

TRIBOLOGY

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INTRODUCTION

Tribology is the study of the adhesion, friction, wear, and lubricated behavior of materials in solid-state contact. The function of tribological research is to bring about a reduction in the adhesion, friction, and wear of mechanical components to prevent their failure and provide long, reliable component life through the judicious selection of materials, operating parameters, and lubricants.

Mechanical systems such as bearings, gears, and seals are examples of components involving tribology. Wherever, however, two or more solid surfaces are in contact with relative motion between the surfaces, tribology is involved. Such mundane activities as a man's morning shave involve both friction and corrosive wear, and considerable tribological research has gone into increasing blade life and reducing friction and shaving discomfort. More complex tribological systems are gyro bearings and instrumentation gears requiring attention to many elements.

The objective of the present paper is to review the adhesion, friction, and wear properties of materials and some of the factors influencing these properties. The forms of lubrication and types of lubricants will also be discussed.

ADHESION AND FRICTION

In a conventional atmospheric environment, the oxygen present in the air interacts with freshly generated metal and alloy surfaces to produce surface films; namely, oxides. These oxides play a very strong role in the adhesion, friction, and wear behavior of metals and alloys. In the absence of these oxides, very strong adhesion, high friction coefficients, and ultimately cold welding of materials from one surface to another are observed. If, for example, two normal metal surfaces are placed inside a vacuum environment with a system capable of achieving pressures to 10^{-10} torr, and the surfaces are very carefully cleaned with argon ion bombardment and then brought into touch contact, adhesion of one surface to the other will immediately occur. Attempts at tangential motion will cause a growth in the area adhered at the interface, that is, in the real contact area with an ultimate complete seizure of the surfaces one to another. With this occurrence, the surfaces are generally severely disrupted (refs. 1 and 2).

When adhered surfaces are separated, the adhesion at the interface between the two dissimilar solid surfaces is sufficiently strong to prevent fracture at the interface, but fracture does generally occur in the cohesively weaker of the two materials in contact (ref. 3). An example of such behavior is shown in the photomicrograph of figure 1. This figure represents the results of an experiment conducted in a vacuum chamber where two solid surfaces were brought into contact; the surfaces had been cleaned in vacuum. Adhesion occurred at the interface, and when separation of the solid surface was attempted, fracture occurred in one of the two materials, leaving material transferred to the opposite surface.

The actual area of real contact at the interface can be seen in figure 1 by a careful examination of the interface region. There appear to be voids in the interface region where complete and intimate solid-state contact across the interface did not occur. However, a great portion of the interfacial area does reflect solid-to-solid contact in adhesive bonding. This adhesive bond was generated as a result of attempting to slide one surface over the other. This resulted in growth in the adhered junctions at the interface, leaving only a small area wherein no intimate contact of the two solid surfaces occurred. On separation, the adhesive bond at the interface remained intact and fracture occurred in one of the solids, as indicated in figure 1 by the rough piece which remained on the solid surface.

This type of adhesion and transfer behavior is observed for all clean metal surfaces and alloys in solid-state contact. That is, when the environmentally

contributed surface films, namely the oxides, are removed, such adhesion is observed with strong bonding and friction coefficients measured in excess of 100 under such circumstances. The surfaces of solids such as metals and alloys are so sensitive to the contact region microenvironment that the admission of very small adsorbate concentrations from the environment to the solid surface can markedly reduce adhesion and friction. For example, fractions of a monolayer on the solid surface will produce a marked reduction in the adhesion and corresponding static friction coefficients for metal in contact (ref. 4).

In addition to metals and alloys, nonmetallic materials are also markedly influenced by the presence of the environment in their adhesion, friction, and wear behavior. The presence of adsorbates on ceramic materials such as aluminum oxide has a pronounced influence on the friction coefficients measured for aluminum oxide (ref. 5).

Polymeric materials are also affected by the presence of environmental constituents on their surfaces. For example, nylon serves as a good solid self-lubricating material in certain mechanical applications. Nylon, however, depends upon the presence of adsorbed moisture for its effective lubrication; that is, for its low friction and wear properties. In the absence of moisture, nylon will not lubricate effectively and it becomes a poor tribological material (ref. 5). Carbon materials are heavily used in mechanical devices such as dynamic seals and are extremely sensitive to environment and environmental constituents.

The flying of aircraft at high altitudes results in excessive wear in carbon generator brush materials; this was established during the second World War. Careful analysis of the aircraft surfaces revealed that the excessive wear of carbon materials, carbon bodies at high altitudes, was due to a reduction in the ambient pressure, and more particularly with the reduction of moisture in the environment. Carefully controlled experiments in the laboratory subsequently demonstrated that carbon lubricates effectively in the presence of moisture, exhibiting low friction, low wear, and little tendency to adhere. In the absence of moisture, however, carbon exhibits extremely heavy wear and becomes a very poor friction and wear material. In fact, by simply reducing the ambient pressure from 760 torr of air to an ambient pressure of approximately 1 torr, a 1,000-fold change in wear properties occurs. Thus, moisture is a lubricant and is needed on these surfaces and at the interface between two carbon bodies in relative contact and in motion, or between the carbon body and some other material in solid-state contact (ref. 5).

If one considers the environment not only as an ordinary air containing principally oxygen and nitrogen with some water vapor, but also considers vapors of hydrocarbons as constituents of the environment, then the particular hydrocarbon molecular structure that may be present in the environment can have a very pronounced influence upon the adhesion, friction, and wear behavior of materials in contact. For example, careful cleaning of iron surfaces in a vacuum environment will result in the generation of extremely energetic surfaces that will adhere one to another when brought into contact with cold welding occurring readily. If, however, a small amount of hydrocarbon gas is admitted to the vacuum chamber and allowed to absorb on the clean iron surface, a structure will develop which will provide that surface with a protective film.

