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FRICTION AND WEAR BEHAVIOR OF GLASSES AND CERAMICS

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ABSTRACT

Adhesion, friction and wear behavior of glasses and ionic solids are reviewed. These materials are shown to behave in a manner similar to other solids with respect to adhesion. Their friction characteristics are shown to be sensitive to environmental constituents and surface films. This sensitivity can be related to a reduction in adhesive bonding and the changes in surficial mechanical behavior associated with Rehbinder and Joffe effects. Both friction and wear properties of ionic crystalline solids are highly anisotropic. With metals in contact with ionic solids the fracture strength of the ionic solid and the shear strength in the metal and those properties that determine these will dictate which of the materials undergoes adhesive wear. The chemical activity of the metal plays an important role in the nature and strength of the adhesive interfacial bond that develops between the metal and a glass or ionic solid.

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INTRODUCTION

There are certain fundamental characteristics of metals, carbons, polymers, glasses and ceramics which these widely different material classes have in common with respect to adhesion, friction and wear. Their surface topography is generally irregular on an atomic scale, they contain surface and bulk defects, adhere in the clean state to themselves or other materials and are extremely sensitive to surface contaminants with respect to adhesion, friction and wear.

There are also certain properties of glasses and ceramics which set them apart from metals and polymers with respect to adhesion, friction and wear behavior. In general, metals and polymers deform plastically very readily, while glasses and ceramics are normally brittle and exhibit very little evidence for plastic flow. This property of plasticity will affect the real area of contact for two solid bodies pressed together under a load. In turn the real area of contact determines in part adhesive forces, friction forces and the propensity for adhesive wear to occur.

In a wide variety of situations, glasses and ceramics are not in contact with themselves but rather with materials of other classes, for example, metals. It is important to understand in such cases which of the materials in contact is contributing to friction and wear and via what particular mechanism.

The objective of this paper is to review those fundamental characteristics of glasses and ceramics which exert an influence on their adhesion, friction and wear behavior. These include mechanical, chemical and physical behavior. In addition, those factors which dictate the friction and wear characteristics for glasses and ceramics in contact with metals will be reviewed.

BACKGROUND

Solid surfaces are generally not atomically smooth but contain surface irregularities called asperities. On a micrographic scale, these irregularities are hills and valleys. When two solids are brought together because of these irregularities, the real area of solid contact is only a small portion of the apparent contact area. As a consequence, when one surface is loaded against another, very high stresses can develop in the zones of real contact. This means, for example with metals, that relatively small applied forces are necessary to exceed the elastic limit of the metal in the area of real contact and result in plastic deformation. Such plastic deformation has also been observed in ceramics such as magnesium oxide[1] and aluminum oxide[2].

When solids are pressed together under a load, first elastic and then plastic deformation will occur and continue until such time as the load is supported. At this point the real contact area between the solids is established. Where surfaces are atomically clean, adhesive

bonds will develop across the interface over the real contact area. Adhesion force is simply that force necessary to separate the two surfaces once the load is removed. Two factors are important in determining the adhesive force. These are the strength of the interfacial adhesive bond or the cohesive bond in the cohesively weaker of the two materials and the real contact area.

The larger the real contact area the greater the number of potential adhesive bonds and consequently the larger the force required to separate the surfaces. In those instances where a load is applied to the surfaces in contact, elastic recovery on removal of the applied load may result in the fracture of many of the adhesive bonds. This occurs readily with high elastic moduli ceramics.

If two adhered surfaces are simply pulled in tension normal to the plane of the interface at some applied force, the adhesive force, the surfaces will separate. Separation or fracture will occur at the interface when these bonds are the weakest. Very frequently and particularly for atomically clean surfaces in contact, fracture will occur locally in the cohesively weaker of the two materials.

Those things which reduce the number of adhesive bonds that form across an interface affect adhesion. Thus, even fractions of a monolayer of surface contaminants have an effect[3]. Ordinary surface oxides are very effective on metal surfaces in reducing adhesion to a small fraction of the value for those same metals in the clean state. Glass, as will be discussed later, is one of the few materials which actually exhibits an increase in adhesive force when a water surface film is present[4].

Friction is very strongly dependent upon adhesion. Generally the stronger the adhesive force the greater the friction force. The friction force is simply the resistance to tangential motion for two bodies in contact. The stronger the adhesive bonds and or the real contact area, the greater is the resistance to tangential shear and consequently the friction force. The friction force may then simply be expressed as

$$f = as$$

where f is the friction force, a the real contact area and s the shear strength of the interfacial junctions.

