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**VARIOUS MODES OF WEAR AND THEIR
CONTROLLING FACTORS**

by Edmond E. Bisson

**Lewis Research Center
Cleveland, Ohio**

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by Edmond E. Bisson

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

The paper discusses the various modes of wear, the mechanisms involved in each, and the mitigation of wear in some of the modes. The various modes of wear included are (1) adhesion, (2) abrasion, (3) corrosion, and (4) surface fatigue. Fretting (fretting corrosion or friction oxidation) is a special combination of adhesive, corrosive, and abrasive wear. Adhesive wear is one of the most prevalent types of wear. It can best be explained using the adhesion theory of friction, which is based on contact of surfaces through asperities. Welding occurs at the contacting asperities, and shear takes place at the welds during relative motion. The shear strength at these welds is strongly influenced by contamination, either deliberate or accidental. There is a marked influence of crystal structure on friction and adhesive wear. In general, the hexagonal structure gives lower friction and wear than the cubic structure. Experimental studies show that the lattice parameters in hexagonal crystals also affect friction. Abrasive wear involves damage to soft surfaces by a hard surface, either one of the two surfaces, or a third body. Hardness, work hardening, crystallite orientation, and elastic modulus of the contacting surfaces can all influence wear. Corrosive wear involves corrosion, followed by wear of the corrosion film. Surface fatigue normally appears as local

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pitting or flaking. Wear damage of this type is a function of the number of stress cycles. All modes of wear lead to loss of dimensional tolerances, high operating costs, and excessive expense (in time and money) for replacement of worn parts. A complete understanding of the basic mechanisms of wear permits alleviation and mitigation.

Introduction

The objectives of this paper are to review the modes of wear, the mechanisms involved and the influence of some controlling factors. The various modes of wear include (1) adhesion, (2) abrasion, (3) corrosion, and (4) surface fatigue. Fretting (variously called fretting corrosion or friction oxidation) is a special combination of adhesive, corrosive, and abrasive wear. The influence of crystal structure on friction and wear is discussed; comparisons are made between hexagonal and cubic structures as well as between single crystal and polycrystalline materials. All modes of wear lead to loss of dimensional tolerances, higher operating costs, and excessive expense (in time and money) for replacement of worn parts. A complete understanding of the basic mechanism(s) of wear permits taking steps to reduce wear or to alleviate the consequences of wear. Some of the material included in this paper is covered in detail in Ref. 1.

Adhesive Wear

Adhesive wear is one of the most prevalent types of wear. As the name implies, adhesive wear involves strong adhesive forces between contacting surfaces. If an attempt is made to displace one of these surfaces, adhesive forces may be sufficient to cause transfer of material from one surface to the other by shear

at the interface. The concept of the adhesion theory of friction can best be used to explain this mode of wear. The adhesion theory of friction, advanced by Merchant [2] as well as Bowden and Tabor [3], is based on the fact that when surfaces are brought into contact they do so through minute asperities. As load is applied, the asperities come into contact with resulting high stresses at the true contact area. The true area of contact is so small that, following elastic deformation, the stress quickly reaches the yield stress of one of the two materials. Hence, plastic flow occurs and a "cleaning" action is obtained at the contact area; that is, some of the surface contaminants are forced out. Because local areas are now somewhat clean and the stress is relatively high, "cold welding" can occur at the junction(s). Moving one surface relative to the other requires shear at these welded junctions. The relative cross-sectional areas and shear strengths, at the welded junction or on either side of the welded junction, will determine where shear takes place. If shear takes place in one of the materials, it transfers material to the other surface. The shear strength at the interface between surfaces is strongly influenced by contamination (either deliberate or accidental). Solids (such as oxide films or reaction films) or liquids (such as lubricants) serve as contaminants and hence reduce shear strength and wear.

It is possible to show, by use of monolayers and multilayers, that an extremely thin film of contaminant at the surface can be effective in reducing friction and wear. For example, a monolayer of stearic acid, which has an approximate thickness of 20 \AA (about 10^{-7} in.), has been shown (Ref. 3) to be effective in producing a marked reduction in friction, as compared with a clean surface. Even the adsorption of gases which produces contaminating films at the surface, may be effective in re-

ducing friction and wear. In particular, if the adsorbed gas is capable of reacting with the surface to form a reaction film, the protection can be very effective. Oxygen, chlorine, and hydrogen sulfide are examples of gases which have been shown (Ref. 3) to reduce friction appreciably when adsorbed on clean iron surfaces.

Buckley [4] has conducted some experiments with oxygen chemisorbed on tungsten. These experiments were done in vacuum (10^{-10} torr) with tungsten cleaned by electron bombardment. Oxygen was admitted into the vacuum chamber in such a way as to chemisorb atoms to various degrees. With tungsten in the clean state, the friction coefficient was 3.0. With oxygen adsorption equal to approximately a quarter of a monolayer (monolayer thickness is approximately 3\AA), the friction coefficient dropped very markedly, from 3.0 to 1.6. These results again prove the point that surfaces need be contaminated to only a slight degree in order to have a marked effect on friction (and possibly wear).

In a discussion of adhesive wear, Burwell [5] notes that one can write an equation for wear as

$$V = kAL \tag{1}$$

where

V volume of wear material

k wear coefficient

A real area of contact

L distance of travel

Since the real area of contact is equal to the ratio of load W to hardness H , this ratio can be substituted in Eq. (1)

$$V = k \frac{WL}{H}$$

or, for a given material,

$$V = k'WL \quad (2)$$

If we divide both sides of Eq. (2) by the apparent contact area A_0 , the equation becomes

$$h = k \frac{PL}{H} = k'PL \text{ (for a given material)}$$

where the average depth of wear $h = V/A_0$ and the average pressure or design stress $P = W/A_0$. In other words, for a given material, the adhesive wear coefficient k' is given by the ratio

$$k' = \frac{h}{PL} \quad (3)$$

Figure 1 shows the results of some wear experiments conducted by Burwell [5]. We see first, that wear is a linear function of distance and, second, that it is an apparent function of load. Figure 2 gives results obtained at the NASA laboratories, which confirm that wear is a linear function of load and is completely independent of apparent area of contact or apparent contact stress. The results of Figs. 1 and 2 confirm that Eq. (2) is applicable; that is, k' is a constant characteristic of the material over a range of speed and load.