Further, clean iron surfaces will chemisorb nearly all hydrocarbons (ref. 6). The hydrocarbon film will reduce adhesion, friction, and wear because the surface energy has been reduced by the hydrocarbon molecules on the surface. The energy on the clean iron surface available for bonding across the interface to another solid surface has been taken up in the interaction of the clean iron surface with the lubricating molecules absorbing on it. The particular molecular structure, however, of the adsorbing hydrocarbon will also affect the tribological behavior. That is, a slight modification in the molecule will produce sensitivities in

adhesion, friction, and wear. These slight differences indicate extreme sensitivity in the tribological behavior of materials to environment and environmental constituents. This effect can be demonstrated by the adsorption of a simple hydrocarbon such as ethylene oxide onto an iron surface and exposure of that same surface to a different simple hydrocarbon with a slightly modified molecular structure, something such as ethylene chloride (or as it is commonly called, vinyl chloride).

If clean iron single crystal surfaces of the same orientation are exposed to equivalent concentrations of these two simple hydrocarbons, namely ethylene oxide and vinyl chloride, entirely different surface structures result. The differences can be seen in the LEED (Low Energy Electron Diffraction) patterns presented in figure 2.

LEED is a device which permits examination of the structural arrangement of atoms in the outermost atomic layer of the solid surface. Thus, in figure 2, we see the molecular arrangement in the diffraction pattern for the adsorbed ethylene oxide and vinyl chloride on the iron surface in the two patterns. Equivalent concentrations of each specie were provided. Thus, everything is constant except the particular molecular structure. The ethylene oxide exhibits the basic ethylene structure with oxygen present in the molecule. Vinyl chloride exhibits essentially the same structure as the ethylene, but chlorine is substituted for oxygen. This subtle difference in the structures, however, causes marked differences in surface coverage (see LEED patterns, fig. 2).

With the ethylene oxide, the six diffraction spots in a hexagonal array indicate that the ethylene oxide molecule completely masked or covered the iron surface. No diffraction spots are seen for the iron in the diffraction pattern of figure 2. A close packing of the molecules of ethylene oxide on the iron surface provides a very effective and continuous surface film.

In contrast to ethylene oxide, however, the vinyl chloride structure is much more open with less-than-complete surface coverage and bonding of vinyl chloride to the surface. The four bright diffraction spots with vinyl chloride adsorption, seen in a rectangular array in figure 2, are associated with the iron. Thus, vinyl chloride does not provide complete coverage, and nascent iron is still exposed at the surface.

As one might anticipate, differences in adhesion and friction behavior are observed with these two films present. With the ethylene oxide, the adhesive forces are appreciably reduced between two clean iron surfaces in contact. Further, the friction forces are less for the ethylene oxide on the iron surface than are observed with the vinyl chloride present. Thus, slight differences in the molecular structure of hydrocarbons present in the microenvironment of solid surfaces in contact can influence the tribological behavior of those surfaces.

WEAR

Various recognized mechanisms cause surfaces to wear. The more common types are adhesion, abrasion, corrosion, erosion, cavitation, fretting, and fatigue. Some of these mechanisms will be briefly discussed.

Adhesive Wear

Adhesion has already been discussed with reference to figure 1. The transfer resulting from the interfacial adhesion is adhesive wear. Material has been lost from one surface and transferred to another. Adhesive wear can occur for a wide variety of materials brought into contact. Abrasive wear, however, is limited to those situations where a very hard material contacts a softer material, or where hard particles are sandwiched between two softer surfaces (e.g., particles of sand

in a bearing). Abrasion occurs when a softer surface is cut or micromachined by a harder surface or particle.

Abrasive Wear

One might intuitively anticipate that the resistance of a material to abrasive wear is strongly a function of the hardness of the surface being abraded. The harder the surface, the greater should be the resistance to abrasion; this has been experimentally demonstrated (ref. 7).

In figure 3 resistance to wear is plotted as a function of hardness for the surface of various metals. The data of figure 3 indicate a direct relation between the hardness of the metal being abraded and its abrasive wear resistance.

The abrasion of solid surfaces involves wear to the abrasive as well as wear to the surface being abraded. For example, with such relatively hard abrasive materials as single crystal aluminum oxide (sapphire) and titanium dioxide (rutile), the resistance to wear is very much a function of their orientation. With certain atomic planes contacting steel, wear resistance of the abrasive substance is greater than for other orientations. This resistance is demonstrated in the data of figure 4 for titanium dioxide.

A marked variation in the wear rate of titanium dioxide (fig. 4) occurs with changes in orientation. Between the minimum and maximum it varies by a factor of seven times. Thus, abrasion can result in wear to the abrasive as well as to the surface being abraded; the latter can be minimized by giving consideration to the physical and mechanical properties of the abrasive material.

Corrosive Wear

The surfaces of solids play an extremely important role in corrosive wear. In corrosive wear, material is lost from a solid as a direct result of chemical interactions of the solid surface with the environment. The active environmental constituent can be the lubricant, an additive, or a component of the surrounding atmosphere. The relative motion between solid surfaces in contact aggravates surface attrition by continuously exposing fresh surface for reaction.

Materials which are very effective lubricants under certain conditions can become extremely reactive under another set of conditions. The lubrication of alloys with halogen-containing lubricants is a good example.

In figure 5 for a cobalt alloy lubricated by a chlorinated fluorocarbon, wear at temperatures to 300° C is extremely low. The values in figure 5 are 100 times less than those obtained for the unlubricated surfaces. Above 300° C, however, the rate of wear begins to increase markedly. This increase is due to excessive chemical reactivity of the chlorine of the chlorinated fluorocarbon with the cobalt surface.

Examination of the cobalt alloy surface after sliding revealed copious quantities of cobalt chloride. This particular compound is an extremely good solid-film lubricant and accounts for the low wear to 300° C. Above that temperature cobalt chloride continues to form, but in such large quantities that the cobalt alloys are consumed as a result of excessive surface reactivity. Thus, effective lubrication, with solid films of the type described here, is a matter of controlled corrosion. A reaction product should form to reduce friction and wear, as in figure 5, but that quantity should be limited.

The data of figure 5 also indicate that no correlation between friction and wear can be drawn from information about one or the other. Corrosive wear is an excellent example of this concept. Wear may increase due to the excessive reactivity, but friction may decrease because of the low shear strength of the reaction product formed.

Corrosive wear can be brought about by increasing temperature, as indicated in figure 5. Similar effects can be produced by both increased loading and increased rubbing speeds.

A wide variety of material properties affects wear behavior. As already indicated with reference to figure 4, the crystallographic orientation of materials affects wear. This property holds true not only for the wear of nonmetals, but for metals as well (ref. 8).

