theory these lubricants appear to be exceptional, in operation some failures due to chemical breakdown have occurred. Researchers have shown that the presence of chemically active surfaces and/or wear particles combined with exposed radicals in the fluid will inevitably result in acidic breakdown of the lubricants (Ref. 137). In order to make synthetic lubricants reliable, more research needs to be done to understand this breakdown process. Another problem with these PFPE lubricants is that traditional mineral oil additives are not soluble in them; thus, new additives need to be developed. Unfortunately, very few materials are soluble in them.

Future NASA missions will require mechanical systems that operate for as long as 30 years. Since some satellite bearings have failed in 3 years or less, it appears that the current liquid lubricant and bearing technology is not adequate to meet these requirements. The larger satellites of the future will require larger bearings capable of operating under more stringent conditions; thus, more difficult tribology problems are likely to occur.

Solid lubricant films are used in cases where it is not convenient to use liquid lubricants or where contamination might be a problem. Since solid lubricant films have finite lives, they are not usually employed where they will experience more than 1 million sliding cycles. In addition to finite lives, some solids produce powdery wear particles that can pose a contamination problem on sensitive surfaces. Clearly, there is a need to develop solid lubricant films that will endure longer and not produce powdery wear particles.

An alternate method of employing solids is to make a bearing cage out of a composite lubricant material so that the lubricant will be transferred to the rolling balls and then to the inner and outer races (Refs. 5, 6, 62-65, 91). Figure 6 shows how this film-transfer mechanism operates (Ref. 17). Generally this form of lubrication is successful only under lightly loaded conditions; however, the technique has been used to lubricate the ball bearings in the space shuttle turbopumps. It appears to work with some success in the liquid hydrogen pumps, but has not performed very well in the liquid oxygen pumps. NASA is currently investigating this problem.

A big problem in space lubrication is the lack of oxygen. Oxide layers on metals play an important role in the boundary film lubrication process. On Earth, most surfaces are covered with an oxide film, which helps prevent high adhesion between surfaces. In the vacuum of space, once these oxides are removed (by some sliding process), they cannot be reformed, and galling of metallic surfaces will occur. This is one reason that boundary additives are necessary in oils; that is, if for some reason metal-to-metal contact occurs and removes an oxide film, the additives can then reform an oxide film or some other type of surface film to prevent metal-to-metal contact. In the case of nonlubricated sliding or solid lubricant sliding where oxide films cannot be replaced if worn away, catastrophic failure can occur. Thus, any metallic surface sliding in a vacuum should be covered with some type of film to prevent metal-to-metal contact.

When a manned outpost is established on the Moon, the high vacuum (10^{-12} torr) combined with a very fine abrasive dust will very likely have a most deleterious effect on sliding components, especially those that are unlubricated. The dust will accelerate the removal of protective oxide films on metals, causing high adhesion when they come into sliding contact. This could be a problem with "track-type" vehicles. Not only will the dust be abrasive, but it also will be positively charged and have a tendency to stick to everything. Lubricants, both liquid and solid, will have to be sealed against the dust. This means that new concepts in sealing will be needed.

Another reason for anticipating problems on the Moon is the wide temperature extremes. In the daytime the temperature can rise to 111 °C, and at night it can drop to -181 °C, as was found during the Apollo missions (Ref. 124). And since the Moon rotates slowly, days and nights on the Moon are 14 Earth days long. In contrast to the lunar temperatures, recorded temperature extremes on the surface of the Earth range from 58.0 °C in Libya in 1922 (Ref. 84) to -88.3 °C in Antarctica in 1960. Currently, there are no liquid lubricants that will operate at these cold lunar temperatures. Either the lubricants will have to be heated (which will expend precious energy) or solids will have to be employed. This is an area where very little research has been done, and we need to better understand how to lubricate at these low temperatures.

Aerospace Plane

The aerospace plane will take off from a runway and "fly" into space. Since the lubricants employed will have to operate both in air and in a vacuum, special lubricants will probably be needed. At this time, we do not know what the specific temperatures and lubricating conditions will be. However active cooling of the aerodynamic surfaces has been suggested, which indicates that some lubricant surface areas may be at cryogenic temperatures. But to achieve the desired thrust, some areas will be extremely hot. Thus a very wide range of lubricants may be needed.