Burwell conducted further experiments at higher loads (Ref. 5) and found some peculiar results. As the load was increased to a point generally exceeding the range of accepted engineering design, the adhesive wear coefficient k' was no longer constant but increased rapidly with load (i.e., with increase in average compressive stress). These results are shown in Fig. 3 which is a plot of the adhesive wear coefficient k' against pressure (average or design stress). These curves

show that the value of wear coefficient is constant up to a value of average pressure which is approximately one-third of the indentation hardness. Above this pressure, the wear coefficient rises sharply, and the curve is finally terminated by the onset of large-scale welding and seizure. The curve of Fig. 3(b) is for the same steel as that for Fig. 3(a) except that the steel has been hardened to about twice the Brinell hardness. The curve for the hard steel again shows that the wear coefficient is constant up to a value of approximately one-third the indentation hardness. It will be noted in this case, however, that the average pressure is appreciably higher because of the higher hardness.

Archard [6-8] has presented a model of adhesive wear in which he makes two assumptions: (1) Each time asperities come into contact to form a junction, there is a constant probability that an adhesive fragment will be formed, and (2) each fragment is assumed to be a hemisphere of diameter equal to the junction diameter. Using these assumptions, he develops an equation which is identical to Burwell's with the exception that Burwell's wear coefficient has been replaced with a wear coefficient $k/3$ which is different by the factor $1/3$. This factor is a shape factor applicable in the assumed case of circular junctions and hemispherical fragments.

Rabinowicz [9] has presented a theory of wear involving interfacial energies. In Rabinowicz's theory, which involves stored elastic energy in a wear particle and adhesional energy acting at the interface, a transferred particle comes off the surface only if the elastic energy is greater than the adhesional energy. Using these assumptions, he derived an equation which predicts the diameter of wear particles as a function of two material properties, p the flow pressure and W_{ab}

the interfacial energy between materials a and b.

Rabinowicz's equation is as follows:

$$d = \frac{60,000W_{ab}}{p}$$

This is a relationship between a measurable quantity d (diameter of the loose wear particles) and two material properties, p and W_{ab} .

Rabinowicz's experiments with various materials (metals and nonmetals) provide some support for this equation. On the other hand, some research results in England and Russia seem to support the view that the formation of wear fragments is primarily by fatigue of the transferred material.

Influence of Crystal Structure on Friction and Adhesive Wear

Hexagonal Versus Cubic

Recent friction and adhesion studies in vacuum at the NASA-Lewis Research Center indicate a marked difference in friction and wear between metals of cubic and hexagonal crystal structures (Refs. 10-14). Polycrystalline metals are agglomerates of crystallites that have these basic unit cells; when welding occurs between two metals, the weld is made up of these crystals. When the crystals in the weld shear, they do so along distinct planes, and the required shear force depends on the plane being sheared. Shear forces in cubic crystals are normally greater than corresponding shear forces in hexagonal crystals because of work hardening of cubic crystals as well as the existence of easy slip planes in hexagonal metals.

In hexagonal crystals, shear forces are usually the least on the basal plane (i.e., when the shear occurs in a plane parallel to the hexagons). This shearing process is illustrated in Fig. 4; the top hexagonal plane of the crystal is shown to

be displaced from the normal axis by the shear deformation process. As surfaces are moved with respect to one another, deformation, shear separation, and recrystallization occur as a continuing process.

The data of Fig. 5 show the differences in force required to shear metals of cubic and hexagonal structures. The crystal form of cobalt at normal temperatures is hexagonal; cobalt, however, transforms from the hexagonal to the cubic structure when heated above 400° C. A marked increase in friction is shown to accompany this crystal transformation (Fig. 5). At low temperatures, the sliding is hexagonal cobalt on hexagonal cobalt; at the higher temperatures, it is cubic cobalt on cubic cobalt. The transition from hexagonal to cubic is shown (Fig. 5) at less than 400° C because friction heating caused the surface temperatures to be somewhat higher than the bulk metal temperatures measured. Adhesive wear rate was about 100 times greater for the cubic cobalt than for the hexagonal cobalt (see the wear rates at temperatures of about 260° and 370° C, Fig. 5). Furthermore, at about 480° C, complete welding of the surfaces occurred. These data suggest that metals which remain in the hexagonal crystal form over the entire operating temperature range are to be preferred for sliding applications.

The crystal transformation temperature for some hexagonal metals can be altered by selective alloying. For example, the addition of 25% molybdenum to cobalt can increase the temperature for transformation, from hexagonal to cubic, appreciably. In the friction studies of Ref. 10, the results for 25% Mo-Co show (Fig. 6) that the friction coefficient remains relatively constant over a wide range of sliding velocities. In comparison, the dashed curve of Fig. 6 is for unalloyed

cobalt. With increased sliding velocities, increases in interface temperature occur. In the range of sliding velocities where a marked change in friction properties of unalloyed cobalt occurred, no change was observed in the friction properties for the 25% molybdenum-cobalt alloy. These results indicate that selective alloying can be utilized to retain the desirable hexagonal structure, and its associated desirable friction properties, for metals over a broad temperature range.

Additional studies showed that the shear force in hexagonal crystals varies with the relative spacing of the atoms within the crystals. In particular, the shear force is controlled by the ratio of the distance c (the spacing between hexagonal planes) to the distance a (the spacing between adjacent atoms in the hexagon). Various metals with hexagonal crystal structures have different values of c/a . Figure 7 shows the variation of friction, in vacuum, for some of these metals. Generally, friction declines with increasing c/a , and those metals that showed low friction give no evidence of gross surface welding.

Titanium is well known as a metal subject to severe welding or galling and otherwise having very poor friction properties. The preceding study on crystal structure effects suggested that improved friction properties could be obtained if titanium were alloyed in such a way as to (1) stabilize the hexagonal structure over a greater range of temperature and (2) increase the c/a lattice ratio. This is necessary because the poor friction properties of titanium can be related to shear and slip mechanisms which, in turn, can be related to c/a lattice ratio (Ref. 11).

Simple binary alloys of titanium with either tin or aluminum provide the desired structural characteristics. Figure 8 (from Ref. 14) shows the friction and lattice

ratio for a series of titanium-aluminum and titanium-tin alloys. Increasing the percentage of aluminum or tin produced a number of results: (1) increased the c/a ratio, (2) greatly reduced friction, and (3) minimized surface failure tendencies (which should therefore result in lower wear).