Crystal structure is another property of materials which influences wear. Transformation in a metal from one crystal structure to another can result in notable changes in wear. This effect is indicated for tin in figure 6. The wear track width is plotted as a function of temperature, and is relatively constant until the temperature for the transformation of tin from a diamond structure (gray tin) to that of the tetragonal (white tin) is approached. At that point wear begins to increase. The tetragonal tin structure has greater ductility than the diamond form.

A further manifestation of the effect of crystal structure is observed when layer lamellar solids are in rubbing contact with metals. With these solids shear readily occurs along basal planes, and transfer to the metal surface is readily observed; this can be seen in table I. In the table pyrolytic boron nitride transfers to all metals except gold and silver; poor adhesion accounts for this failure.

In practical engineering applications, metals are not used in their elemental form, but rather as alloys. The alloying elements can have varying effects on wear. For example, in figure 7, adding 10-atomic-percent aluminum to copper does not affect its rate of wear. The addition of 10-atomic-percent of alloying element such as silicon, tin, or indium to copper does, however, appreciably reduce wear (fig. 7).

The wear behavior differences for copper alloyed with various elements are maintained even with variations in the concentration of the lubricant additive, as is indicated in figure 8 for the alloys copper-10-atomic-percent aluminum and copper-10-atomic-percent indium. At all concentrations of stearic acid, wear is greater with aluminum alloyed with copper than it is for indium alloyed with copper.

LUBRICATION

Liquids

The purpose of lubrication is to separate surfaces in relative motion by a material which has a low resistance to shear so that the surfaces do not sustain major damage. This low-resistance material can be any of a variety of different species (e.g., adsorbed gases, chemical reactions films, liquids, solid lubricants), some of which have already been discussed.

Depending on the type of intervening film and its thickness, a number of lubrication regimes can be identified. A classical way of depicting some of these regimes is by use of the well-known Stribeck curve (fig. 9). Stribeck (ref. 9) performed comprehensive experiments on journal bearings around 1900. He measured the coefficient of friction as a function of load, speed, and temperature. He had difficulty, however, condensing this data into usable form. Some years later, Hersey (ref. 10) performed similar experiments and devised a plotting format based on a dimensionless parameter. The Stribeck curve, or more appropriately, the Stribeck-Hersey curve, takes the form of the coefficient of friction as a function of the viscosity of the liquid (Z), velocity (N), and load (P) parameter, ZN/P .

At high values of ZN/P which occur at high speeds, low loads, and at high viscosities, the surfaces are completely separated by a thick ($>0.25 \mu\text{m}$)

(>10⁻⁵ in.)) lubricant film. This area is that of hydrodynamic lubrication where friction is determined by the rheology of the lubricant. For nonconformal concentrated contacts where loads are high enough to cause elastic deformation of the surfaces and pressure-viscosity effects on the lubricant, another fluid film regime, elastohydrodynamic lubrication (EHL), can be identified. In this regime film thickness (h) may range from 0.025 to 2.5 μm (10⁻⁶ to 10⁻⁴ in.).

As film thickness becomes progressively thinner, surface interactions start taking place. This regime of increasing friction, which combines asperity interactions and fluid film effects, is referred to as the mixed-lubrication regime.

Finally, at low values of the ZN/P parameter, one enters the realm of boundary lubrication. This regime is characterized by the following:

1. This regime is highly complex, involving metallurgy, surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics.
2. The most important aspect of this regime is the formation of protective surface films to minimize wear and surface damage.
3. The formation of these films is governed by the chemistry of the film-forming agent, as well as the surface of the solid and other environmental factors.
4. The effectiveness of these films in minimizing wear is determined by their physical properties, which include shear strength, thickness, surface adhesion, film cohesion, melting point or decomposition temperature, and solubility.

Besides the Stribeck-Hersey curve (fig. 9) already described, an idealized plot of wear rate as a function of relative load can also delineate the various lubrication regimes and some wear transitions (fig. 10, ref. 11).

Region OA of figure 10 encompasses the regimes of hydrodynamic and EHL, the latter as point A is approached. Since no surface interactions occur in this region except for startup or shutdown, little or no wear occurs. (This excludes rolling-element fatigue, which can occur without surface interactions.) Region AX is the mixed-lubrication regime where surface interactions begin to occur at A and become more prevalent as point X is approached. Wear is low because fluid film effects still exist.

Next there is region XY in figure 11, which is the region of boundary lubrication. The degree of metal-to-metal contact and the wear rate increase as the load increases. Wear is mild and tends to be corrosive to the left of B and adhesive to the right of B. The location of B is quite variable and depends on the corrosivity of the lubricant formulation. For a noncorrosive lubricant, adhesive wear can occur at X. On the other hand, a corrosive additive can extend the boundary regime to Z¹ before boundary film failure occurs. Region YZ is the regime of severe wear where severe adhesion and scoring occur. Machinery cannot operate successfully in this region, and, therefore, the location of this transition point is quite important. At point Z total surface failure occurs, followed by seizure.

In the boundary lubrication regime many properties of the liquid lubricant become important. These include shear strength, film thickness, melting point, and chemical reactivity with the surface. Operating variables which will affect lubricant film performance include load, speed, temperature, and atmosphere, as already discussed. Additives present in the lubricant to serve specific functions will also affect behavior. These additives include anti-wear, anti-foam, anti-oxidants, viscosity improvers, and others. A good review of boundary lubrication can be found in reference 12.

Solids

At temperatures below which liquid lubricants become solid, and above which they either thermally or oxidatively decompose, solids are used. The solids

include inorganic compounds, polymers, and low-shear-strength metals. A review of the subject can be found in reference 13.

Of solid lubricants, those most widely used and studied are the layer-lattice inorganic compounds. These materials have a hexagonally layered crystal structure. Their shear properties are anisotropic with preferred planes for easy shear parallel to the basal planes of the crystallites. In some of the compounds such as molybdenum disulfide (MoS_2), a low shear strength is intrinsic to the pure material, while in others, notably graphite, the presence of absorbed gases or intercalated "impurities" between the basal planes appears to be necessary to develop desirable friction characteristics. The most common representatives of this class of lubricants are graphite and the dichalcogenides, notably MoS_2 and WS_2 .

