NASA Technical Memorandum 86965

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(NASA-TM-86965) TRIBOLOGICAL SYSTEMS AS APPLIED TO AIRCRAFT ENGINES (NASA) 23 p HC A02/MF A01 CSCL 13I

N85-21657

Unclas
G3/37 14422

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Prepared for the
Sixtieth AGARD Structure and Materials Panel Meeting
San Antonio, Texas, April 21-26, 1985

NASA

TRIBOLOGICAL SYSTEMS AS APPLIED TO AIRCRAFT ENGINES

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E-2478

SUMMARY

Tribological systems as applied to aircraft are reviewed. The importance of understanding the fundamental concepts involved in such systems is discussed. Basic properties of materials which can be related to adhesion, friction and wear are presented and correlated with tribology. Surface processes including deposition and treatment are addressed in relation to their present and future application to aircraft components such as bearings, gears and seals. Lubrication of components with both liquids and solids is discussed. Advances in both new liquid molecular structures and additives for those structures are reviewed and related to the needs of advanced engines. Solids and polymer composites are suggested for increasing use and ceramic coatings containing fluoride compounds are offered for the extreme temperatures encountered in such components as advanced bearings and seals.

INTRODUCTION

Considerable research effort has been put into advanced aircraft systems over the past 50 yr, however, major significant accomplishments have been relatively few over the past 20 yr. Most of the advances have been incremental improvements in systems, components and materials. There is a need to develop a visionary spirit which transcends the examination of the next generation aircraft while still tending to current demands. This need exists for the entire aircraft but particularly the tribological systems and even more specifically those associated with engines.

Many exciting advances have been made in the past 20 yr in our understanding of materials, for example, and their interactive behavior. All too frequently the materials, particularly those associated with tribological applications are not given adequate consideration in initial design stages. Rather than incorporating new materials and application concepts into design the more conservative approach of making materials selections from the present inventory has been the choice.

A sound fundamental understanding of tribological concepts and some of the opportunities available to the designer could offer the prospect for future significant advances. Once a basic understanding is achieved as to why certain materials behave as they do and what properties of materials are important to tribological behavior the tools are in hand for these advances.

The objective of this paper is to: (1) review fundamental properties of materials important to adhesion, friction and wear, (2) examine properties important in the material selection process for tribological applications, (3) address lubrication regimes and new lubricants, and (4) examine surface treatments that may be incorporated in current and more particularly advanced aircraft engine bearing and gear components. The goal is understanding rather than specific recommendations.

FUNDAMENTAL TRIBOLOGICAL CONCEPTS

Understanding the adhesion, friction, wear and lubricated behavior of solids in contact is extremely important to understanding bearing, gear and seal performance in aircraft engines. It provides the basis for material selection, design considerations, lubricant use and material treatments.

Figure 1 schematically depicts two solids in contact as might occur in bearings, gears or seals. Real area of asperity contact is depicted at the interface by the black patches. The lesson to be remembered from this figure is that the load in mechanical components is borne by these areas and not the apparent contact area.

A second observation to be made for figure 1 is that when any two surfaces can come into intimate solid state contact strong bonds of adhesion can develop and these bonds effect friction. The stronger the bond, the higher the friction and the less efficient is the tribological component.

Yet a third point to be made with figure 1 is that associated with the wear of the two solid surfaces. There are various mechanisms of wear, adhesion, abrasion, corrosion, cavitation, erosion and fatigue all of which occur and are important to aircraft tribological components. These mechanisms will be discussed in the next section of this paper.

The final area to be considered in figure 1 is that associated with reducing, adhesion, friction and wear and thereby improving life namely lubrication. The objective of lubricating is to keep the surfaces from interacting and forming surface bonds. The lubricants as will be discussed in a latter section can be liquids or solids. The more effective they are in keeping the surfaces separated the better they are as lubricants.

MATERIAL PROPERTIES

There are a host of fundamental properties of materials which are related to tribological performance (ref. 1). The designer by keeping these in mind while selecting materials can do much to optimize the materials selection process.

Some recent advances in material properties, by way of example, which can be related to tribological performance are indicated in figures 2 to 5. They demonstrate fundamental relationships to particular tribological properties.

Figures 2 and 3 deal with the ever present fretting problem encountered in aircraft engine components. Fretting is a result of two wear mechanisms operating, adhesion and corrosion. Recent studies indicate that certain bulk and surface properties of metals can be related to fretting (ref. 2).

In figure 2 the fretting wear volume of pure metals is related to the shear strength of the metal. The higher the shear strength the less is the fretting wear. The selection of materials for aircraft components where fretting may be a problem should factor in this relationship.

The data of figure 2 indicates the adhesion component of fretting, namely the higher the shear strength the more difficult it is to generate an adhesive wear particle. The data of figure 3 reflects on the corrosive component of fretting.

The data of figure 3 indicate a correlation between fretting wear at high humidity (RH_{max}) and the heat of oxygen adsorption on the metal. The stronger the oxygen bond the lower is the material loss due to fretting. In a strict sense the adsorbed species are acting as a lubricant preventing adhesive wear from occurring. Remember what was said earlier relative to lubricant effectiveness. The better able the lubricant is to separate surfaces the more effective it is as a lubricant. Strong bonding, of course, reflects tenacity.

From a consideration of the data of figures 2 and 3 the designer with a fretting problem or potential one is better able to make a material selection. At least there are some guides provided.

Another form of wear frequently encountered in aircraft component design is that of abrasive wear. Abrasion can cause the rapid loss of material from bearing, gear and seal surfaces resulting in frequent component replacements. Are there basic guides to assist the designer with combating this form of wear? There certainly are properties directly relatable to abrasion. The most well know is that of hardness. The harder the material the greater is the abrasive wear resistance (ref. 3). This has been known for some time as reflected in the year of reference 3. There are more recently studied properties of materials which can be related to abrasive wear and to friction. One of these concerns fundamental alloy concepts (ref. 4).

An examination of simple binary alloys indicates that there is relationship between an atomic property, namely lattice radius ratios and abrasive wear. Further, it establishes an inverse relation to friction. The friction data of figure 4 is for silicon carbide abrading simple iron binary alloys.

The data of figure 4 indicate that during abrasion friction is at a minimum where the atomic ratio of the alloying element to iron is unity. Deviation to either side in size results in increased friction, increased hardness and increased wear resistance.