The above expression will apply where glass is in contact with glass or ceramic in contact with ceramic. Where glass or ceramics are in contact with soft metals or polymers, another factor must be considered, namely the large disparity in deformation characteristics of the two classes of materials. The metal or polymer will deform very readily, to the extent depending on geometry, where the glass or ceramic body becomes partially buried in the metal or ceramic. When the glass or ceramic is then moved tangentially, it physically plows metal or polymer and this action offers resistance to tangential motion. A plowing term must therefore be incorporated in the friction expression for such situations and

$$f = as + p$$

where p is the plowing term.

Adhesion is not only important to friction but to wear as well. One of the most severe types of wear is adhesive wear. This type of wear occurs when fracture takes place in the cohesively weaker of the two materials in contact because of the strong interfacial adhesive bond. Adhesive wear occurs very frequently for metals in contact with ceramics or glasses.

GLASSES

Mechanical Factors

The load or force with which two glass surfaces are pressed into contact affects the real contact area and correspondingly friction force. This is demonstrated in the data of figure 1. In figure 1 the friction force for glass sliding on glass is presented as a function of load in two environments, air saturated with water vapor and a vacuum of 10^{-10} torr. The friction force is proportional to load in both environments. This is a basic law of friction for materials and it was first recognized by Leonardo da Vinci (1452-1519). Figure 1 indicates that it applies to glass as well as other materials.

The friction force is proportional to load not only for glass sliding on glass but for metals sliding on glass as well. In figure 2, friction force is plotted as a function of load for aluminum sliding on glass in vacuum. The curve of figure 2 can be superimposed over the one obtained in vacuum in figure 1. The friction force at any particular load is essentially the same for glass sliding on glass and aluminum sliding on glass. Similar results have been obtained with other metals such as iron sliding on glass.

The similar behavior for glass sliding on glass and metals sliding on glass is explained by an examination of the surfaces after sliding. With metals sliding on glass, the glass surface undergoes wear just as do the glass surfaces for glass sliding on glass. Microscopic examination of the metal surface after sliding indicates the transfer and embedment of glass into the metal surface. Thus, in a vacuum the metal surface becomes charged with glass and ultimately glass is sliding on glass.

Mechanistically initially with metals in contact with clean glass, adhesion of the metal to the glass occurs. With tangential motion, fracture takes place in the weakest zone. Both the interfacial adhesive bond and the shear strength of elemental aluminum are greater than the force necessary to fracture glass.

The resulting effect is that glass transfers to the metal. What would appear to be an abrasive wear process from an examination of only the glass surface is in fact an adhesive wear process.

Increasing load as has been seen influences friction behavior. Other mechanical parameters also effect friction. The speed with which glass slides over glass or metal over glass alters friction behavior.

Environment

Most materials are extremely sensitive in their adhesion, friction and wear behavior to the environment[4-8]. Glasses are no exception to this general rule. In figure 1 friction force is presented for glass sliding on glass in a vacuum of 10^{-10} torr and in air saturated with

water. A marked difference in friction behavior exists in the two environments. At 1000 grams load the friction force in vacuum is one half the value obtained in air.

The results obtained in figure 1 indicate that environment does affect friction force. The results are, however, unusual in that generally for most materials adhesion, friction and wear are greater in a vacuum environment. This is the case with metals[9], carbons[10] and ceramics[11]. The subject of environmental effects on the friction and wear characteristics of ceramics will be discussed later in this paper.

In figure 3 the coefficient of friction (friction force over the normal load) is plotted as a function of ambient pressure for glass sliding on glass. From 10^{-10} torr to a pressure of 1 torr friction coefficient remained unaffected. As the pressure was increased from 1 torr to atmospheric pressure, the coefficient of friction increased from 0.5 to 1.0. The air contained the normal moisture content; none was deliberately added.

The anomalous behavior of glass with respect to friction can be explained on the basis of increased adhesion of glass in the presence of water vapor. Adsorbed water increases the adhesion force. For example, the adhesion force for glass in the presence of water is more than three times what it is for glass in the presence of octane[4]. With increased adhesion, there is an accompanying increase in friction.

Glass-Metal Interactions

When metals are in sliding or rubbing contact with glass in air at atmospheric pressure and when the air contains moisture, metals are observed to transfer to glass[4]. Friction coefficients under such conditions are typically from 0.5 to 0.7 depending on the shear properties of the metal involved. With metals sliding on glass in a vacuum, glass, as has already been discussed, transfers to the metal. Friction coefficients are approximately 0.5. Thus, while the friction coefficients are not markedly different in the two cases the mechanism is.