The maximum useful temperatures for solid lubricants depend strongly upon the composition of the ambient atmosphere, the required life at temperature, factors such as oxygen availability at the lubricated surface (is the coating openly exposed to the atmosphere, or shielded within conforming bearing surfaces?), air flow rates, lubricant particle size, and the influence of adjuvants and binders.

Dichalcogenides

The maximum temperature for lubrication with MoS_2 in an air atmosphere is limited by oxidation to about 400°C under favorable conditions. Some oxidation kinetics data for loosely compacted MoS_2 powders of μ average particle size are given in figure 11(a) from reference 13. At a modest airflow rate over the compact, 50 percent of the MoS_2 was oxidized to molybdic oxide (MoO_3) in 1 hour at 400°C . At a six-times-higher airflow rate, the temperature for an oxidation half-life of 1 hour was reduced to 300°C . Figure 1(b) compares the oxidation kinetics of MoS_2 and WS_2 at the lower airflow rate. The curves for MoS_2 and WS_2 intersect, with MoS_2 oxidizing more rapidly above about 340°C .

Friction experiments were conducted with a pin-on-disk apparatus using a hemispherically tipped pin in sliding contact with the flat surface of a rotating disk. A comparison of the oxidation data of figure 11 and the friction data of figure 12(b) (ref. 13) shows that the loss of lubricating ability of MoS_2 and WS_2 in air coincides with the temperatures at which rapid conversion to the oxides occurs.

Figure 12(a) also shows that both compounds lubricate to much higher temperatures in a nonreactive argon atmosphere. In an inert gas or vacuum, the maximum useful temperature is a function of the thermal dissociation rates, rather than the oxidation rates of the lubricants. Thermal dissociation rates and the friction coefficients of molybdenum and tungsten disulfides, diselenides, and ditellurides in vacuum have been systematically studied (ref. 14). The major results, summarized in table II, indicate that the disulfides are the most stable, the diselenides are intermediate, and the ditellurides are the least stable. However, thin, burnished films of the diselenides with their higher densities evaporate more slowly than the disulfides. Apparently, for the very thin, burnished films, the evaporation rates were the controlling factor in determining the maximum temperature for effective lubrication. The limiting temperatures for a significant wear life of these coatings ranged from 600° to 700°C .

Vacuum-deposited coatings are increasingly being used in tribological applications; these fall into two main composition categories: soft-lubricating coatings, and very hard, wear-resistant coatings. The methods of application are also in two principal categories: sputtering and ion-plating. These techniques have been rapidly adopted by industry especially for aerospace applications. A very large variety of these vacuum-deposited coatings is becoming available for lubrication application.

The most common vacuum-deposited tribological coatings are the sputtered dichalogenides, especially MoS₂ and ion-plated soft metals such as gold. These coatings are often very thin, on the order of 2000 to 5000 Å in thickness. Compounds such as MoS₂ are usually applied by sputtering, because with proper procedures, pure, essentially stoichiometric, compounds can be deposited. In contrast, ion-plating tends to dissociate chemical compounds. However, ion-plating is an appropriate technique for the deposition of elemental metals because (1) dissociation is obviously not a problem; (2) high ion-impact energies can be used to enhance adhesion; (3) excellent throwing power is achieved when coating parts with complex shapes; and (4) rapid deposition rates can be achieved.

Sputtered hard coats are used primarily for wear control. The oxidation temperatures and hardness of some important carbides and nitrides are presented in table III. Coatings of all of the compounds listed are hard enough to be expected to have good wear resistance, assuming adequate bond to the substrate can be achieved. However, a considerable variation in oxidation resistance exists. Chromium carbide, boron carbide, silicon nitride, and silicon carbide are oxidatively stable to at least 1000° C, while tungsten and titanium carbides oxidize during long-duration exposure in air at temperatures above about 540° C. Tungsten carbide tends to oxidize more rapidly than titanium carbide because its oxides are volatile at high temperature, and their sublimation tends to accelerate the oxidation.

Titanium nitride is another promising hard-coat material, but it too will convert to the oxide above 550° C. However, some TiC- and TiN-sputtered coatings have shown surprisingly good resistance to oxide conversion at higher temperatures than those listed in table III. Oxidation occurs, but the rate is very low, probably because of high coating density and the passivating nature of the initially formed oxide films, which protect the coating against catastrophic oxidation.

CONCLUDING REMARKS

The adhesion, friction, and wear behavior of materials in solid-state contact are strongly dependent upon material properties and environmental factors. Adsorbed surface films and oxides on metals markedly influence tribological behavior.

Relatively subtle differences in the molecular structure of hydrocarbons can profoundly influence adhesion and friction. With liquid lubrication, distinct regimes of lubrication are identified. Both the physical properties of the lubricant and operating variables affect lubricant performance.

With solids as high-temperature lubricants, both thermal and oxidative stability are important, as well as the lubricating properties of the solids over a broad temperature range. Techniques such as ion-plating and sputtering are being increasingly used for the application of solid film lubricants.

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TABLE I. - TRANSFER OF MATERIAL FOR VARIOUS METALS IN SLIDING CONTACT WITH PYROLYTIC BORON NITRIDE

Metal	Metal to boron nitride	Boron nitride to metal
Aluminum	No	---
Titanium	No	Yes
Iron	No	Yes
Platinum	No	Yes
Copper	No	Yes
Gold	No	No
Silver	No	No
Tantalum	--	Yes
Niobium	--	Yes
Zirconium	--	Yes
Vanadium	--	Yes
Rhodium	--	Yes

TABLE II. - 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 films 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)

^aFriction coefficient greater than 0.2 at all temperatures.

TABLE III. - BULK PROPERTIES OF SOME HARD-COAT MATERIALS^a

Material	Microhardness, kg/mm ²	Oxidation temperature ^b , °C
B ₄ C	4200	1090
TiC	3200	540
SiC	2900	1650
Cr ₃ C ₄	2650	1370
WC	2050	540
Si ₃ N ₄	2000	1400
TiN	1950	540
Cr ₂ O ₃	^c 1800	----

^aData from: Engineering Properties of Ceramic Materials, Battelle Memorial Institute, Published by American Ceramic Society, Columbus, Ohio, 1966.