Space Simulation Problems

Since the tribological properties of materials are extremely systems dependent (i.e., the friction, wear, and lubricating ability are strongly dependent on such operating conditions as load, velocity, type of contact, temperature, atmosphere, etc.) , it is imperative that technology testing simulate as closely as possible the particular space application. The vacuum, load, velocity, and such can be simulated fairly easily on the ground, but we cannot simulate microgravity. And it is very hard to simulate the radiation and atomic oxygen environment of low Earth orbit (LEO).

Another mechanical and lubrication problem that is difficult to simulate though technology testing is the effect of forces and vibrations that mechanical components experience during launch. These parameters can cause lubricant or component failure immediately, or they can decrease the life that was predicted through ground-based testing.

Problems with lubrication can also result from storage of satellites. Satellites are sometimes stored for years before launch. During this time oils tend to creep away from contact zones, and solid lubricants can oxidize or absorb water, thereby decreasing their lubricating ability. More research needs to be done in these areas to determine the parameters that are important and those that are not.

Accelerated Testing Problems

Designers would like to know how long a particular mechanical component will operate before it fails. Currently, the only way to ascertain this is to operate the component in a full-scale ground test. The problem is that these tests have to run for years. Accelerated testing can be done on some solids lubricants, since wear rate is often velocity independent. When this is the case, the sliding velocity can simply be increased to increase the number of sliding cycles.

The life of a liquid lubricant is not velocity independent, however, so velocity cannot be increased to accelerate the test. Therefore, we need to better understand the failure mechanisms, so that the mechanisms can be analytically modeled to simulate a life test. We may be able to determine failure precursors on bearing surfaces (such as chemical changes or microcracks) by using surface science, which would allow us to predict bearing life under various testing conditions and to make corrections for extending bearing life.

POTENTIAL NEW LUBRICATION TECHNOLOGIES

Inerted Lubrication Systems

Since the oil oxidation rate increases as temperature increases, which decreases the upper operating temperature of lubricants, NASA investigated the use of nitrogen-gas-filled oil systems (inerted) to increase the operating temperature of liquid lubricants. These studies were conducted in the 1960's and 1970's (Ref. 78). The objective was to operate the lubricants in an inert environment so that the upper temperature limitation of lubricants could be increased. These systems tended to work very well but were not popular with aircraft companies, since relatively large quantities of nitrogen were required to make the systems inert. In the future, as operating temperatures increase, this technique could be revived.

Mist Lubrication

In the 1960's and 1970's NASA also investigated the possibility of using "once through" liquid-lubricant-mist systems to increase the operating temperatures of rolling element bearings (Refs. 98, 99). The lubricant was injected into the bearing contact areas as a very fine mist and then cast off. The theory was that since the lubricants would be in the bearing contact for only a very short period of time, and only once, any decomposition that occurred would not matter. Good results were obtained with this system, but again, it was not used because large quantities of lubricant would have had to be carried on the aircraft.

Vapor Deposition

Klaus and others (Refs. 52, 68, 79, 94) have demonstrated that lubrication at high temperatures may be possible by using the decomposition products of an oil. Essentially, the high temperatures of an engine would cause the oil to decompose into mostly gaseous, but some solid, materials. The solids would deposit on lubricating surfaces where they would act as a boundary lubricant at high temperatures. The technique has shown promise, but it is still in its infancy insofar as actual application is concerned.

Catalytically Gas-Generated Carbon

Lauer and Bunting (Ref. 75) have proposed that gases injected into a lubricating contact area at high temperatures could react to form a solid lubricant film directly on the bearing surfaces. They have demonstrated that a gas phase conversion of hydrocarbons to carbon can occur on a variety of metallic and ceramic surfaces containing a nickel catalyst. The carbon films produced have been shown to reduce friction at a sliding interface at elevated temperatures. This technique is still in its infancy and much more work is needed to prove that it would provide adequate lubrication.

Powder Lubrication

Hesmat (Refs. 57, 58) has been investigating the use of fine powders to lubricate rolling-element and sliding bearings. His studies have indicated that the powders (under certain conditions) flow much like liquids in hydrodynamic lubrication. The results are preliminary, but there is some potential for using powders to lubricate at high temperatures where liquids will not function.