The difference in transfer characteristics in the two environments rests within the fracture properties of glass. The fracture behavior of glass is strongly effected by water[12]. Water impedes fracture and is a manifestation of the Joffe effect in an amorphous solid. From the transfer characteristics observed with metals sliding on glass, it must be concluded that the fracture strength of glass is less in the absence of water vapor than it is in its presence.

CERAMICS AND OTHER IONIC SOLIDS

Mechanical Behavior

Ceramics and other ionic solids like glass are load sensitive with respect to their friction behavior. The friction coefficient for two orientations of single crystal aluminum oxide in vacuum are presented in figure 4 for various loads. Aluminum oxide friction behavior with load differs from glass in that the friction coefficient

is not directly proportional to load. For both the basal (0001) and prismatic ($10\bar{1}0$) orientations of aluminum oxide, the friction coefficient decreases with increasing load, reaches a minimum and then begins to increase. With glass, in figure 1, the friction coefficient (friction force divided by the normal load) is independent of load.

In figure 4 a marked difference in friction coefficient for the two orientations of aluminum oxide exist indicating its anisotropic friction properties. This will be discussed in more detail later.

Properties of Ionic Solids Related to Friction

There are certain basic properties of solids which can be expected to relate to adhesion, friction and wear. For example, the greater the cohesive energy of a solid, the greater its elastic modulus and hardness. These properties under a given load should give rise to a smaller real contact area. This in turn should lead to lower adhesion and friction forces. The data of Table I for various ionic solids with a rock salt structure indicate that this is in fact the case.

In Table I magnesium oxide has the greatest cohesive energy, elastic modulus and hardness and correspondingly the lowest friction coefficient. Potassium bromide has the lowest cohesive energy, elastic modulus and hardness and it has the highest friction coefficient. Note in Table I that a diamond slider was used. Thus, the deformation is taking place in the ionic solid.

The comparisons made in Table I can only be validly made when a solid with the same basic type of crystal structure is involved. Crystal structure in and of itself can exert a considerable influence on the friction behavior of solids[13].

Anistropy

Much like metals the adhesion, friction and wear characteristics of ionic solids are anisotropic. The friction data of Table II for sapphire sliding on sapphire indicates the anisotropic nature of aluminum oxide. Friction is not only anisotropic for aluminum oxide with respect to planar orientation but to crystallographic direction as well. This can be seen on both the prismatic and basal planes of aluminum oxide as the data of Table II indicate. Friction is least on the preferred slip plane and when sliding in the preferred crystallographic slip direction.

Analogies have been drawn between the crystallographic deformation behavior of hexagonal metals and the rhombohedral-hexagonal crystal structure of aluminum oxide[14]. Similar friction analogies exist. The preferred slip planes and crystallographic directions for both hexagonal metals and aluminum oxide result in the lowest friction.

In addition to friction the wear for ionic solids is highly anisotropic. This anisotropy is demonstrated for single crystal rutile in figure 5. The wear rate is plotted as a function of polar angle.

The data were obtained from reference 15. Wear varies with orientation in figure 5 by a factor of at least six times. Thus, an understanding of the anisotropic behavior of ionic solids can result in an appreciable reduction in friction and wear to these surfaces when the proper orientations are selected.

Temperature Effects

With metals, generally increasing the temperature of the metal in air results in increased surface oxidation. This increased oxide surface coverage generally reduces metal to metal contact across the interface and this results in a reduction in friction coefficient. Where not only the surface but the entire solid is oxide the results are somewhat different.

The friction coefficient for polycrystalline aluminum oxide as a function of temperature is presented in figure 6. As the temperature is increased, the friction coefficient increases. At 400°C it reaches a maximum value of 0.8 and then it begins to decrease. The initial friction coefficient of 0.2 at room temperature is considerably less than that obtained with metals. The value at 400°C is comparable to that obtained with metals.

The marked increase in friction coefficient seen in figure 6 is due to the presence of adsorbed water. The experiments were conducted in dry air. If a small amount of water vapor were admitted to the system at 400°C, the friction coefficient immediately decreased. Water then, in a strict sense, is a lubricant for aluminum oxide.

Further evidence for the change in friction with temperature being due to desorption of water was obtained in vacuum studies. If aluminum oxide was simply heated in vacuum water was detected in a mass spectrometer. On subsequent cooling to room temperature in vacuum, a friction coefficient comparable to that measured in air at 400°C was obtained.

Environment and Surface Films

The effect of environment on the adhesion, friction and wear behavior of glasses and ionic solids has already been discussed. Water vapor as has been indicated can act as a lubricant and changes in friction for aluminum oxide with temperature were simply a manifestation of the effects of that environmental constituent.