Single Crystal Versus Polycrystal

A comparison of results of various metals sliding against either single crystal Al_2O_3 or polycrystalline Al_2O_3 is shown in Fig. 9 (from Ref. 15). With five different metals sliding on single crystal Al_2O_3 , the friction coefficient is approximately the same. In this case, fracture or cleavage occurred in the single crystal Al_2O_3 (Ref. 15); hence, the friction coefficient is a measure of the shear strength of the single crystal Al_2O_3 .

With various metals sliding on the polycrystalline Al_2O_3 , however, much higher coefficients of friction were observed (Fig. 9). The surfaces of the polycrystalline Al_2O_3 disks all indicated transfer of metal to the disk surface. This metal transfer is shown in Fig. 9 for aluminum and zirconium. Since the metals showed transfer to the polycrystalline Al_2O_3 disk, shear of the metal was responsible for friction. Hence, there are appreciable differences from metal to metal as well as from cubic to hexagonal structure. For the cubic metals, Buckley states that the friction coefficients approach those predicted by Ernst and Merchant [16]. With the exception of titanium, all the hexagonal metals show appreciably lower friction coefficients than do the cubic metals, as might be anticipated.

Buckley [12] points out that ". . . polycrystalline materials are aggregates of individual crystallites. The grain boundaries serve as atomic bridges to link the

lattice of one crystallite with that of an adjacent crystallite . . . grain boundaries serve as a barrier to the motion of the dislocations of the crystallites. Such a structure could be expected to offer both greater resistance to shear and higher friction than single crystals." Buckley obtained data for single and polycrystalline iron sliding on Al_2O_3 in vacuum; these data are presented in Fig. 10 (from Ref. 13). The results of Fig. 10 show that the friction coefficient at light loads for the single crystal iron is much lower than that for polycrystalline iron at the same load (0.8 vs. 1.6). Buckley explains the data at higher loads as follows: "As load is increased, the interface temperature increases and recrystallization occurs at both contacting surfaces. This condition represents, then, an increase in friction for the single crystal [and] a decrease in friction for the polycrystalline metal because recrystallization is followed by texturing (orientation), which reduces shear stress. At higher loads the friction coefficient should be the same because the interfacial surface films are the same". The results of Fig. 10 show, in fact, that the curves for single crystal and polycrystalline iron are the same at the higher load levels. X-ray Laue patterns of the crystal surfaces after the maximum load runs of Fig. 10 confirmed that recrystallization and texturing (orientation) of the iron surfaces took place for both single crystal and polycrystalline iron.

It would appear that any method of producing a surface which results in recrystallization and texturing of the surface may appreciably change the friction and wear properties of a given material.

Abrasive Wear

Burwell points out that abrasive and cutting wear are, in general, the same

type of damage to the surface. Damage is accomplished by a hard surface plowing or gouging out a softer surface. There are two general situations for this type of wear: (1) the hard surface in question is the harder of the two rubbing surfaces (cutting wear), or (2) the hard surface is a third body, generally a small particle of grit or abrasive caught between the two surfaces and sufficiently harder than these surfaces that it abrades either one or both of them (abrasive wear). Cutting wear is strongly influenced by the choice of the combination of materials, while abrasive wear is strongly influenced by the type of foreign object (abrasive) present between the surfaces. Frequently, the foreign objects are formed by chemical reaction with the surrounding atmosphere.

Kruschov and Babichev [17] correlate resistance to wear with hardness of various "technically pure metals". These results are shown in Fig. 11. The points labeled "40" and "y12" are for carbon steel specimens of 0.41 and 1.1% carbon, respectively. As noted in the figure, these points fall on the same curve as do the technically pure metals. Spurr and Newcomb [18] have obtained wear results as a function of hardness which show general agreement with the data of Kurschov and Babichev.

Kruschov and Babichev [17] also found that alloys gave results similar to those shown in Fig. 11 for technically pure metals. Figure 12 (from Ref. 17) shows general trends of resistance to wear as a function of three principal methods of increasing hardness: (1) alloying, (2) quenching and tempering, or (3) work hardening. As indicated, alloying to increase hardness should result in an increase in the resistance to wear; similarly quenching and tempering, which results in increased

hardness, should also give increased resistance to wear. On the other hand, work hardening (strain hardening) of the surface should have no effect since abrasive wear is itself a work-hardening process according to Kruschov and Babichev. Hence, wear resistance, as measured in abrasive wear tests, is a function of materials in their maximum work-hardened state.

To confirm the general trends shown in Fig. 12, Kruschov and Babichev obtained data with a number of steels of various composition and various heat treatments. The results of experiments with four steels after quenching and tempering at different temperatures are shown in Fig. 13 (from Ref. 17). The steel labeled X-12, containing a high percentage of carbon and chromium, shows appreciably higher wear resistance than do the other three steels. The data at maximum hardness for each of the four steels, represents the steel "as quenched" or "as-quenched and mildly tempered". For each of these steels, points at lower hardness than the maximum represent different degrees of tempering.

Figure 14 (from Ref. 17) shows relative wear resistance as influenced by work hardening for a number of different materials; these materials include aluminum, copper, nickel, and a steel of 0.45% carbon. The nearly horizontal lines at a particular value of resistance to wear represent specimens which have been work hardened to different degrees, either by roll hardening or by shot peening. It will be noted that work hardening has no influence on the relative wear resistance.

Corrosive Wear

The third important wear mechanism under sliding conditions, according to Burwell [5], is corrosive wear. Here corrosive wear is distinguished from

abrasive wear in that corrosion is assumed to take place at the surfaces first, after which rubbing of the sliding surfaces removes the surface compound(s). A combination of corrosive and abrasive wear can, of course, be obtained if the corrosion compound acts as an abrasive wear particle. Corrosion is very much dependent on (1) the nature of the atmosphere, (2) the nature of the materials, and (3) the presence or absence of a film such as a lubricant. A lubricant film may act in two ways: (1) to reduce the severity of the rubbing process, and (2) to act as a blanket between the atmosphere and the materials and thus prevent reaction.

Surface Fatigue

The final major category of wear is that of surface fatigue in which damage to the surface takes place by local pitting or flaking. Normally, surface fatigue is a function of the number of stress cycles to which a given unit volume of the surface is subjected. It may be the predominant mode of failure in parts, such as rolling element bearings or gears, subjected to rolling or combined rolling and sliding.