Another common form of wear encountered in aircraft, particularly engine components is that of erosive wear or erosion. While it does not generally cause incipient component failure as can be experienced with adhesion it limits component life. Are these any basic material properties that we can relate to this form of wear? Again recent fundamental studies indicate that there are such properties (ref. 5).

The data of figure 5 indicate a correlation between melting point of metals and their erosion resistance for various erodents, particle sizes, particle velocities and angles of impingement. Other properties, such as surface energy, strain energy, bulk modulus, hardness, ultimate resilience and atomic volume have also been correlated with resistance to erosion (ref. 5).

BEARING, GEAR, AND SEAL MATERIALS

Through the years a host of alloy materials have been employed for rolling element bearings and a number have been used in aircraft applications. Table I presents some representative steels. The currently most popular material is, of course, M-50.

An interesting observation to be made from the list in table I is that not a single one of the alloys was specifically uniquely designed in its composition for aircraft engine bearing applications. Through a process of extensive and expensive empirical testing M-50 has by and large been the survivor. But what about the future? Are engines going to run on M-50 henceforth? Insight is needed to formulate new bearing materials for future aircraft.

In deciding a new bearing composition for future aircraft applications thought must be given to what properties this new material should have incorporated into its structure. Table II presents some requirements for future bearing materials. With a knowledge of the limitations of M-50 and the areas in need of improvement from table II there is the basis for beginning of selecting property requirements of a new alloy and formulating its composition. It will for its development require the joint effort of both the designer and materials engineer. In the interim some of the surface treatments discussed in another section of this paper may offer improvement in the performance of existing bearing materials.

Table III presents some of the more commonly used gear materials in aircraft systems. In addition gears have been made from a host of material classes including polymers, brasses and bronzes, sintered powder-metal alloys and other steels. Again, as with bearings there are certain requirements for advanced gears materials as indicated in table IV. With gears, processing technology appears to be the current greatest impediment to significant advances.

Seal materials in aircraft are required for lip, ring, face, and labyrinth seals. Rubbers, acrylates, silicones, fluoroelastomers, and fluorocarbons (TFE) have all been used in lip seals. Higher temperatures in advanced engines will require materials with greater thermal and oxidative stability.

Today aircraft gas turbine mainshaft and accessory gear box ring and face seals are carbon-graphite structures. While these materials can be improved upon, new more oxidation resistant materials should be examined including ceramics such as silicon nitride and carbide, refractory metal alloys and coatings.

With labyrinth seals current technology involves the use of solid metal knife edges where the opposing lands are solid metal or abradable coatings applied to nickel alloy substrates. There is considerable room for improvement with the application of composite structures.

SURFACE MODIFICATION TECHNIQUES

In recent years considerable advances have been made in the deposition of protective surface coatings and treatments of surfaces to modify various properties. Coatings and surface treatments have been employed for altering catalytic behavior of surfaces, reducing corrosion, altering surface hardness, reducing friction, extending life, and the reduction of wear. Many of the techniques offer considerable promise for use in aircraft tribological components such as bearings, gears, and seals.

The principal recent advances in coating technology have resulted from the use of plasma physics deposition techniques. They have allowed for the deposition of soft metal films and soft inorganic compounds such as molybdenum disulfide for solid film lubrication, hard face coatings such as carbides and nitrides for higher hardness and improved wear life and noble metals for catalysis and corrosion protection.

Surface treatments involve the use of beam energy sources such as laser, ion, and electron. A variety of surface property changes can be induced with these treatments. Figure 6 presents schematically both the coating and treatment approaches. With coatings such processes as ion plating, sputter deposition, and chemical vapor deposition (CVD) offer protective surface films to reduce adhesion, friction, and wear as well as extend the life of mechanical components.

Ion plating provides an ideal process for achieving both corrosion and tribological protection. The process allows for the application of extremely thin (1500 A) films of high density, uniformity in thickness (50 A) with a diffuse or graded interface for maximum interfacial adhesion. It is especially adapted for the deposition of metallic films and alloys with not too greatly different vapor pressures for the alloying elements. The coating material is brought to the surface in a flux of argon ions and the coating materials consists of a mixture of atoms and ions. They penetrate the surface of the negatively charged substrate to be coated providing for the diffuse or graded interface between coating and substrate.

Sputter deposition allows for the application of nearly any type of coating, polymer, metal, alloy, ceramic or inorganic solid lubricants to nearly any substrate. The incoming flux to a surface can consist of ions, atoms, molecules, and molecular fragments. It is, for tribological applications, particularly useful in applying polymeric films of materials such as polytetrafluoroethylene and solid film lubricants such as molybdenum disulfide. While complex geometric surfaces such as small gear teeth can be coated with sputter deposition it does not have the "throwing power" of ion plating (ability to get into complex configurations). Further, the interface between coating and substrate is not diffuse or graded as with ion plating. Its principal merits lie in the ability to apply a wide variety of coatings to a host of substrate materials.

Chemical vapor deposition (CVD) has been introduced into tribology primarily with the deposition of hard face coatings for improved wear resistance and longer wear life. Refractory metal carbides, borides and nitrides have been deposited by this technique. Gaseous carriers are employed to bring components of the coating material to the substrate. For example, if one were to desire a silicon nitride coating, two gaseous species would be admitted into the plasma silicon tetrachloride ($SiCl_4$) and either nitrogen (N_2) or ammonia (NH_3).

Balancing gaseous ratios is important in achieving proper coating chemistry. One disadvantage of the process is that frequently the substrates must be heated to high temperature (i.e., 500 °C) during deposition. In coating heat treated bearings and gears such temperatures could destroy prior heat treatments.

With respect to surface treatments laser glazing is a relatively recent approach to altering near surface metallurgy and topography and it has considerable merit. Using a laser beam one can produce a smoothing in bearing or gear surface topography, heal surface defects such as microcracks, particularly those produced in production. It also can be used by rapid heating to surface melting and then quenching to generate "amorphous" surface layers. Wear studies on "amorphous" metals or metallic glasses indicate that the absence of crystal structure can provide superior wear resistance for such applications as foil bearings.

Ion beam treatments of surfaces can include ion etching, ion nitriding and ion implantation. In all cases a beam of ions is directed at the surface. The specie and the energy varies.

In ion etching a beam of inert gaseous ions will be directed at the surface to remove surface layers. It could be used to remove processing defects, undesirable surface contaminating layers, produce carbides in relief and roughen the surface, without introducing stresses, for the purpose of generating lubricant reservoirs.