It is not necessary to increase the temperature of an ionic solid such as aluminum oxide to see the effect environmental constituents such as water vapor have on friction coefficient. In figure 7, simply increasing the load resulted in a change in friction behavior. At loads of less than 1000 grams, the friction coefficient was less than 0.2. When the load was increased above 1000 grams, the friction coefficient rose to in excess of 0.2. This increase was due simply to a penetration of the adsorbed water layer by the aluminum oxide asperities resulting in increased adhesion and correspondingly increased friction.

The presence of water and organics on the surface of ceramics influences the mechanical behavior of these materials[15-21]. If these films influence such properties as the deformability of the surface, then they will influence friction.

The presence of surface-active agents on ceramics can arrest brittle fracture during sliding. Similar observations have been made with other ionic solids such as lithium fluoride. This increase in the ability of surfaces to deform plastically in the presence of surface-active species is the Rebinder effect.

Sliding friction experiments have been conducted with the ionic solid lithium fluoride to determine the influence of surface films on friction and deformation. A sapphire ball was slid across a freshly cleaved lithium fluoride (100) surface. The lithium fluoride specimen was then cleaved normal to the sliding track and subsequently etch-pitted. The subsurface deformation and the development of cleavage cracks is shown in Figure 8(a). Examination of that figure reveals that slip has taken place along the $\{011\}$ and $\{101\}$ sets of planes. Since these are the slip planes, plastic deformation might be expected to occur in such a manner. In addition to the slip bands, cleavage cracks, originating at the surface, developed along the $\{011\}$ slip bands. Cracks can form in lithium fluoride at the intersection of $\{110\}$ slip planes according to the equation: $1/2\ a\ [011] + 1/2\ a\ [10\bar{1}] = 1/2\ a\ [110]$. It is important to note from the etch pitted slip bands in Figure 8(a) that a brittle material such as lithium fluoride will deform plastically in sliding.

To show the marked influence that atmospheric constituents can have on the mechanical behavior of ionic crystals in sliding friction studies, equivalent experiments were conducted with lithium fluoride in water. Rather than simply comparing behavior in moist air with dry air, water was used. The lithium fluoride crystals were cleaved in water and friction experiments were conducted with water present on the crystal surface. The crystals were then cleaved normal to the wear track and etched. Track subsurface deformation is shown in Figure 8(b). Note that while slip bands are evident from the dislocation etch pits along the (110) plane, a subsurface crack has formed in the crystal. This crack lies in a (001) plane. In dry air (Figure 8(a)) the crack formed at the surface along (110) planes rather than at the subsurface. With plastic deformation of lithium fluorde, cracks can develop along a (100) plane with the intersection of $\{110\}$ slip bands in accordance with the equation: $1/2\ a\ [110] + 1/2\ a\ [1\bar{1}0] = a\ [100]$. The crack developed in Figure 8(b) was the result of both compressive forces acting on the crystal surface in the form of the normal load and tangential forces associated with sliding.

Figure 8(c) is a sliding friction track in cross section after a sliding friction experiment was conducted in a 5.0×10^{-6} normal solution of myristic acid. In the presence of the acid, there was no evidence of either surface or subsurface crack formation as seen in Figures 8(a) and (b). In Figure 8(c) the subsurface depth to which the (011) slip bands extend is appreciably greater than observed in the other two environments. Thus, a greater degree of plasticity appears to exist

in the presence of the myristic acid. The energy associated with the sliding friction process appears to have been absorbed completely in plastic behavior.

The influence of environment on the behavior of ionic solids is further shown in some sliding friction experiments conducted on the (111) cleavage face of calcium fluoride. Figure 9 presents deformation as a function of molar concentration of dimethylsulfoxide in water. It indicates that with decreasing concentrations of dimethylsulfoxide or increasing concentrations of water, the width of the wear track increases. This increase in width may be attributed to an increase in surface plasticity.

The foregoing discussion on the influence of surface films on the deformation and fracture of lithium fluoride and calcium fluoride indicates that the presence of surface films on ionic solids not only influences surface behavior, but subsurface behavior as well. The ability of surface films to influence deformation behavior will not only influence friction because it determines true contact area, but it will also influence wear of solid surfaces in contact. The presence of surface or subsurface cracks can, with repeated traversals over the same surface, give rise to the formation of wear particles. This has been demonstrated with the ionic solids lithium and calcium fluorides. Deformation results with calcium fluoride indicate the extreme sensitivity of ionic solids to small changes in environmental constituents.