Gas Bearings

An alternative to lubricating a moving component with oil or solids is to use a high-pressure gas film, either externally pressurized as in a hydrostatic gas bearing or self-acting as in a hydrodynamic foil bearing. Gas bearings have been used for many years, but one problem with them is that at startup or shutdown the sliding surfaces come into contact. As a result, they have to be hydrostatically elevated, or some solid lubricant coating must be applied to the surfaces to lubricate during these intervals (Ref. 7). Also, overloads and shock loads on gas bearings can cause high-speed sliding contact, which further demonstrates the need for a solid lubricant coating. Gas bearings are somewhat limited in their load-carrying ability, but work very well for high-speed applications.

Magnetic Bearings

Magnetic bearings, which are usually a combination of permanent and electromagnetic materials, use opposing magnetic fields to separate the sliding surfaces. Though magnetic bearings are not widely used today, they have considerable promise for future lubricating systems. One disadvantage that has inhibited their use has been the complicated and heavy electronic systems that had to be used to ensure their success. With the development of improved electronics in recent years, their future appears very promising.

CONCLUDING REMARKS

The purpose of this report has been to give an overview of the current state of the art of tribology, to outline some current and future perceived problem areas, and to point out some potential new lubricating technologies. Tribological technology development has experienced incremental improvements over the last 20 to 30 years.

We have a better understanding of elastohydrodynamic lubrication; some new lubricating and wear theories have been developed; and some new liquid and solid lubricants have been formulated. However, the big problem of reliable lubrication for long periods of time at high temperatures or cryogenic temperatures has not been solved.

In the area of space tribology, very little new technology has been developed since the Apollo years. In fact, Apollo program technology is still being used today, 20 years later. This technology has been adequate for most missions that have flown to date, but as NASA and the Department of Defense plan missions that are longer and more demanding, the technology probably will not be sufficient.

RECOMMENDATIONS

In order to ensure the success of current and future NASA space and aeronautics missions, the following recommendations are proposed:

1. Create a corporate memory process by generating and maintaining a data base of past experiences, both successes and failures.

2. Institute a research program to develop technology in those areas where the data base indicates technology is lacking.

3. Establish a handbook or guideline of acceptable lubrication practices for specific applications.

4. Initiate generic life testing immediately to establish a data base and to determine possible failure mechanisms.

5. Develop accelerated testing methods along with analytical methods to predict component life and to determine possible failure mechanisms.

6. Expand the technology data base by conducting fundamental tribology research to determine failure mechanisms and to develop new lubricants and additive packages.

7. Establish an Aerospace Mechanisms National Testing Laboratory for the testing and evaluation of NASA, Department of Defense, and commercial hardware. Such a laboratory would be a national resource (like a National Institute of Standards and Technology (NIST)) for mechanical components and tribology. It would maintain both testing standards and established design practices, thereby providing guidance to aircraft and spacecraft builders. It would also be a bridge for providing NASA basic technology to NASA, military, and commercial space applications clients.

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TABLE 1. - LIQUID LUBRICANT ADDITIVES

Type	Purpose
Wear inhibitor	Reduces boundary lubricant wear
Extreme-pressure additive	Reacts with metal to form surface films to prevent metal-to-metal contact under high loads
Friction modifier	Absorbs or reacts with surface of a low-shear-strength film to reduce friction
Corrosion inhibitor	Forms protective coatings or deactivates corrosive contaiminants in the lubricant
Oxidation inhibitor	Prevents oxidation of lubricant
Pour point depressant	Permits flow at temperatures below the pour point of the liquid lubricant
Viscosity index improver	Causes minimal increase in viscosity at low temperatures, but considerable increase at higher temperatures
Detergent	Cleans surface deposits
Dispersant	Keeps contaminants suspended in the lubricant
Foam decomposer	Prevents excessive lubricant foaming
Emulsion modifier	Stablizes emulsions of water in oil
Tackiness agent	Helps lubricant adhere to surfaces
Seal swell agent	Swells or shrinks seals

TABLE 2. - FACTORS AFFECTING SOLID LUBRICANT PERFORMANCE

• Type of materials in sliding contact
• Geometry of sliding materials
• Contact stress or pressure
• Surface to which solid lubricant is applied
• Substrate hardness
• Substrate surface topography
• Temperature
• Velocity
• Environment
- Atmosphere
- Fluids
- Dirt