With ion nitriding nitrogen ions are directed at the surface. They interact with nitride forming elements present at the tribological surface to produce the nitrides. It is a "clean" process in that it is conducted in a vacuum system with pure nitrogen gas.

The ion implantation process is capable of implanting ions of a desired species into surficial layers of the material. It is a high energy process with ion energies from 10 to 200 keV. Gaseous species such as nitrogen have been implanted into bearing materials as well as metallic ions such as titanium.

Electron beams and the energy associated therewith have been used to produce surface heating without raising the entire component to some desired surface temperature. It also is effective in altering or modifying polymeric material surfaces. The electrons can serve to produce bond scission with recombinations in structures that vary in composition from the original material.

LUBRICATION

All components of aircraft requiring lubrication are in fact lubricated by one of four principal lubrication regimes. With liquids these regimes are as indicated in figure 7. When the surfaces are separated by thick films with shear in the fluid as in journal bearings the hydrodynamic regime of figure 7 is operating (ref. 7). In this regime the fluids viscometric properties and oxidative and thermal stability are important as are the wetting and acceptability to the surface of additives. In looking to future aircraft applications those fluids offering high temperature oxidative and thermal stability must be examined. To that end research is presently being conducted with the fluorinated polyethers and the temperature range of stability is indicated in figure 8. These fluids offer promise to 315 °C but to achieve even higher temperatures more research will have to be expended on materials such as the fluoroether triazines which as indicated in figure 8 have potential for usefulness to 350 °C.

With new fluids arises the need for additives which are compatible with these new molecular structures. One additive used in many fluids is the antioxidant. This additive is particularly important with fluorinated fluids such as those indicated in figure 7. Studies with phosphorus containing additives indicate oxidative degradation of these materials can be considerably arrested by the use of such additives (ref. 8).

Figure 9 presents data for the oxidative degradation reactions of perfluoroalkylethers with and without oxidation inhibitors. Even in the presence of active titanium alloys degradation of the fluid lubricant can be appreciably retarded. All three additives of figure 9 were effective in reducing the breakdown of the perfluoroalkylethers in the presence of oxygen. For advanced aircraft systems considerable research is needed to explore additive surface interactive chemistry in order that optimum additive selection is made for advanced fluids.

In the elastohydrodynamic regime of figure 7 many of the same concepts already discussed in reference to hydrodynamic lubrication apply. The rheology of the fluids become extremely important in this area so important to rolling element bearings. While EHL theory is well in hand there is a strong need for the incorporation of real surface effects into the theory. Fluid temperatures in this regime have been experimentally measured and reach 350 °C and the topography of the bearing surface has been shown to be extremely significant. These real effects must be factored into future analysis.

Of all the regimes indicated in figure 7 the one that has received the least attention and that is in most need of understanding is the mixed film regime between boundary and elastohydrodynamic lubrication. What happens when the EHL films breakdown and solid state contact occurs. This certainly happens in aircraft components but has not been addressed with sufficient effort to arrive at an understanding.

It can be stated with certainty that the regime of figure 7 having received the greater attention is that of boundary lubrication and rightly so. It is in this regime that solid state contact occurs and the friction and wear reducing properties of the lubricant become all important.

First, there is the lubricating and stability properties of the fluid where liquid lubrication is employed. In most aircraft applications it is not so much the base fluid that is depended upon but rather the additives in the fluid for boundary lubrication. The base fluids thermal and oxidative stability are extremely important as the fluid must carry the additives to the surfaces needing lubrication and carry away heat.

In the search for new fluid lubricants for advanced aircraft systems the stability of the molecule must be examined. A good guide in examining structures is to determine the weakest bonding in the molecule and establish the dissociation energy of that bonding. This will provide insight into the thermal stability of the fluid as indicated in figure 10.

The data of figure 10 indicates the stronger the bond energy the higher the decomposition temperature (ref. 9). Using this approach one can verify that the fluoroether triazines of figure 8 have thermal stability to 350 °C.

As already mentioned it is in the boundary regime where additives are so all important in keeping the surfaces in solid state contact from wearing. With advanced aircraft design attempts to increase the load carrying ability of mechanical components will require both antiwear and extreme pressure (EP) additives superior to those presently in use. Figure 11 indicates how these additives effect both load carrying ability and wear in the boundary lubrication regime (ref. 10).

From an examination of figure 11 it is readily apparent that improvements in wear (ΔK) can be achieved with antiwear additives while the load carrying ability (ΔF) of a base oil can be markedly improved with the proper extreme pressure additives). Considerable research is currently being conducted into the mechanism of EP additive lubrication so that new and superior additives will be available for advanced lubricants.

There are those components of aircraft which can not be lubricated with conventional fluid film lubrication, for example, where the temperatures exceed the 350 °C discussed earlier. Under such conditions solid films with lubricating properties are employed. Lubrication with these materials are in the boundary regime because solid state contact is continuous.

Some of the most successful solid film lubricants have been the dichalcogenides, MX_2 compounds of S, Se or Te with a hexagonal-layered crystal structure. The easy shear parallel to the basal planes of the crystallites make them ideal solid lubricants. Some of these materials and their properties are presented in table V.

The data of table V indicates that these solids have application in aircraft parts at temperatures well above that experienced for liquids (ref. 11). These materials are, however, just as are fluids, sensitive to environment. This sensitivity is demonstrated in the data of figure 12 for molybdenum and tungsten disulfides (ref. 12).

In argon both compounds in figure 12 exhibit low coefficients of friction to 400 °C and acceptable values to 1000 °C. When the atmosphere is air, however, at 400 °C for the molybdenum disulfide and 600 °C for the tungsten disulfide friction increases appreciably due to the oxidation of these compounds to their respective oxides. When designing components for aircraft employing these materials the designer must maintain cognizance of these sensitivities particularly since these materials are seeing ever increasing use in aircraft.

A very promising lubrication system for advanced aircraft is to make greater use of polymer composite structures (refs. 13 to 19). These materials provide self-lubricating structural members. Various fillers can be incorporated into a basic polymer structure such as a polyimide. The filler can be metal, glass or graphite either powders or fibers.

Figure 13 presents an example of the application of a polymer composite to a spherical bearing. The composite as indicated in the figure may be used as the ball (upper schematic) or it can simply be used as a liner (lower schematic). There are broad opportunities offering considerable promise for the use of such materials in future aircraft systems where liquids can not be effectively used.