A comparison of the friction behavior of various solids in three different environments is made in Table III. Diamond and copper were added to Table III for comparative purposes. An examination of Table III indicates that for all materials except glass, an increase in friction coefficient is observed when the environment is changed from air to vacuum. The increase for the ionic solids is by a factor of from approximately two to four. With diamond, however, the material exhibiting the lowest friction coefficient in air, there is a nine fold increase in friction and with copper metal it is in excess of one hundred. Other metals exhibit a behavior similar to copper. Thus, while glasses and ionic solids are sensitive to environment with respect to friction, that sensitivity is not as great as observed for diamond and metals.

When the surfaces of the solids in Table III are lubricated with a mineral oil, the results are as presented in the third column of Table III. Again, while the friction coefficients are reduced from those values obtained in air with glasses and ionic solids, the differences were not as great as that seen with copper. The results obtained with copper are typical of metals in general.

It is of interest to note in Table III that two of the ionic solids, sapphire and magnesium oxide, were not influenced in their friction behavior by the presence of the lubricating oil. The moisture in the air was just as good a lubricant as the oil.

Metal-Ceramic Systems

In addition to contact area and shear or fracture at the interface, another term which can influence friction coefficient is plowing. The greater the deformability of one of two surfaces in contact, the deeper the second material can embed into the surface and thereby impede tangential motion and increase friction coefficient. Material must be plowed. This results in an increase in friction force.

Plowing is extremely important when metals contact ceramics. The marked difference in elastic and plastic deformation of ceramics and metals can result in plowing being the principal contributor to measured friction forces. This is demonstrated by Figure 10.

In Figure 10 a rider (hemisphere) of sapphire slid on a single crystal flat of copper. The specimen materials were then reversed so that a single crystal copper rider slid on a sapphire flat. The coefficient of friction for the sapphire sliding on copper was 1.5. With copper sliding on sapphire, it was 0.2. In both instances, adhesion of copper to sapphire occurred. The differences in friction coefficient for the two experiments are due to the effects of plowing.

When metals contact ceramics, surface chemistry also plays a very important role in the observed friction and wear behavior. Various metals were slid on a flat of sapphire with the basal orientation in the sapphire parallel to the sliding interface. With the metals which form stable oxides such as copper, nickel, rhenium, cobalt and beryllium, adhesion of the metal occurred to the oxygen ions in the outermost atomic layer of the sapphire.

With sliding of these metals across the sapphire surface, fracture took place in the sapphire along the basal cleavage plane. This resulted in plucking out large particles of the sapphire disk. These results indicate that the fracture strength along the basal plane was less than the strength of the interfacial bond or the metal to metal bonding. The friction coefficient for all of the metals in contact with sapphire was essentially the same, 0.2. This force is dictated by the cleavage strength of the sapphire. Friction results are presented in Figure 11.

A number of metals were examined in sliding contact with polycrystalline aluminum oxide. Some metals had cubic structures while others had hexagonal crystal structures. Friction results obtained are presented in Figure 10. The first observation to be made for metals sliding on polycrystalline aluminum oxide is that the coefficient of friction with nearly all metals, the exceptions being rhenium and lanthanum, was greater than was obtained when metals slid on sapphire.

The reason for the increase in the friction coefficients was that shear took place in the surface layers of the metal with sliding rather than fracture occurring in the aluminum oxide, as was observed with the single crystal sapphire experiments. Metal transferred to the polycrystalline aluminum oxide disk surface. The shear properties of the metal were therefore determining the friction forces measured rather than the forces necessary to cleave along basal planes in sapphire. In these experiments, the weakest bond in the interfacial region was the metal bond.

Differences existed in the friction coefficients for hexagonal and cubic metals in Figure 11 because of the differences in slip and the shear behavior of these metals. In general, hexagonal metals have fewer operable slip systems, shear more readily and do not work harden rapidly and, as a consequence, they exhibit lower friction coefficients than cubic metals. Titanium shows complex slip, making it behave more as a cubic rather than hexagonal metal, which accounts for its friction behavior in Figure 11.

If a metal does not form a stable oxide, the observed friction coefficient is less than that in Figure 11. Both gold and silver were slid on sapphire in a vacuum. The friction results obtained in these experiments are presented in Figure 12. With both gold and silver, the friction coefficient was 0.1 or half that obtained in Figure 11 with the oxide forming metals. Examination of the sapphire surface after sliding revealed no evidence for fracture occurring in sapphire.

With silver and gold sliding on sapphire, the lack of strong interfacial bonding between the metal and sapphire resulted in the shear of these interfacial bonds. They were the weakest bonds in the interfacial region. From a practical point of view this is the most desirable area to have shear occur since both friction and wear are least under such conditions.

In addition to the metal chemistry playing a role in metal-ceramic interactions, the crystallographic nature of the metal exerts a marked influence on friction beyond simply the crystal structure discussed in reference to Figure 11. Even with a single metal, changes in surface orientation with sliding and the accompanying changes in associated slip systems affect friction.