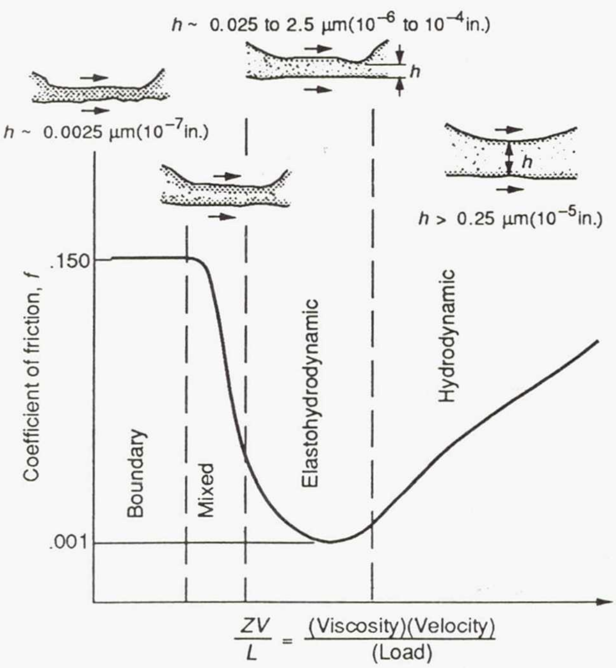

Fig. 1 Coefficient of friction as function of viscosity-velocity-load parameter (Stribeck-Hersey curve, Ref. 61); h = film thickness.

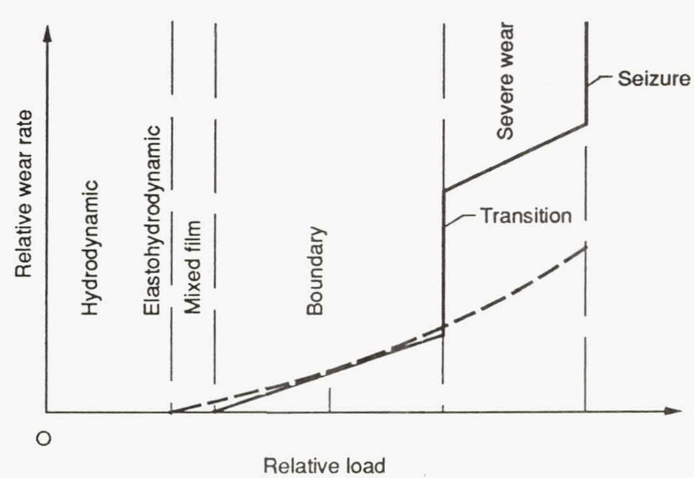

Fig. 2 Wear rate as a function of relative load, depicting various regimes of wear (Ref. 61).

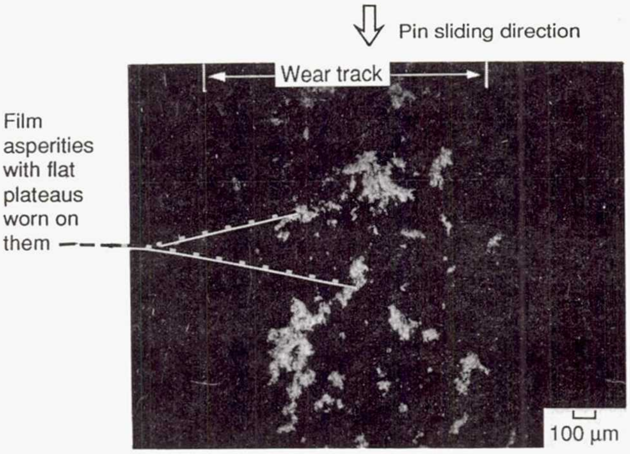

Fig. 3 Photomicrograph of a wear track of a polyimide-bonded graphite fluoride film after 15 kilocycles of sliding showing that only the highest of the film asperities support the load (Ref. 40).