The fatigue life, in stress cycles, is very strongly influenced by the contact stress. In fact, for rolling element bearings, the fatigue life is inversely proportional to the ninth or tenth power of contact stress. Any reduction of stress, consequently, has a major effect on fatigue life. For example, in a rolling element bearing, a lubricant film may modify the stress pattern acting on a given unit volume and may therefore greatly influence fatigue life.

Fretting (Fretting Corrosion)

Fretting or fretting corrosion is a special combination of adhesive, corrosive, and abrasive wear. Because fretting usually involves vibration with small ampli-

tudes, it results in a very severe cleaning action (since it does not permit relubrication of the contact area). Hence, any contaminant on the contacting asperities is usually worn off, and contact of the nascent metals takes place.

For years there have been two-schools of thought on the mechanism of fretting: (1) the "chemical action" school believes that, in an oxidizing atmosphere (air is the usual), oxides of the metals are formed first, then the oxides are rubbed off, and (2) the "mechanical action" school believes that adhesive wear takes place first, releasing finely divided wear particles, which are then or subsequently oxidized. Chemical reaction rates of these adhesive wear particles with available oxygen would be expected to be high in view of the following three factors: (a) high surface-to-volume ratio of the particles, (b) relative cleanness of the particles, and (c) probability that the particle temperature may be higher than ambient.

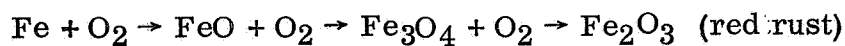
Fretting of steel parts occurs very frequently and can be recognized easily because of the presence of $\alpha - \text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ (red rust) in specimens which are lubricated such that ordinary corrosion is not likely. Early work by Tomlinson, Thorpe, and Gough [19] in England showed that relative motion was absolutely necessary for fretting damage, although the amplitude could be as small as 10^{-6} inch. Bulk motion which could be absorbed by elastic deformation at the asperities produced no damage.

A classic example of damage by limited motion has occurred on cross-country shipment of such things as automobiles and jet engines. With autos, tight tie-downs and vibration caused oscillation at small amplitudes and damage to wheel bearings. The damage resembles Brinelling and hence was called "false Brinelling". Early cases of such damage were cured by loosening the tie-downs; this allowed greater

oscillation and hence permitted relubrication of the contact area. A flareup of this type of damage is now taking place in long-distance shipping of cars in triple-tiered railroad cars. In these shipments, the auto must be tied down tightly; hence, the early "cure" cannot be used and other means must be found.

Mechanism of Fretting

Mechanical action school. - Godfrey's classic experiments (Refs. 20 and 21) at the NACA (now NASA) Cleveland Laboratory in the late 1940's showed that fretting could be attributed to the removal of "finely divided and apparently virgin material due to inherent adhesive forces . . .". In these experiments, a steel ball was vibrated in contact with a glass microscope slide so mounted that the area of contact could be viewed while the action was taking place (Fig. 15). The action showed that black material was removed from the real area of contact; this black material moved radially outward from the area of contact, gradually changing color as it did so. The color changes suggested progressive oxidation as follows:



If vibration was stopped, observation showed that the color changes moved progressively inward until the wear particles were rust colored. This action is shown in the film of Ref. 21.

Further experiments with fully oxidized materials, like quartz, mica, and Al_2O_3 , showed that the action, as viewed microscopically, was very similar to that for steel versus glass with the exception that the wear debris showed no color changes. Experiments were also conducted with platinum versus glass (platinum was chosen because it will not oxidize in air at any temperature). Again the action,

as viewed microscopically, was similar to that for steel versus glass except that no color changes took place.

The results with fully oxidized or nonoxidizing materials indicate that fretting is initiated primarily by mechanical action. This mechanical action has been followed, in the case of oxidizable materials, by oxidation of the wear debris.

Fretting is the result of the strong adhesive forces between the contacting materials at the interface. These adhesive forces can become very strong because fretting is one of the strongest cleaning actions known. The rubbing action at small amplitudes tends to remove (by wear and abrasive action) contaminant films of all kinds including the normally present oxides. Since the amplitude is very small, the probability of recontamination of the surfaces is extremely small. Hence, the surfaces become very clean and the adhesive forces very strong. Subsequent removal of virgin material results in particles which are subject to easy oxidation.

Chemical action school. - Uhlig [22] has postulated a theory of combined chemical and mechanical action; this theory is based on experiments conducted by his co-workers at MIT. Uhlig has written an equation for fretting involving both chemical and mechanical factors. He postulates that an asperity rubbing on a metal surface is considered to produce a track of clean metal which immediately oxidizes, or upon which gas adsorbs readily. The next asperity wipes off the oxide or initiates reaction of metal with adsorbed gas to form the oxide. This is the so-called chemical factor of fretting. In addition, asperities dig below the surface to cause a certain amount of wear by welding or shearing action in which metal particles are dislodged. This is the mechanical factor of fretting.

Fretting in a "Real" Case

The foregoing discussions have to do mainly with the initiation of fretting; in a "real" case, the resultant damage may be strongly influenced by effects which are secondary, in a chronologic sense, but not necessarily in importance. In fact, while Godfrey and Bisson [20] state that the mechanism is primarily mechanical, they also point out that the chemical factor is not negligible.

Many conflicting results have been obtained in research on fretting. A good summary on fretting and fretting corrosion presenting conflicting results was published as Ref. 23. For example, diametrically opposed statements can be found on the effects of load, amplitude, friction coefficient, and surface finish. In each case, however, a complete understanding of the basic mechanism makes it possible to explain some of these conflicting results. If for example, an increase in load is sufficient to suppress vibration completely, there will be no fretting damage. If, on the other hand, the increase in load does not suppress vibration, the fretting damage would be expected to increase. Similarly, an increase in friction coefficient could (1) suppress vibration, resulting in no damage or, (2) increase the fretting damage if it does not suppress vibration.

Mitigation of Fretting

Since the NACA experiments indicated that the initiation of fretting was primarily from strong adhesive forces, mitigation of fretting should follow from mitigation of adhesion. Hence, all the principles of the adhesion theory of friction should apply. In fact, the introduction of contaminating films between the surfaces should reduce fretting. This result has been achieved in many experiments, as

well as in practical applications. The contaminants can be liquid lubricants, greases, solid lubricants, soft metal platings, etc.