Sliding friction experiments have been conducted with sapphire having a fixed orientation sliding on a large grained polycrystalline tungsten disk surface. The disk which contained only seven grains was 5.0 centimeters in diameter. Friction coefficients measured in both air and vacuum for the sapphire sliding on the tungsten are presented in Figure 13.

Figure 13 indicates the marked dependency of friction coefficient on the orientation of the tungsten grains. In vacuum as much as seven fold differences in friction exist with changes in the orientation of the metal. Just as with glasses in contact with glasses or ionic solids with ionic solids, metal-ionic solid interactions are sensitive to environment. This is demonstrated by the differences in friction behavior seen in Figure 13 in air and vacuum. The influence of orientation in the metal is less pronounced in air where oxides and adsorbates are present than it is in vacuum with a clean metal surface.

The friction behavior of metal-ceramic or ionic solid couples are sensitive not only to the metals chemistry and crystallography but to mechanical changes as well. Thus far the discussion of friction behavior

has been restricted to sliding friction. In addition to sliding friction, there is rolling friction. This type of friction is seen in such mechanical components as ball and roller bearings. A change in mechanical parameters such as load or speed generally does not have as marked effect in rolling friction as those same changes would produce in sliding.

Figure 14 is a plot of the depth of plastic deformation in magnesium oxide as a function of the number of repeated passes or cycles over the surface with a steel ball. The rolling was conducted at three different speeds or velocities. The load was held constant. Evidence for the depth of plastic deformation was obtained by dislocation etch pitting after rolling. Slip depth is the depth below the surface to which etch pits along slip bands could still be seen.

In Figure 14 with the increasing number of stress cycles associated with the increasing rolling cycles, there is an increase in the depth to which plastic deformation occurs in the magnesium oxide. The depth to which deformation occurs is strain-rate sensitive. Deformation takes place to a greater depth at the slower rolling velocities. Similar behavior has been observed with calcium fluoride under sliding conditions[22].

Rolling repeatedly over a magnesium oxide surface with a steel ball produces strain hardening in the magnesium oxide just as it does in metals. Evidence for this is presented in the hardness data of Figure 15. Hardness is plotted as a function of the number of rolling cycles for two different load conditions. At both loading conditions the magnesium oxide undergoes strain hardening with repeated cycles.

DISCUSSION

In many aspects glasses and ionic solids behave in a manner similar to metals with respect to adhesion, friction and wear. Adhesion plays an important role in the friction and wear behavior of glasses and ionic solids just as it does with metals. With clean metals brought into contact with themselves, the forces to fracture the adhered junctions equal the tensile strength of the bulk metal[23]. Likewise with ionic solids the adhesive forces developed across an interface are equal to that of the bulk solid. This has been very effectively demonstrated with such ionic compounds as sodium chloride[24].

The friction behavior of glasses and ionic solids are similar to metals in that they all exhibit sensitivity to environment. The magnitude of change in friction force for metals with a change in environment is significantly greater than it is for glasses and ionic solids. With metals, removal of surface adsorbates and oxides result in the friction force increasing to complete seizure (friction coefficient > 100). For glasses and ionic solids, they do not rise to such high values. The data of Table III do not indicate a friction coefficient in excess of 1.3.

An anomaly exists with respect to glass. It is the only material which upon removal of surface adsorbates (principally water) exhibits a decrease in friction coefficient. This unusual behavior of glass may be a manifestation of the Joffe effect. Water is known to affect the mechanical behavior of glass[25-26].

From sliding friction studies in air, a calculation of shear strength for amorphous glass results in values of 140 Kg/mm^2.[24] This value represents the surficial shear strength. The bulk shear strength for glass is approximately 25 Kg/mm^2. Removal of the adsorbed water results in a reduction of the value calculated from friction measurements. Thus, the presence of adsorbed water affects mechanical behavior (shear strength) and accordingly friction characteristics.

Adhesive wear which is one of the most severe types of wear encountered with metals also occurs with ceramics. Its most pronounced appearance occurs where metals are in contact with glasses or ionic solids. With metals in contact with glass in air metal is generally observed to transfer to the glass[27]. In vacuum where the surficial strength of the glass appears to be reduced, glass transfers to metal with the end result that glass is sliding essentially on glass.

The adhesive wear behavior of ionic solids in contact with metals is strongly dependent upon the particular ionic solid involved and its form. For example, with aluminum oxide in its single crystal form, adhesion to metals resulted in fracture along basal planes in the sapphire and wear to the sapphire. With polycrystalline aluminum oxide and its random surface orientations, shear took place in the metal and the metal underwent wear.