^bTemperature for appreciable detrimental oxidation passivating oxide films form at lower temperatures.

^cEstimated conversion from published Moh hardness of 9.



Figure 1.- Severe surface welding resulting from unlubricated sliding (2% Al-Ni alloy from 10⁻⁹ mm Hg vacuum experiment).

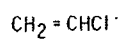
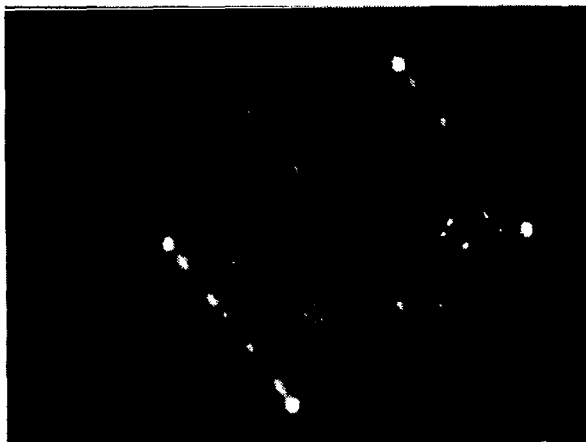
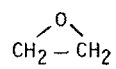


Figure 2.- LEED patterns obtained with two polymer forming hydrocarbons on iron (001) surface (100 L exp.).

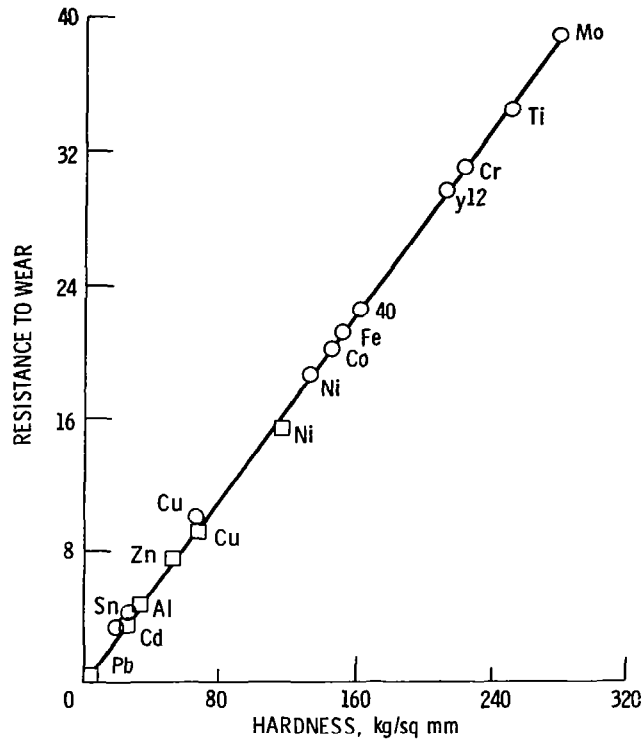


Figure 3.- Resistance to wear as a function of hardness. (See ref. 7.)

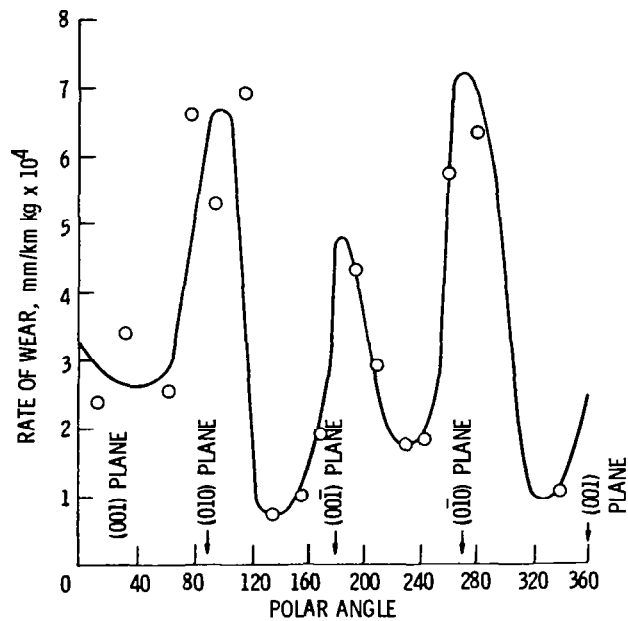


Figure 4.- Rate of wear of a rutile single-crystal sphere on a great circle in the plane of the a- and c-axes. C-axis is normal to plane of sliding at 0° and 180°. Slide direction is in plane of great circle.

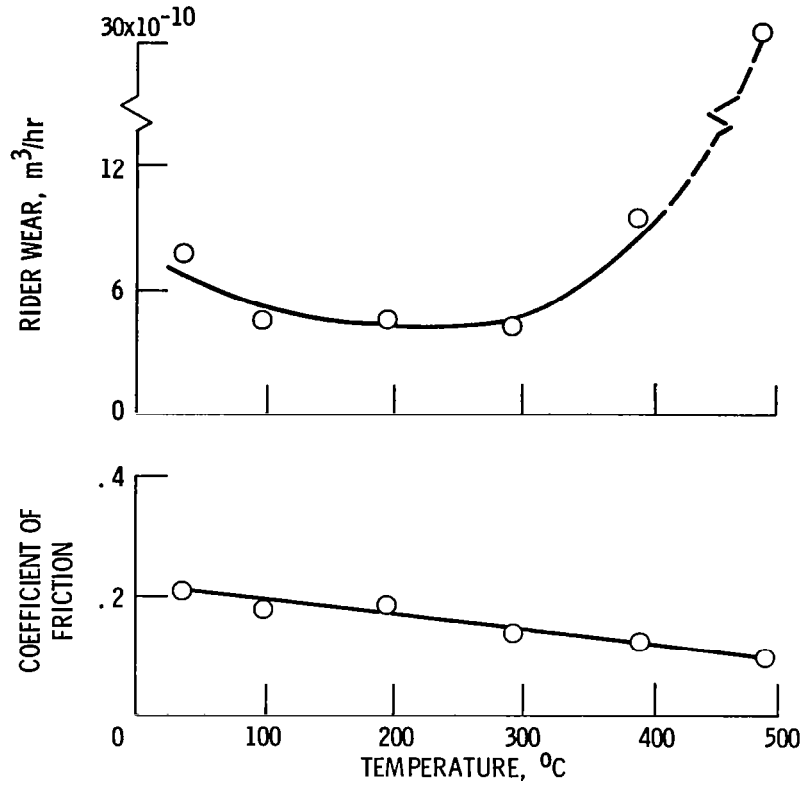


Figure 5.- Friction and wear of cobalt alloy sliding on itself at various temperatures and lubricated with a chlorinated fluorocarbon.