All these can be quite effective, but each has a particular application. For example, greases can be quite effective provided they are sufficiently feedable or that the oscillations are great enough to permit the fretted surfaces to relubricate themselves. Similarly, bonded solid lubricants and plated metals can be quite effective even under very small amplitude vibrations. These latter films have limited life, however, since they are themselves fretted. NACA results showed that any lubricant is effective but bonded MoS_2 films were quite effective as shown in the following table (from Ref. 20):

<u>Steel ball versus glass flat</u>	<u>Number of cycles to start of fretting</u>
Clean	1 - 30
Mineral oil	1,500
MoS_2 , dusted	72,000
MoS_2 , resin-bonded	28,000,000
<u>Steel flat versus steel flat</u>	
Clean	<100
MoS_2 , resin-bonded	10,000,000

The results of the table show that any contaminant (even mineral oil) delays the start of fretting; this effect is believed to result from reduction of the adhesive forces responsible for fretting.

Concluding Remarks

This paper discusses the various modes of wear, the mechanisms involved in each, and the mitigation of wear in some of the modes. The various modes of wear include (1) adhesion, (2) abrasion, (3) corrosion, and (4) surface fatigue. Fretting (fretting corrosion or friction oxidation) is a special combination of adhesive, corrosive, and abrasive wear. Adhesive wear involves adhesive forces which are strong enough to form cold welds at the contacting asperities. During relative motion, shear takes place at the welds. The shear strength at these welds is strongly influenced by contamination, either deliberate or accidental.

Abrasive wear involves damage to soft surfaces by a hard surface whether by one of the two surfaces or by a third body. Hardness, work hardening, crystallite orientation, and elastic modulus of the contacting surfaces can all influence abrasive wear.

Corrosive wear involves reaction of the surfaces with the atmosphere, after which surface compounds so formed may be rubbed off. A combination of corrosive and abrasive wear can be obtained if the corrosion compound is hard and acts as an abrasive wear particle.

The fourth major category of wear is that of surface fatigue which occurs by local pitting or flaking. Normally, wear damage of this type is a function of the number of stress cycles. In ball bearings, the fatigue life is strongly dependent on contact stress; in fact, fatigue life is inversely proportional to stress to the ninth or tenth power.

All modes of wear lead to loss of dimensional tolerances, high operating costs, and excessive expense (in time and money) for replacement of worn parts. A complete understanding of the basic mechanisms of wear permits alleviation and mitigation of the causes.

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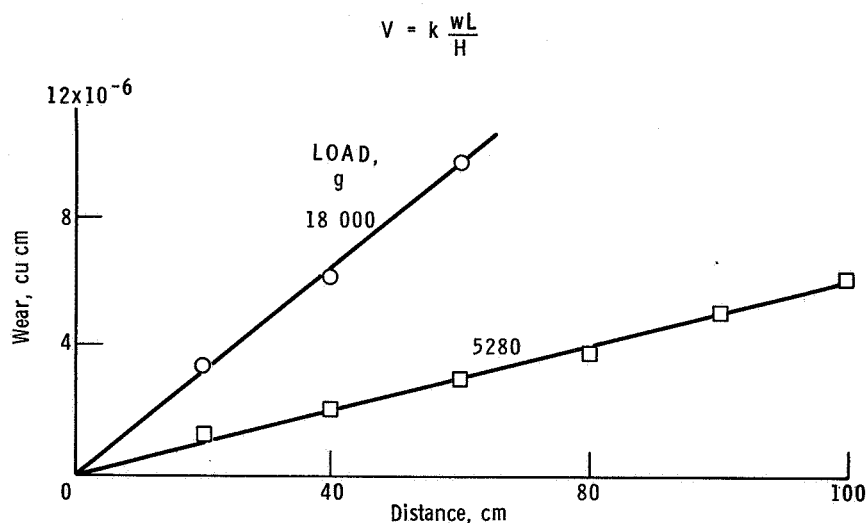


Figure 1. - Wear volume as function of distance of travel (from ref. 5).

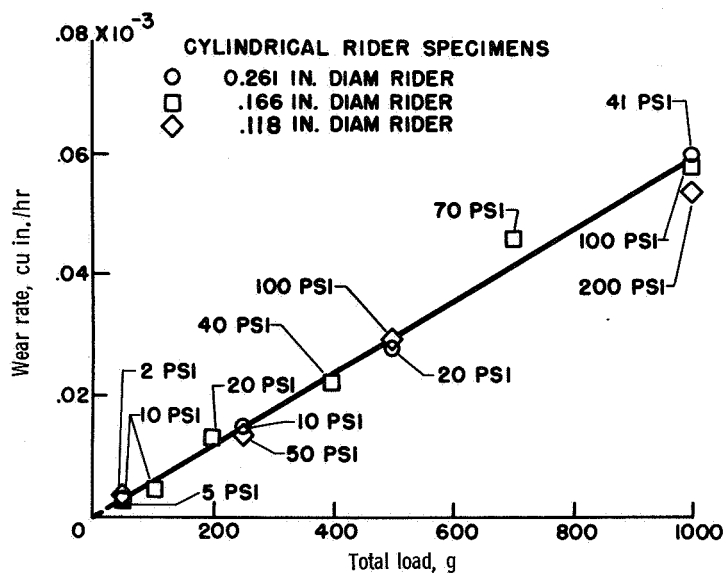


Figure 2. - Effect of total load and unit load on wear of carbon against chromium plate. Sliding velocity, 10, 000 ft/min; temperature, 360° F; atmosphere, dry air.

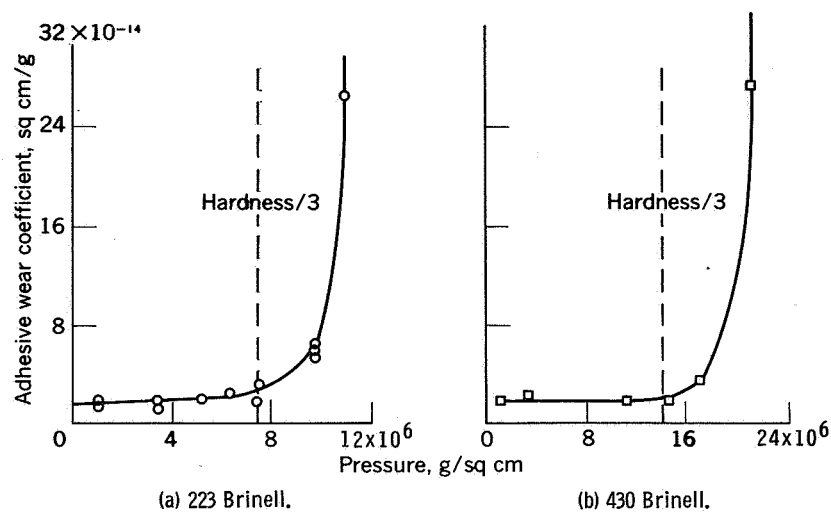


Figure 3. - Wear coefficient as function of average (design) stress (from ref. 5).