CONCLUSIONS

Adhesion, friction and wear of glasses and ionic solids are in many respects similar to the behavior of other solids. They will adhere strongly to themselves as well as to other solids. Their friction characteristics are strongly dependent upon environmental constituents and surface films. They undergo adhesive wear particularly when in contact with metals.

Unlike many other solids, glasses and ionic compounds are sensitive in their surficial mechanical behavior to surface active species and they manifest such characteristics as the Rehbinder and Joffe effects. These properties or characteristics influence the adhesion, friction and wear measured with these materials. Despite these sensitivities such materials do not manifest the wide variations in such properties as friction behavior that is seen in metals with changes in environment.

REFERENCES

1. K. F. Dufrane and W. A. Glaeser, NASA CR-72295 (1967).
2. R. P. Steijn, J. Appl. Phys., 32[10] 1951 (1961).
3. D. H. Buckley, NASA TN D-5689 (1970).
4. F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, Oxford Press (1950).
5. D. H. Buckley, Friction, Wear and Lubrication in Vacuum, NASA SP-277 (1971).
6. F. P. Bowden and A. E. Hanwell, The Friction of Clean Crystal Surfaces, Proc. Roy. Soc., A295 [1442] 233 (1966).
7. I. V. Kragelskii, Friction and Wear, Butterworths (1965).
8. E. Rabinowicz, Friction and Wear of Materials, John Wiley & Sons, Inc., (1965).
9. F. P. Bowden and T. P. Hughes, Proc. Roy. Soc., A172 263 (1939).
10. D. H. Buckley and R. L. Johnson, ASLE Trans., 7 91 (1964).
11. D. H. Buckley, ASLE Trans., 10 134 (1967).
12. S. M. Wiederhorn, Environment-Sensitive Mechanical Behavior of Materials, Gordon and Breach, 293 (1966).
13. D. H. Buckley, ASTM STP 431, 248 (1967).
14. M. L. Kronberg, Acta Met., 5 [9] 507 (1957).
15. E. J. Duwell, ASLE Trans., 12 34 (1969).
16. J. H. Westbrook, Environment-Sensitive Mechanical Behavior of Materials, Gordon and Breach, 247 (1966).
17. P. A. Rehbinder, Proc. Sixth Physics Conf., Moscow (1928).
18. A.R.C. Westwood, Strengthening Mechanisms - Metals and Ceramics, Syracuse Univ. Press, 407 (1966).

19. W. G. Johnston, J. Appl. Phys., 33 2716 (1962).

20. P. L. Pratt, R. Chang, and C. H. Newey, Appl. Phys. Letters, 3 83 (1963).

21. A.R.C. Westwood and D. L. Goldheim, J. Appl. Phys., 39 3401 (1968).

22. D. H. Buckley, NASA TN D-5580 (1969).

23. D. V. Keller, Jr., Jour. Vac. Sci. Tech., 9 133 (1972).

24. R. F. King and D. Tabor, Proc. Roy. Soc., A223 225-238 (1954).

25. S. M. Wiederhorn, J. Am. Ceram. Soc., 52 99 (1969).

26. P. A. Rehbinder and V. I. Likhman, Second Intl. Cong. on Surface Activity, III, 563 (1957).

27. W. A. Wooster and G. L. MacDonald, Nature, 160 260 (1947).

TABLE I

Properties of Ionic Bonded Crystals with Rock Salt Structure

Crystal	Cohesive energy (kcal/mole)	Elastic modulus (10^{11} dynes/sq cm) (100)	Relative hardness (kg/sq mm)	Coeff. of frict.[a] (100)(110) air
MgO	940.1	24.5	400⟨100⟩ 700⟨110⟩	0.07
LiF	240.1	7.35	100	.24
KCl	164.4	4.80	18	.71
NaCl	153.1	4.37	17	.70
KBr	140.8	3.70	7	.85

[a] 5 gm-load, 0.02–0.04 cm/sec, diamond 12.7 micron slider, 760 Torr.

Table II. Influence of Crystallographic Direction on the Coefficient of Friction for Sapphire Sliding on Sapphire in Vacuum (10^{-10} mm Hg)*

Plane	Direction	Coefficient of friction
Prismatic	$[11\bar{2}0]$	0.93
$(10\bar{1}0)$	[0001]	1.00
Basal	$[11\bar{2}0]$	0.50
(0001)	$[10\bar{1}0]$	0.96

*Load 1000 g, sliding velocity 0.013 cm/s.