For future applications such as labyrinth seals where abradable seal materials are used and temperatures of rubbing surfaces are extremely high it may be necessary to lubricate with ceramic coating that have built in lubricating properties. Some of these materials have been successfully used in bearings at temperatures to 900 °C (ref. 20).

Figure 14 presents friction data for two of these compositions containing, nichrome, calcium fluoride, glass and one containing the addition of silver to reduce friction coefficient at lower temperatures. They can provide effective lubrication to 900 °C as indicated in the data of the figure.

SUMMARY REMARKS

A review of the present state of the art in tribological systems for aircraft engine applications indicate that there have been many recent advances in our understanding of materials and lubrication which can assist in improving tribological performance. If the design engineer gains a better fundamental understanding of the properties of materials which are related to adhesion, friction and wear more judicious selection of the appropriate materials can be made for bearing, gear and seal applications.

The significant progress in surface treatment technology offers a variety of opportunities in extending tribological component life. The use of plasma assisted deposition processes allow for thin films to be deposited on complex geometries, with uniformity, high density and with outstanding tenacity. Soft metals, polymers and inorganic compounds can be deposited for lubrication, hard face coatings for wear resistance and surface treatments such as ion nitriding for extended life.

In the area of lubrication new fluids and additives are being studied to extend the useful temperature range of liquid lubricants. Synthetic molecular structures are being examined for both oxidative and thermal stability and additives compatible with these fluids. Where liquids can not be used because of temperature limitations solids, such as soft metals and diechalcogenides are employed as well as polymer and polymer composite structures. For the extreme temperatures, beyond 500 °C, ceramic coatings containing fluorides have been shown to be effective.

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TABLE I. - BEARING MATERIAL

AISI M-50	AISI 9310 (C)[a]
AISI M-10	CBS 600 (C)[a]
AISI M-1	CBS 1000M(C)[a]
WB-49	CRB - 7
AISI 440-C	
SAE 52100	
AMS 5749	

[a](C)-carburized grades.

TABLE II. - REQUIREMENTS FOR FUTURE BEARING MATERIALS

Improved wear resistance
Improved corrosion resistance
Improved fracture toughness
Present hot hardness
Improved fatigue strength

TABLE III. - GEAR MATERIALS

AMS (AISI 9310)*
CBS 600
VASCO X2
PYROWEAR 53

TABLE IV. - REQUIREMENTS FOR FUTURE GEAR MATERIALS

High hot hardness
Improved fatigue life
Better fracture toughness
Superior wear resistance

TABLE V. - RESULTS OF THERMAL STABILITY AND FRICTIONAL EXPERIMENTS IN VACUUM OF 10^{-9} to 10^{-6} torr

Compound	Probable onset of thermal dissociation as detected by TGA, °C	Dissociation products first detected by mass spectrometry, °C	Maximum temperature at which burnished film provided effective lubrication, °C
MoS_2	930	1090	650
WS_2	870	1040	730
$MoSe_2$	760	980	760
WSe_2	700	930	760
$MoTe_2$	700	700	540
WTe_2	700	700	(a)

[a]Friction coefficient greater than 0.2 at all temperatures.

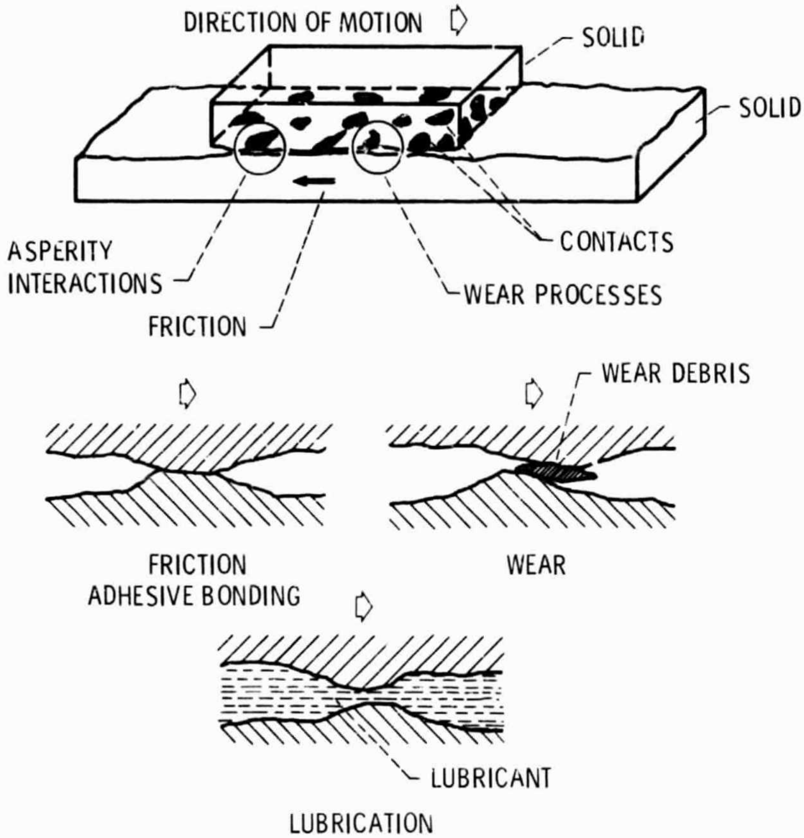


Figure 1. - Tribological properties of materials (adhesion, friction, wear and lubrication).

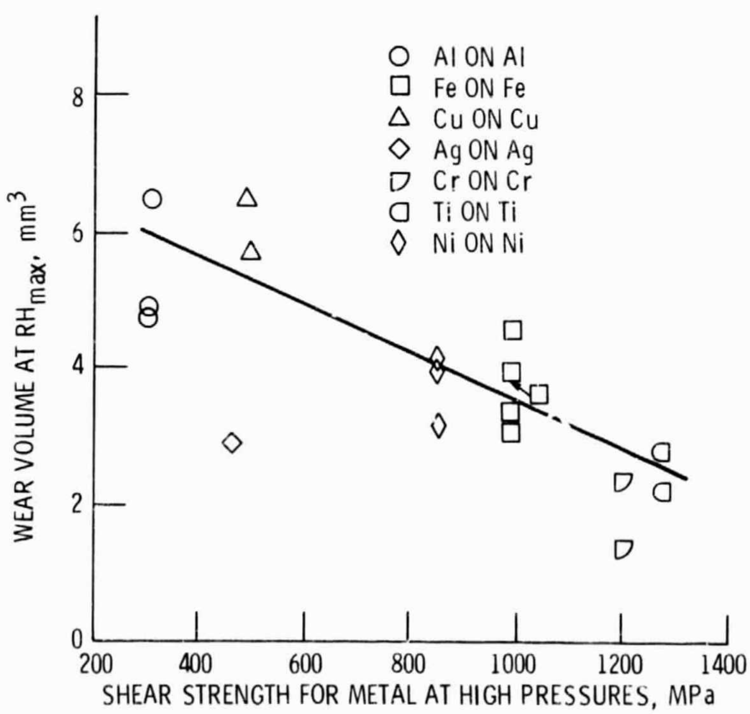


Figure 2. - Fretting wear volume at RH_{max} as a function of shear strength for pure metal at high pressures.