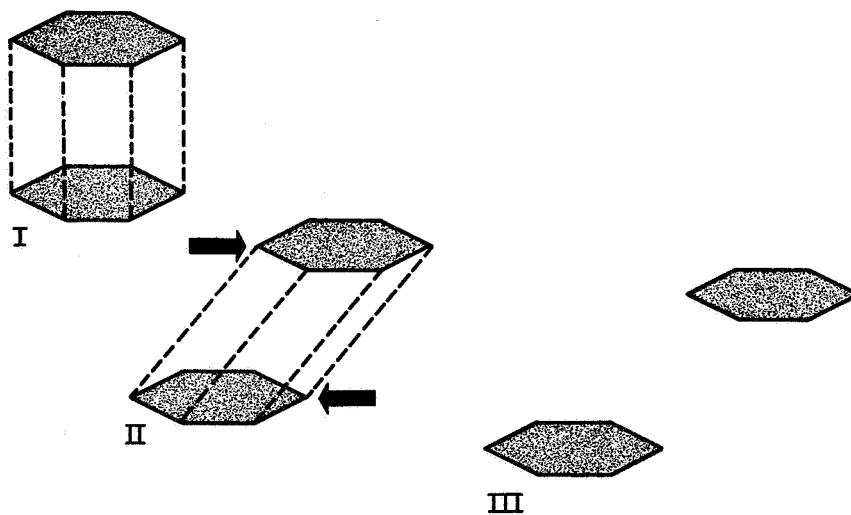


Figure 4. - Displacement of planes in hexagonal crystals with shear.

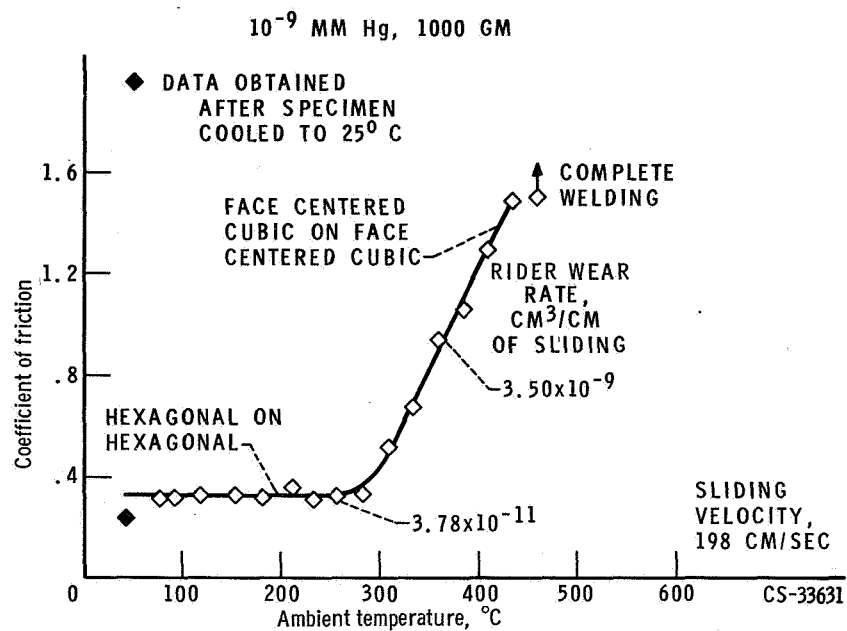


Figure 5. - Coefficient of friction for cobalt sliding on cobalt in vacuum at various temperatures (from ref. 10). Pressure, 10^{-9} mm Hg; load, 1000 g.

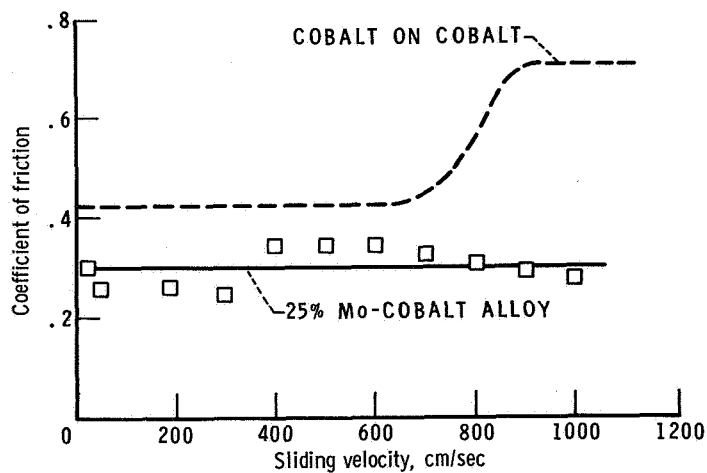


Figure 6. - Coefficient of friction for molybdenum-cobalt alloys sliding on disks of same material in vacuum (from ref. 10). Pressure, 10^{-9} mm Hg; load, 1000 g; temperature, 25° C.

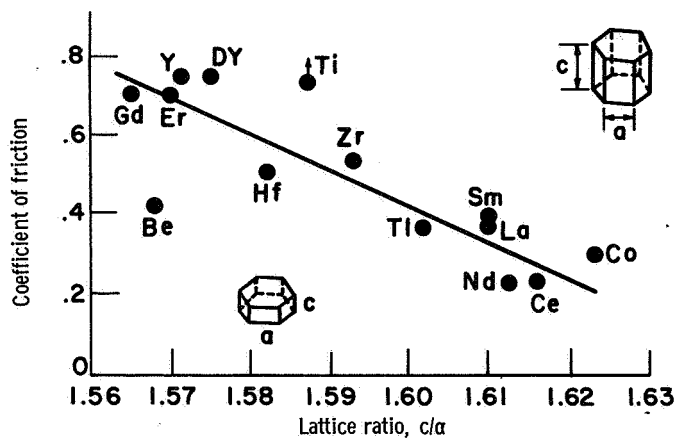


Figure 7. - Friction of various hexagonal metals (from ref. 10).
Pressure, 10^{-9} mm Hg; load, 1000 g; sliding velocity, 390 ft/min,
on 440-C steel.)