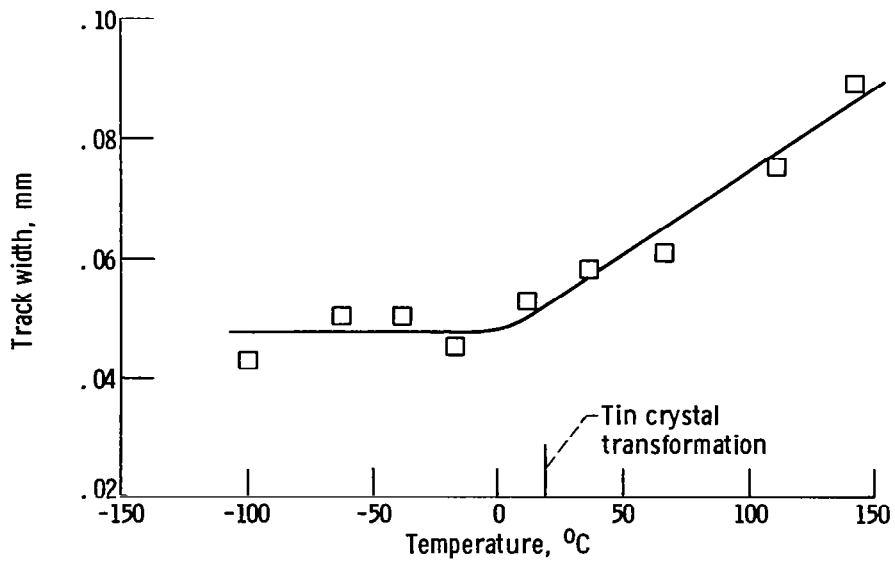


Figure 6.- Track width on tin single-crystal surface as function of temperature. Sliding velocity = 0.7 mm/min; load = 10 g; pressure = 10^{-8} N/m² (10^{-8} N/m²); rider = iron (110); single pass.

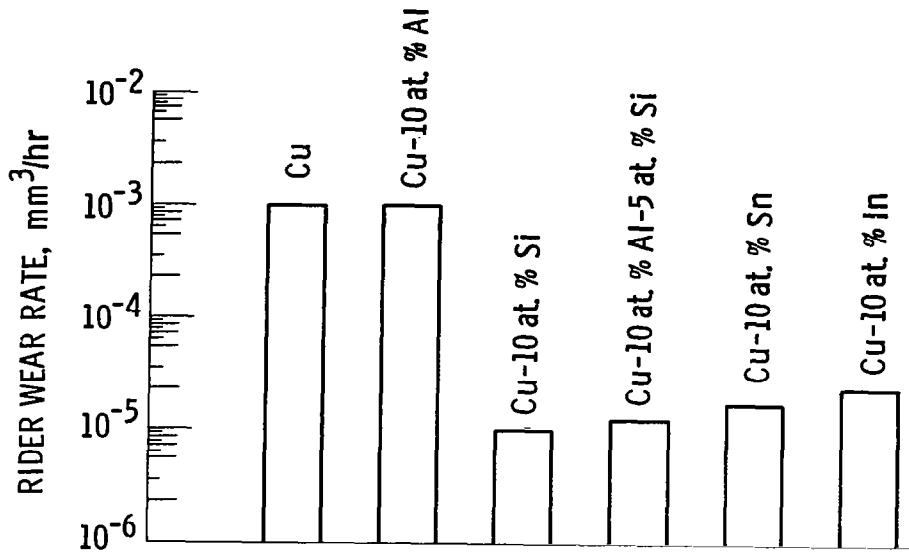


Figure 7.- Rider wear for various copper alloys sliding on themselves in hexadecane containing 0.1 volume percent stearic acid. Load = 250 g; sliding velocity = 300 cm/min; temperature = 25°C.

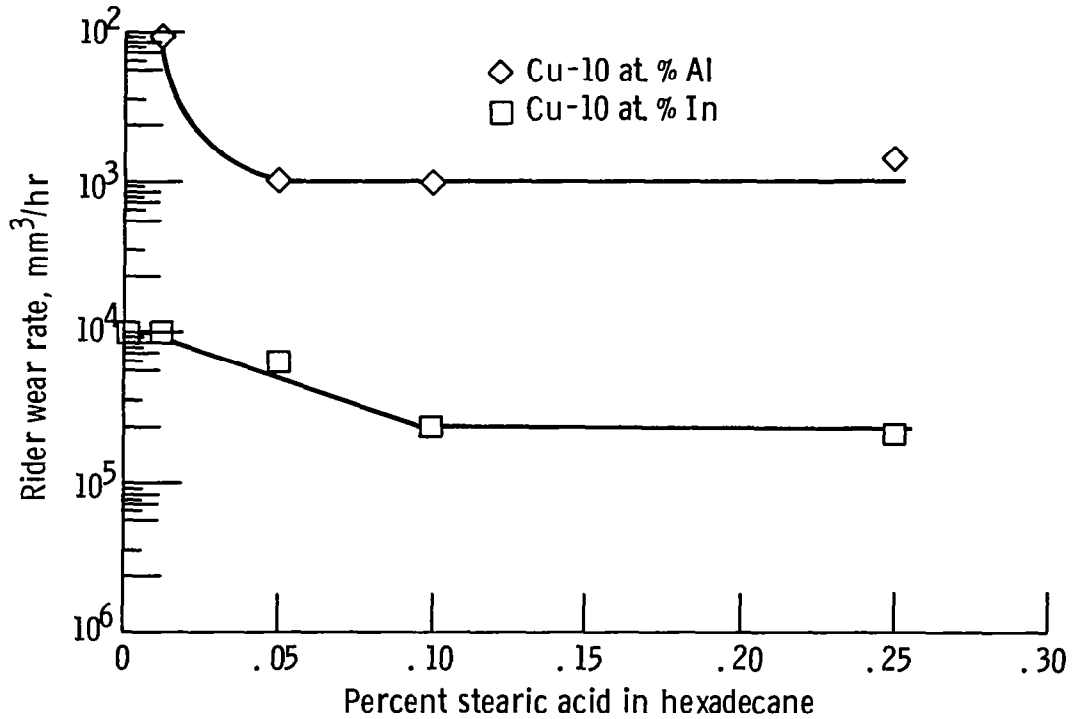


Figure 8.- Rider wear rate for two copper alloys sliding on themselves with various concentrations of stearic acid in hexadecane as lubricant. Load = 500 g, sliding velocity = 300 cm/min; temperature = 25°C.