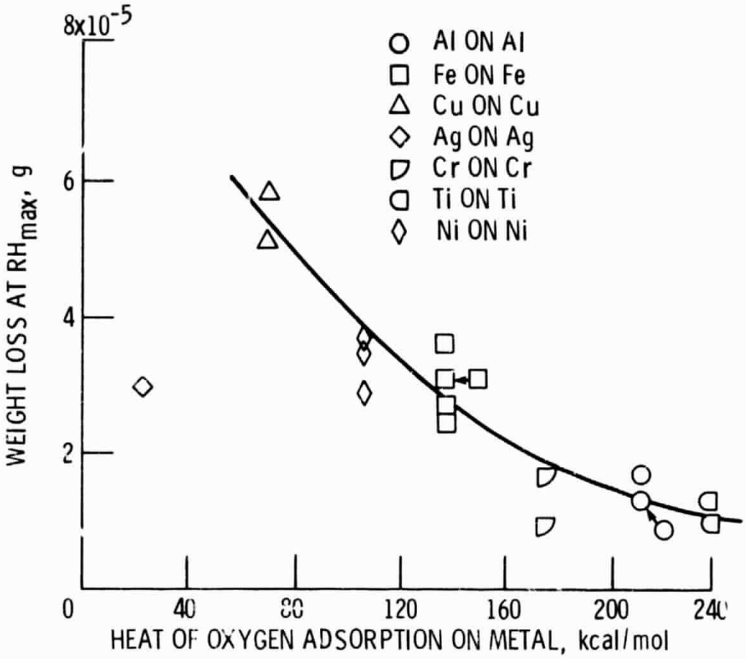
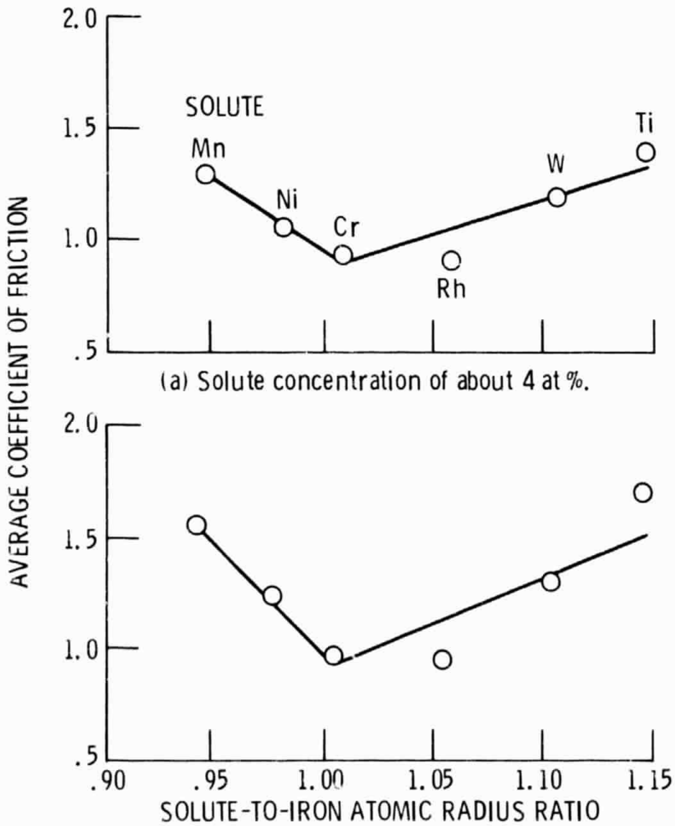


Figure 3. - Weight loss due to fretting wear at RH_{max} as a function of heat of oxygen adsorption on metal surface.



(a) Solute concentration of about 4 at %.

(b) Maximum solute concentrations of alloys.

Figure 4. - Coefficients of friction for iron-based binary alloys as function of solute-to-iron atomic radius ratio. Single-pass sliding on single-crystal silicon carbide (0001) surface.