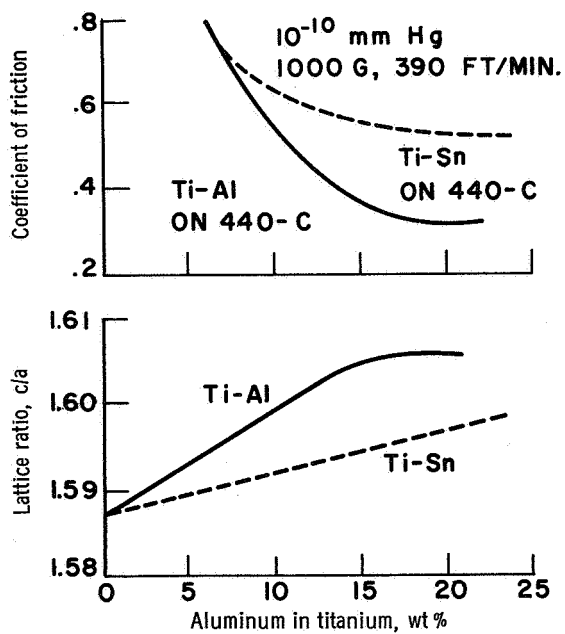


Figure 8. - Friction and lattice ratios for titanium alloys (from ref. 14).

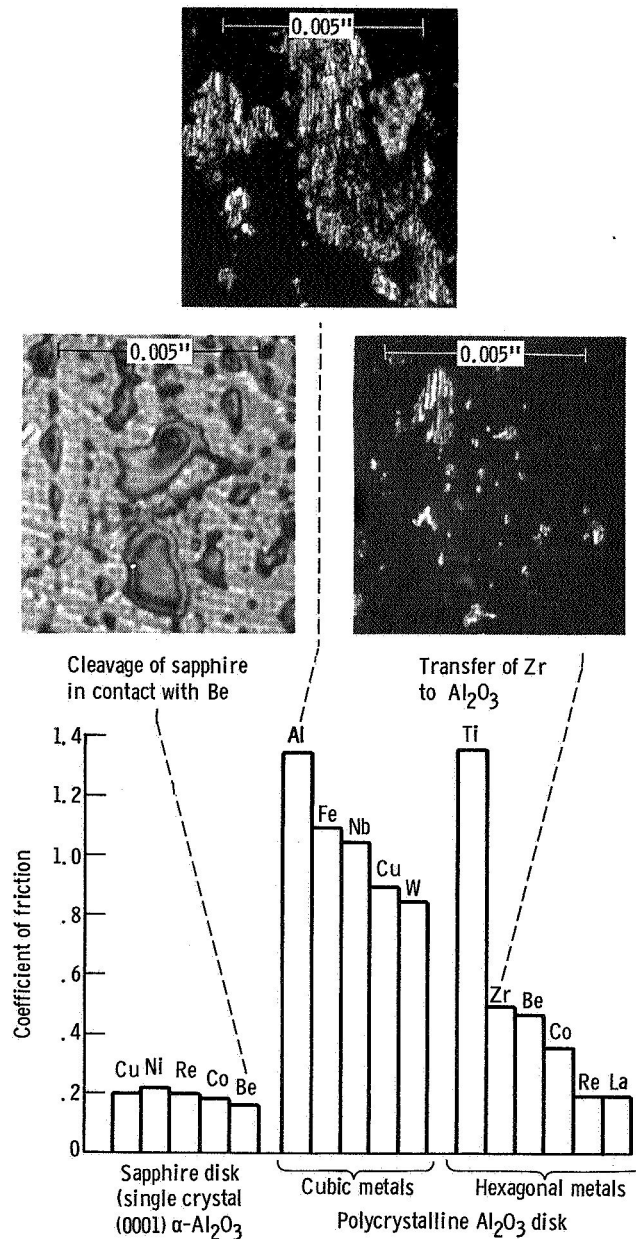


Figure 9. - Coefficient of friction for various metals sliding on aluminum oxide in vacuum (10^{-10} torr). Load, 1000 g; sliding velocity, 0.013 cm/sec; duration of experiment, 1 hr (from ref. 15).

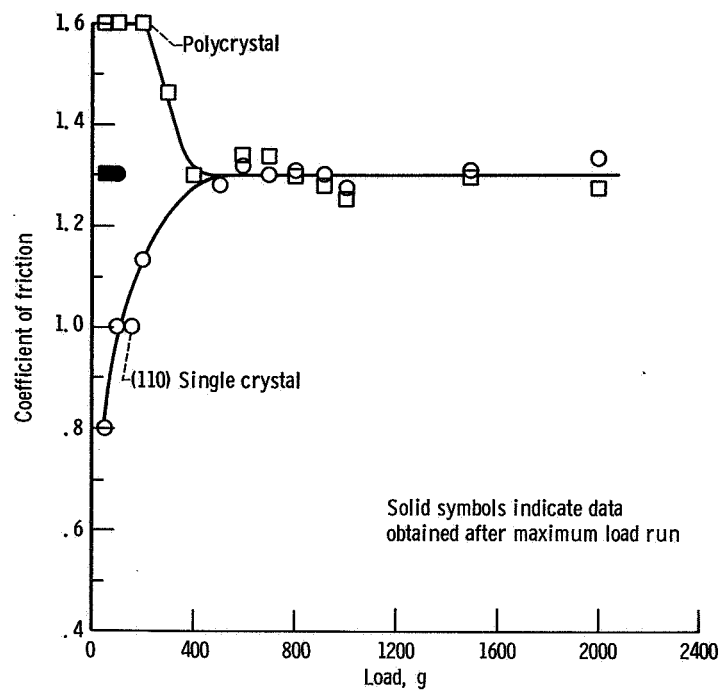


Figure 10. - Effect on friction of recrystallization of single crystal and polycrystalline iron sliding on Al_2O_3 in vacuum (from ref. 13). Sliding velocity, 0.001 cm/sec; temperature, 20° C; pressure, 10^{-11} torr.