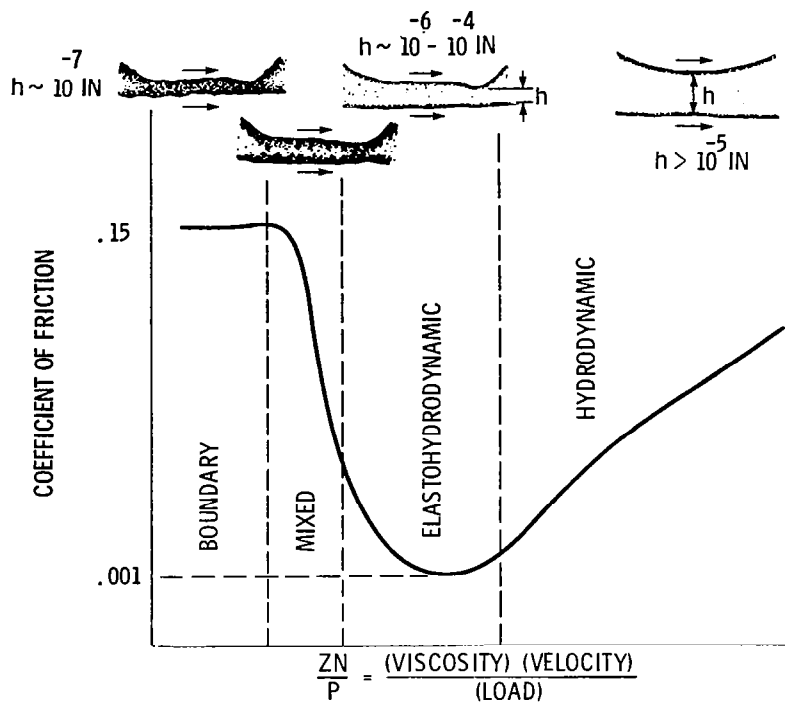


Figure 9.- Coefficient of friction as a function of speed-velocity-load parameter (Stribeck-Hersey curve). (See ref. 9.)

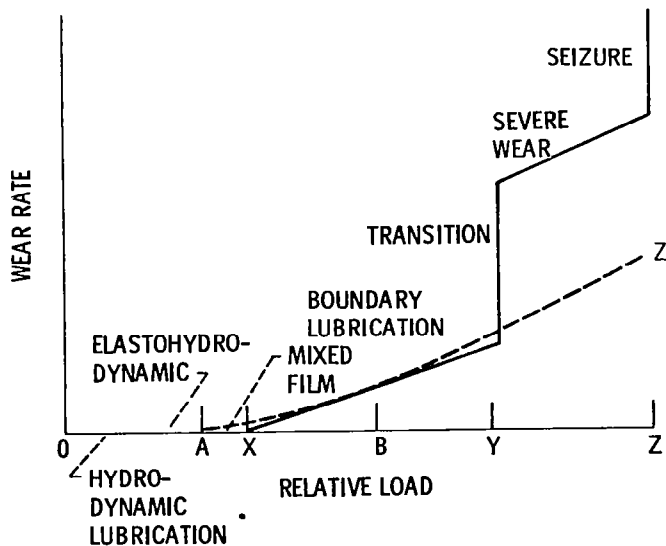
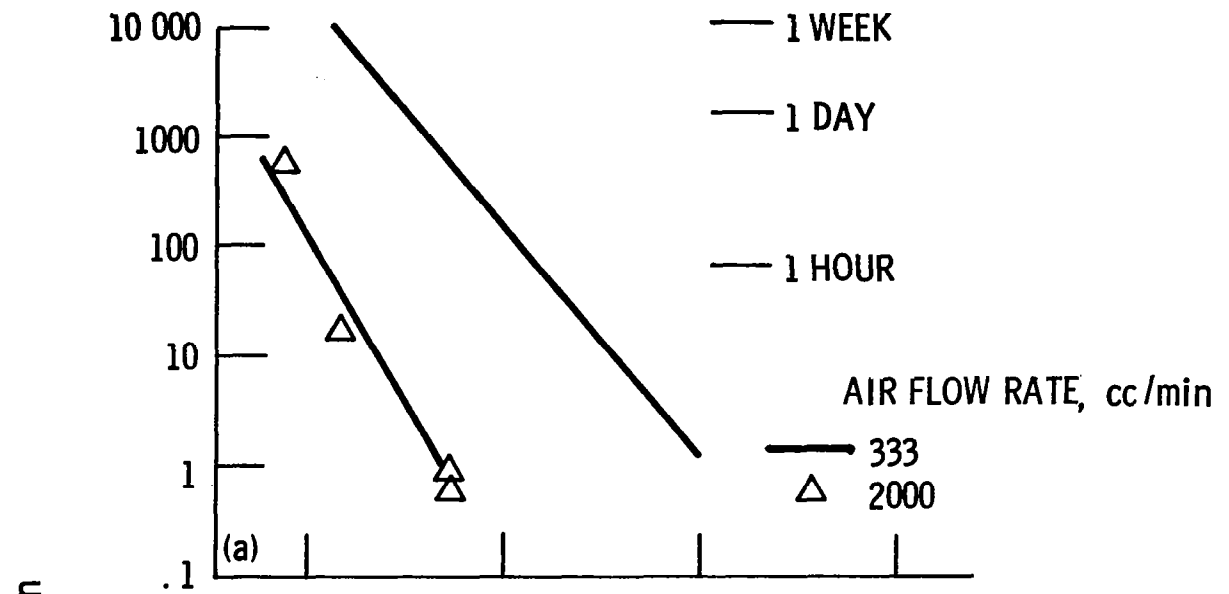
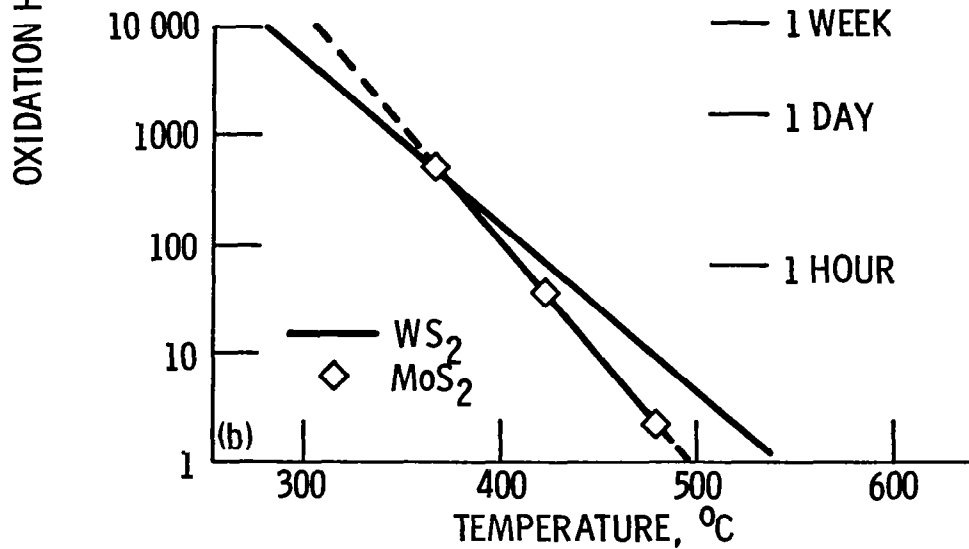