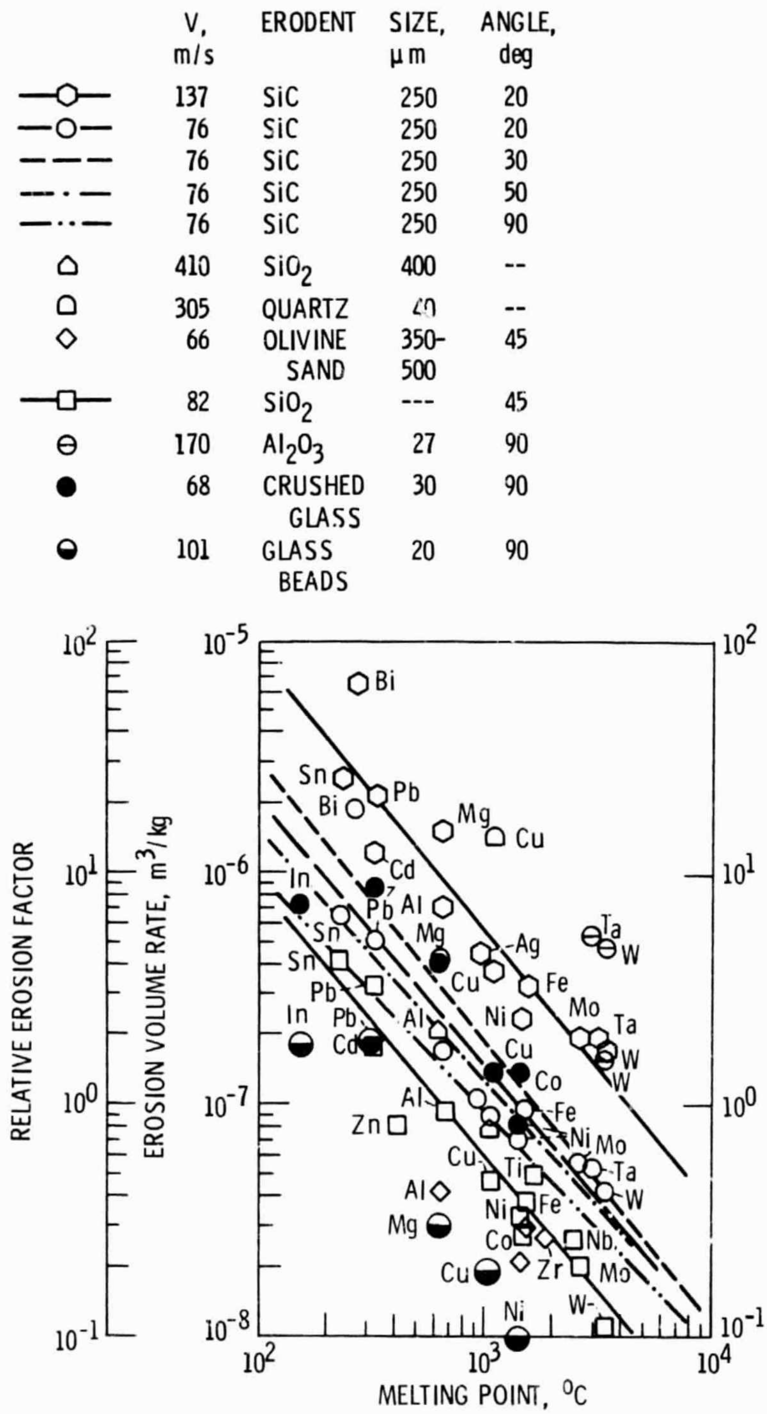


Figure 5. - Erosion rates of different metals as a function of melting point.

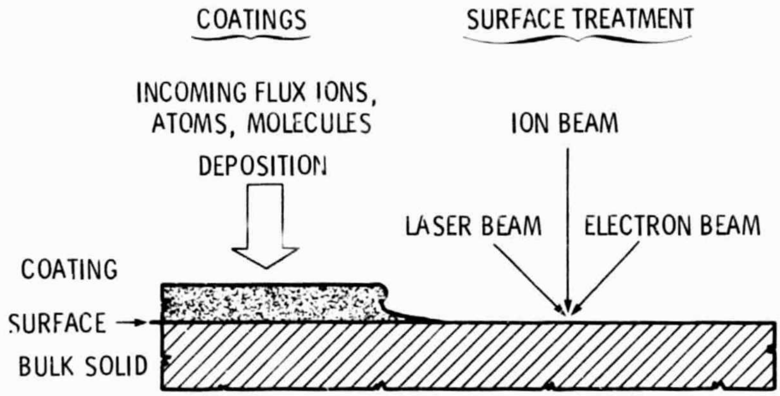


Figure 6. - Surface modification techniques.

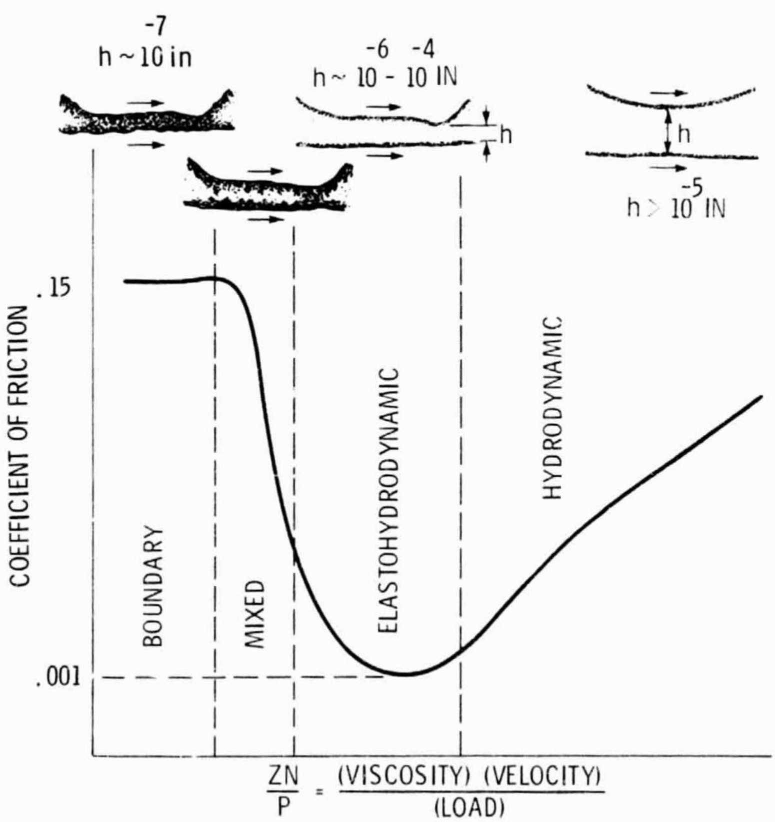


Figure 7. - Coefficient of friction as a function of speed-velocity-load parameter (Stribeck-Hersey curve) (ref. 1).