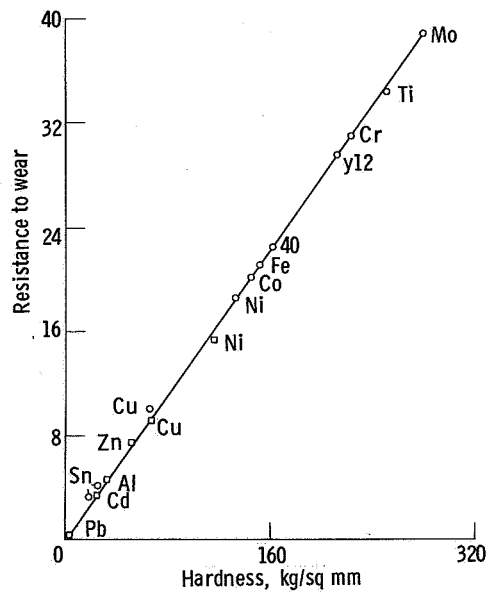


Figure 11. - Resistance to wear as function of hardness (from ref. 17).

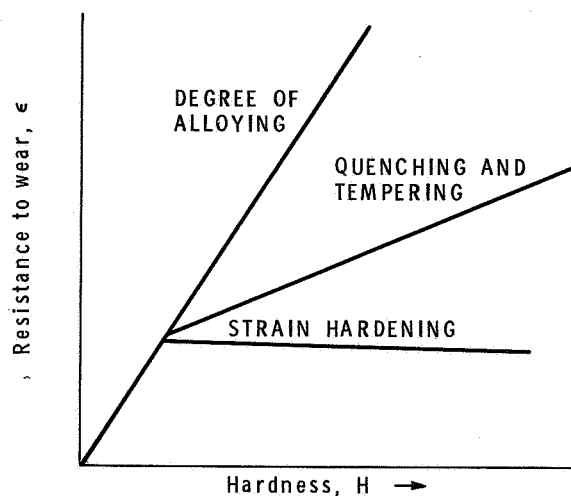


Figure 12. - General trends of resistance to wear as function of alloying, heat treatment, and work hardening (from ref. 17).

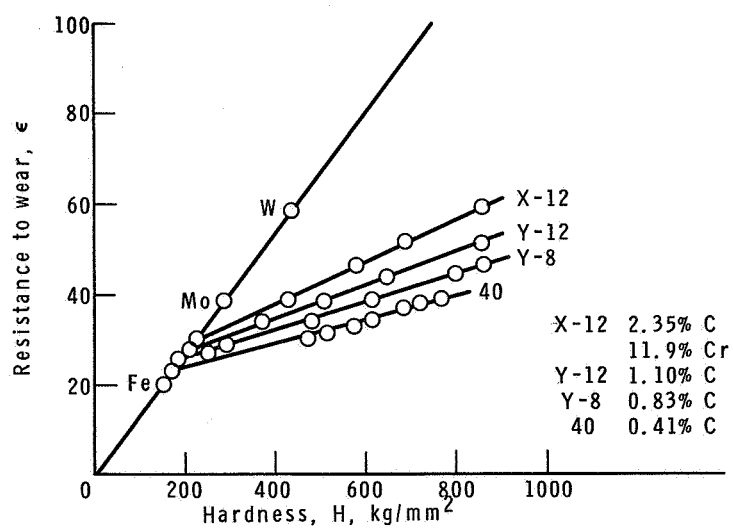


Figure 13. - Relative wear resistance after quenching and tempering at various temperatures (from ref. 17).

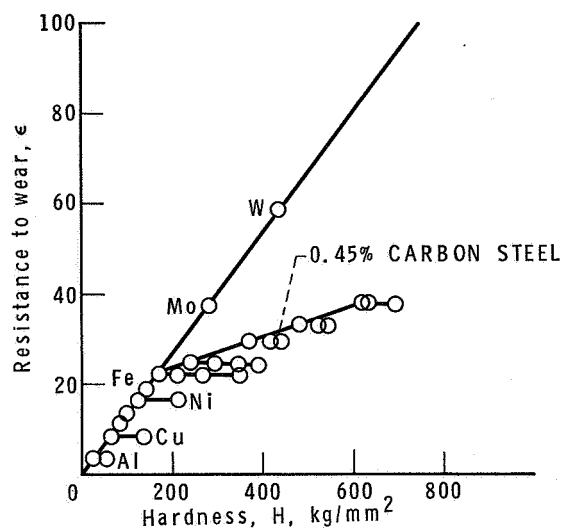


Figure 14. - Relative wear resistance as function of work hardening (from ref. 17).

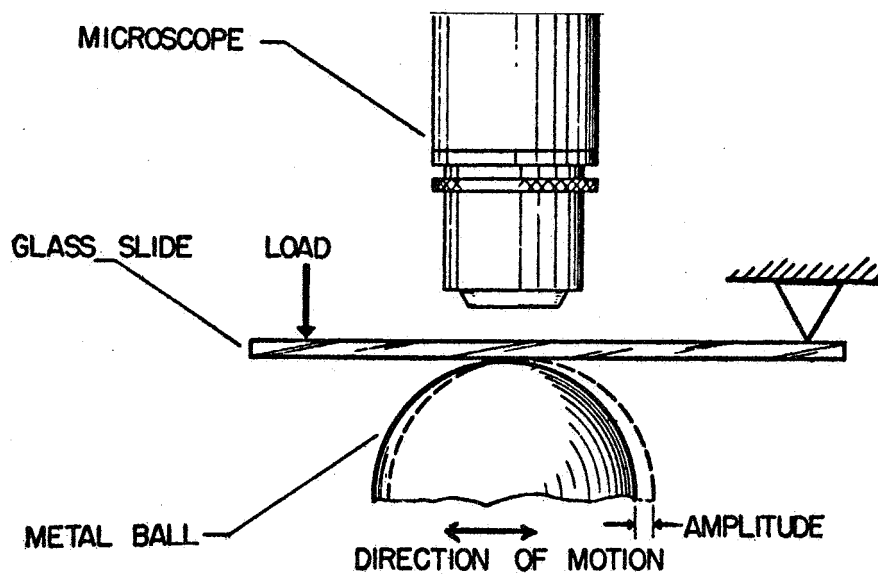


Figure 15. - Schematic diagram of fretting apparatus (from ref. 20).