Figure 10.- Wear rate as a function of relative load depicting the various regimes of lubrication (ref. 11).



(a) Oxidation characteristics of MoS₂ at two air flow rates.



(b) Comparative oxidation of WS₂ and MoS₂ air flow rate, 1/3 L/min.

Figure 11.- Oxidation kinetics of MoS₂ and WS₂. Average particle size = 1 μm; compact density = 50%.

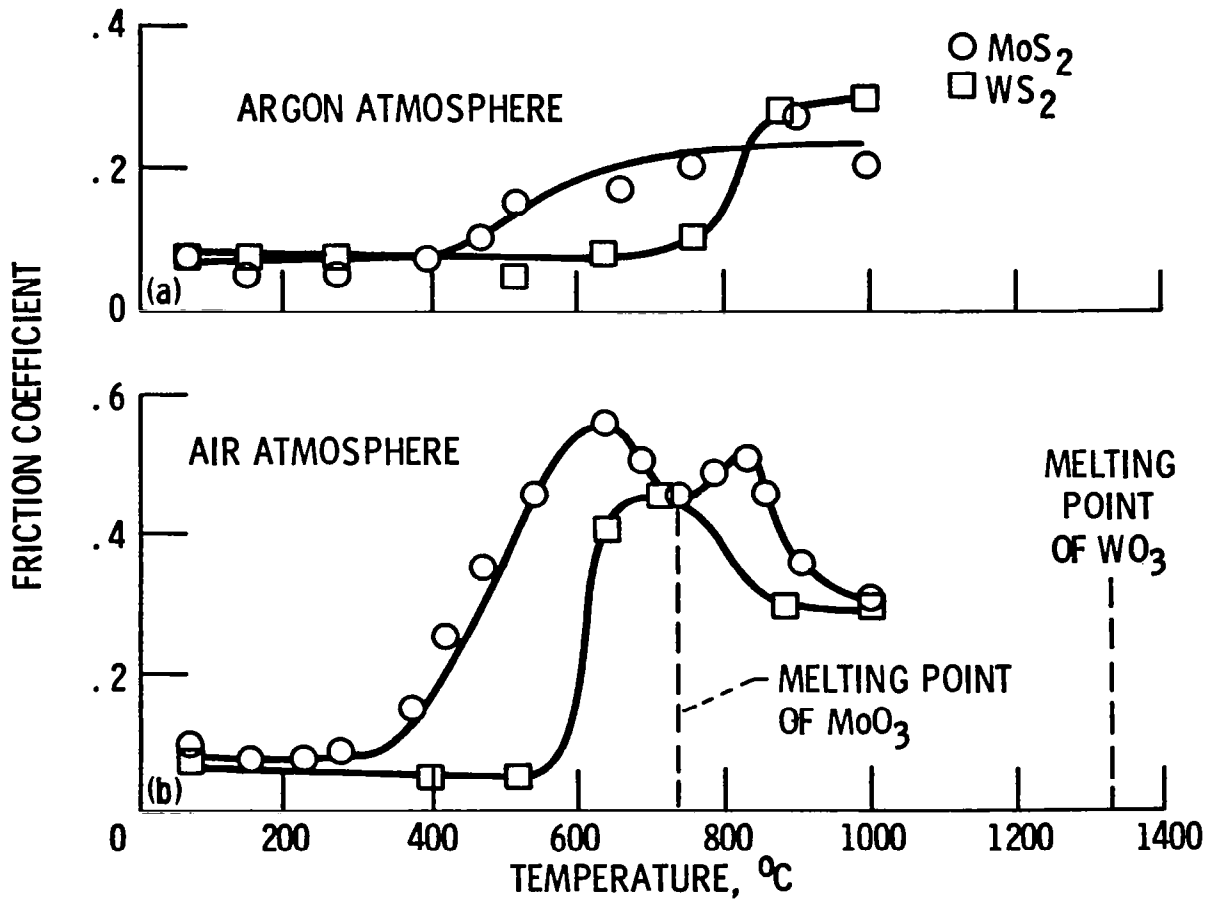


Figure 12.- Friction characteristics of MoS₂ and WS₂ in argon and in air.