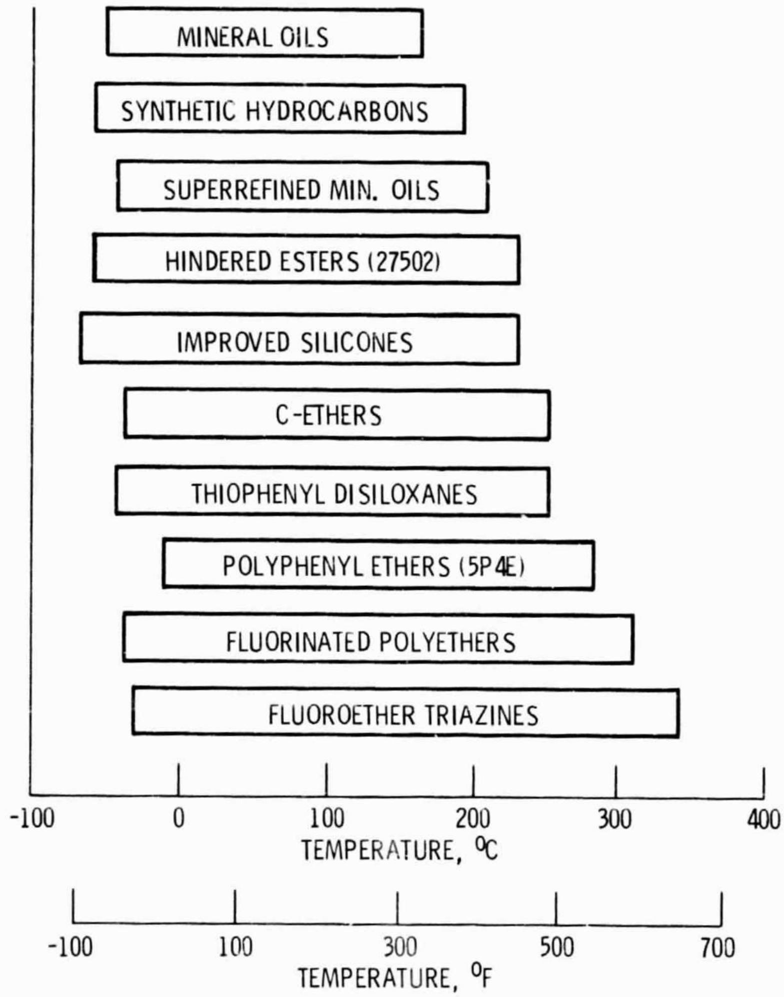


Figure 8. - Operating temperature range for classes of high temperature lubricants.

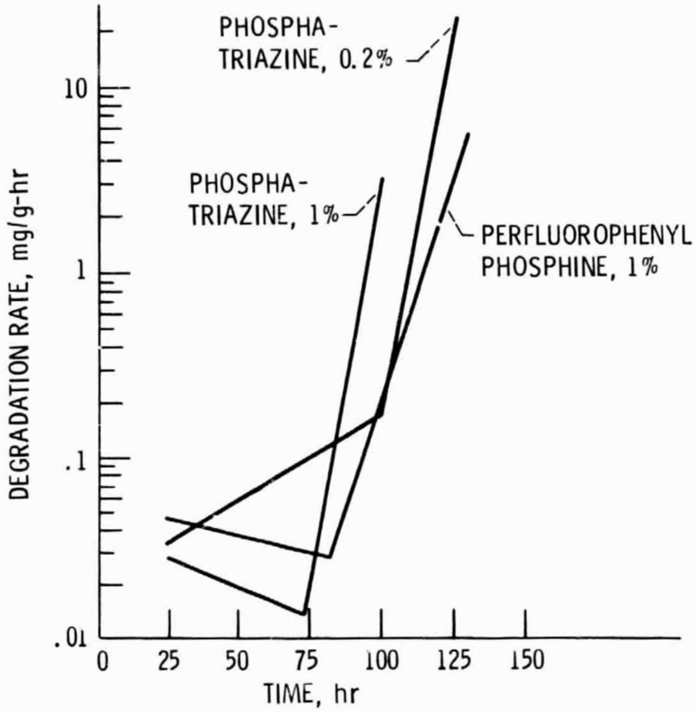


Figure 9. - The effects of metals and inhibitors on thermal oxidative degradation reactions of unbranched perfluoroalkylethers (288 °C, O_2, Ti (4Al, 4Mn) alloy).

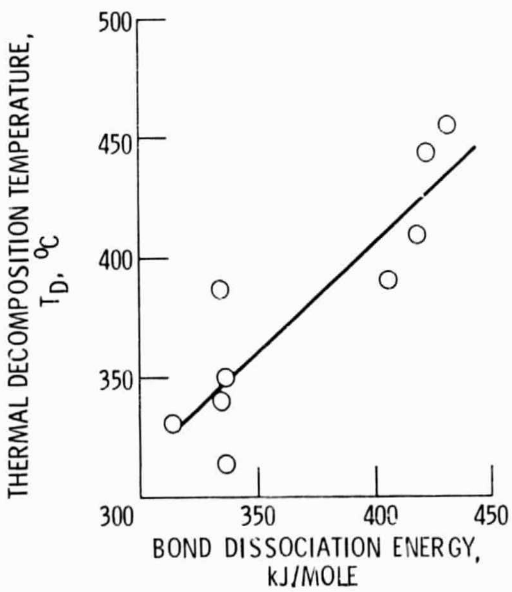


Figure 10. - Thermal decomposition temperature (T_d) as a function of bond dissociation energy.

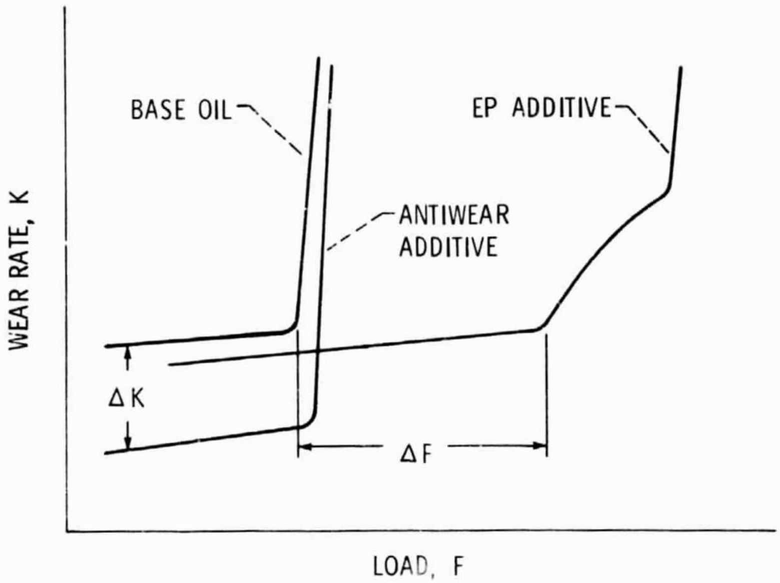


Figure 11. - Wear behavior of boundary-lubrication systems (ref. 10).