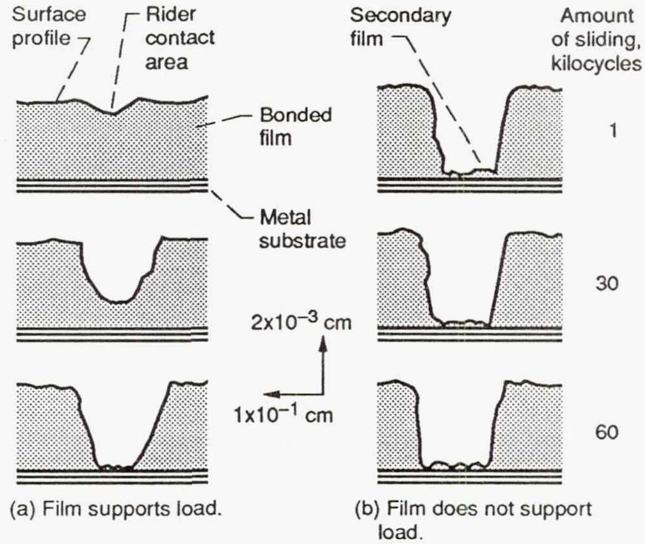

Fig. 4 Cross section of the wear areas on a bonded film (polymer or other type of solid lubricant film) after 1, 30, and 60 kilocycles of sliding illustrating the two different types of macroscopic lubricating mechanisms (Ref. 40). (Note: the vertical magnification is 50 times horizontal magnification.)

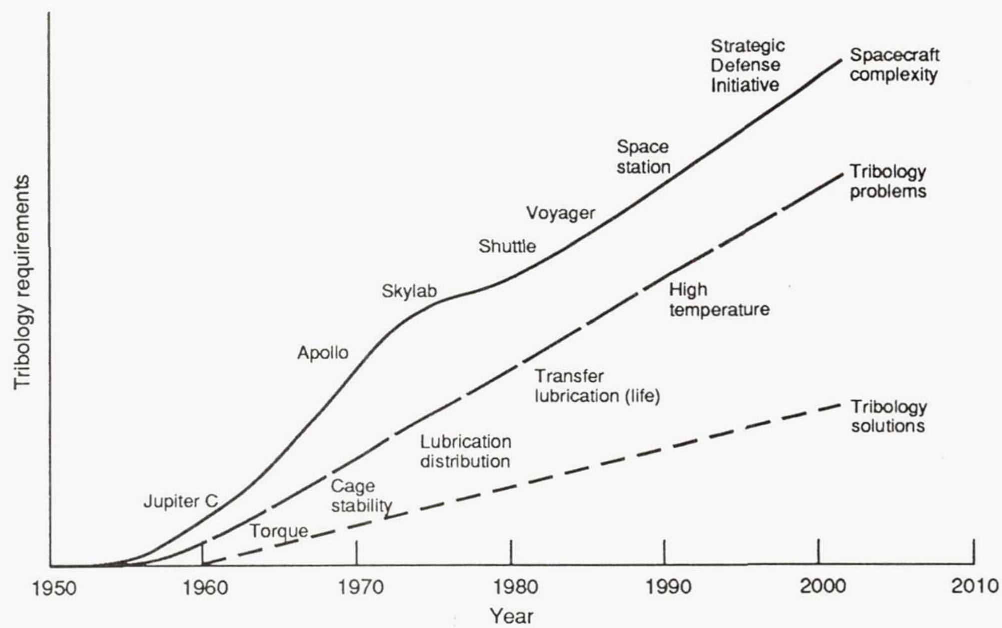

Fig. 5 Growth of tribology requirements with advances in space (Ref. 62).

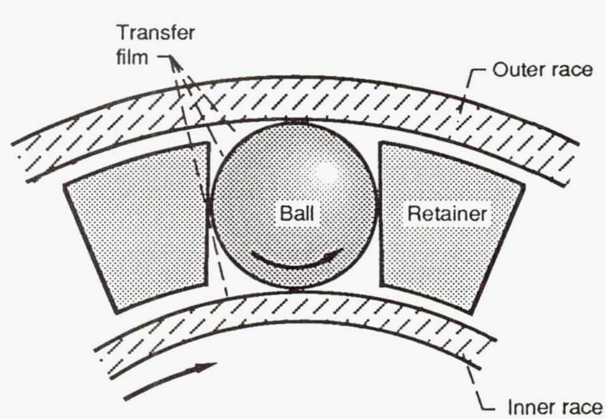

Fig. 6. Illustration of ball bearing film-transfer mechanism (Ref. 17).

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Future aeronautical and space missions will push tribology technology beyond its current capability. The objective of this paper is to discuss the current state of the art of tribology as it is applied to advanced aircraft and spacecraft. This report will discuss materials lubrication mechanisms, factors affecting lubrication, current and future tribological problem areas, potential new lubrication techniques, and perceived technology requirements that need to be met in order to solve these tribology technology problems.

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