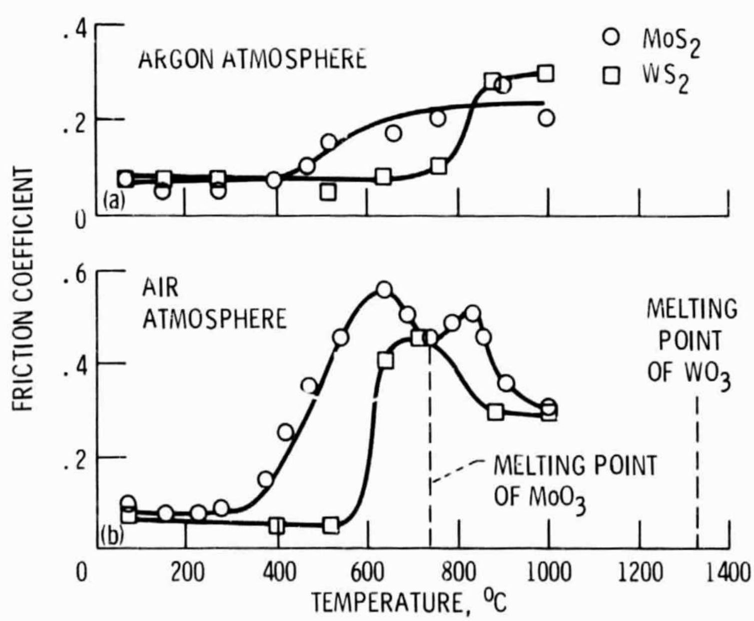


Figure 12. - Friction characteristics of MoS_2 and WS_2 in argon and in air.

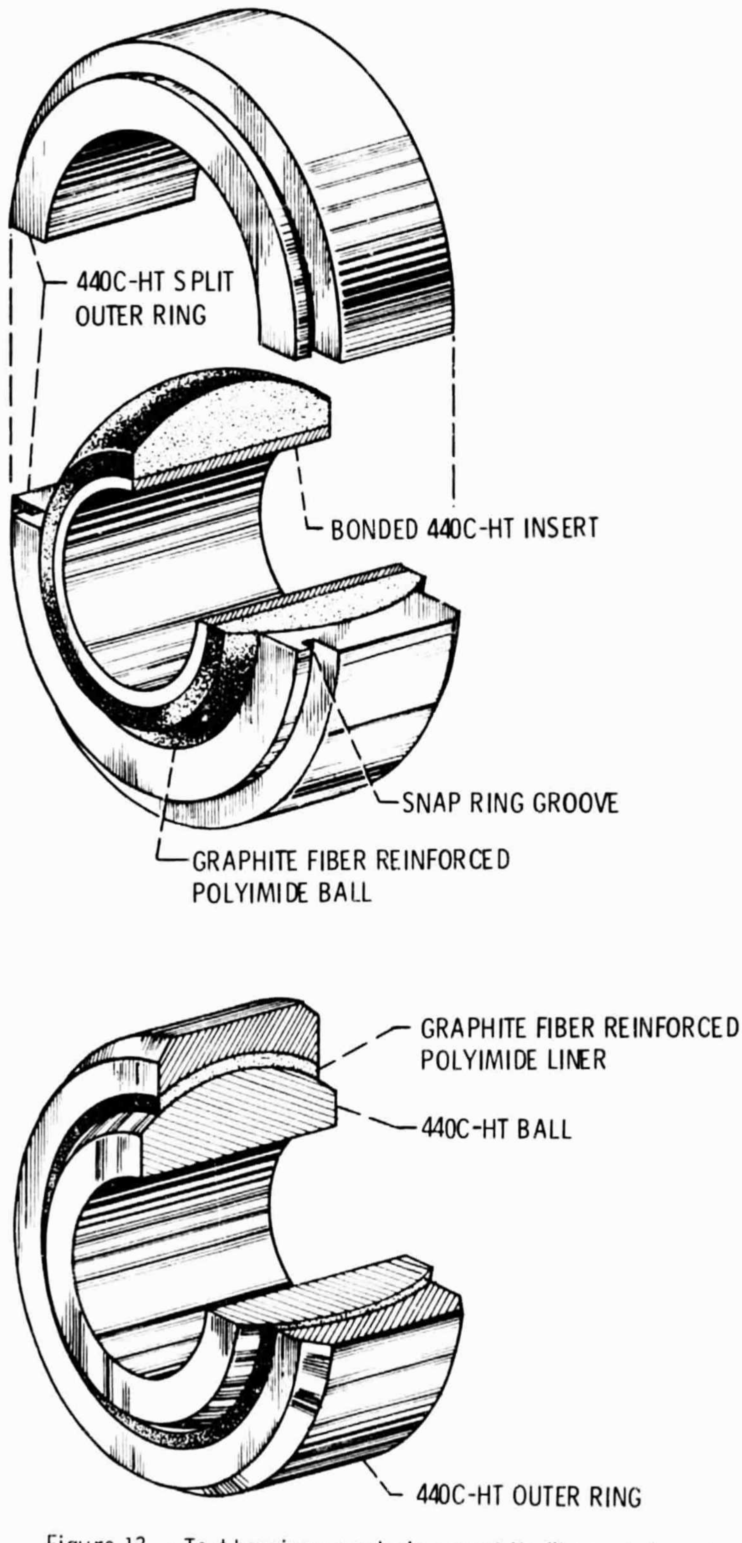


Figure 13. - Test bearings employing graphite fiber reinforced polyimide.

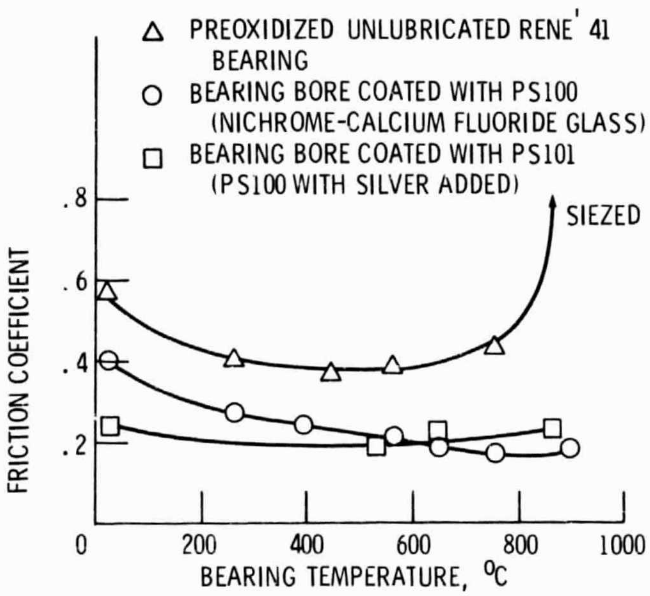


Figure 14. - Bearing friction.