TABLE III. Coefficient of Friction for Various Solids in Three Different Environments

Material Combinations	COEFFICIENT OF FRICTION		
	AIR (Moisture)	VACUUM (10^{-9} - 10^{-10} torr)	LUBRICATED (Mineral Oil)
Soft Glass/ Soft Glass	1.0	0.5	0.28
Sapphire/Sapphire	0.2	0.8	0.20
Magnesium Oxide/ Magnesium Oxide	0.2	0.8	0.21
Quartz/Quartz	0.35	0.7	0.20
Sodium Chloride/ Sodium Chloride	0.70	1.3	0.22
Lithium Fluoride/ Lithium Fluoride	-	1.2	0.22
Diamond/Diamond	0.1	0.9	0.05
Copper/Copper	1.0	>100	0.08

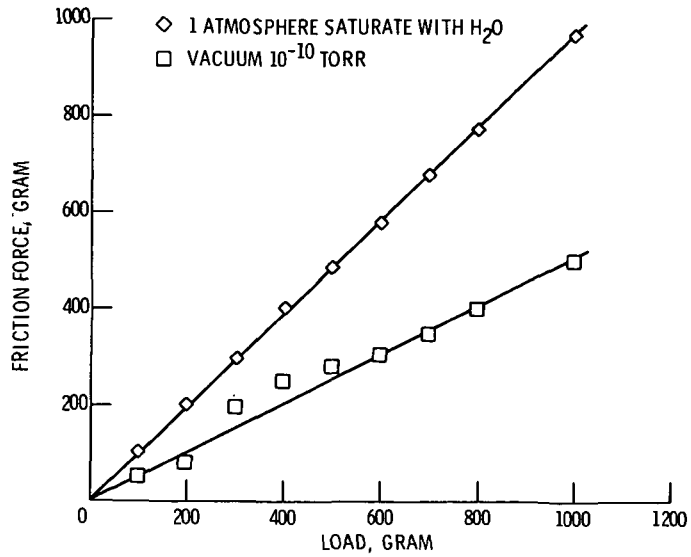

Figure 1. - Friction force as a function of load for glass sliding on glass. Sliding velocity 30 cm/min, load 100 grams and 23° C.

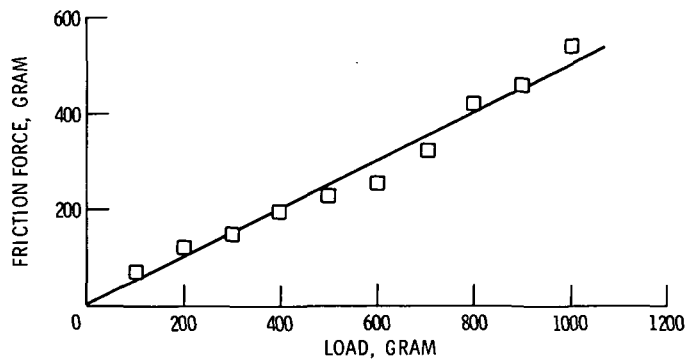

Figure 2. - Friction force as a function of load for aluminum sliding on glass. Sliding velocity 30 cm/min, load 100 grams and 23° C.

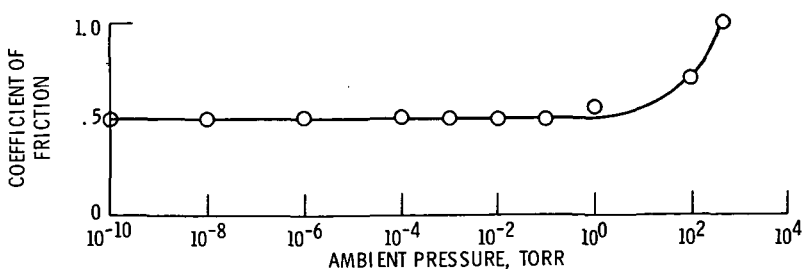

Figure 3. - Friction coefficient for glass sliding on glass as a function of ambient pressure. Sliding velocity 30 cm/min, load 100 grams and 23° C.

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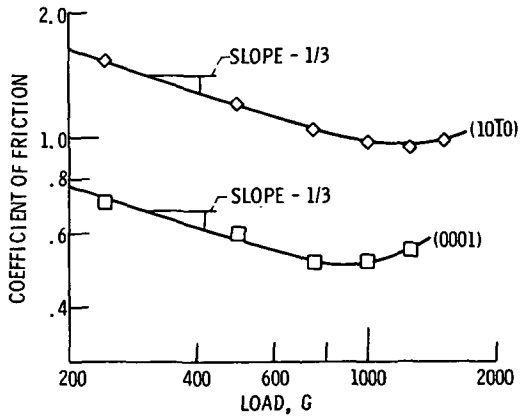

Figure 4. - Friction for two orientations of sapphire with load

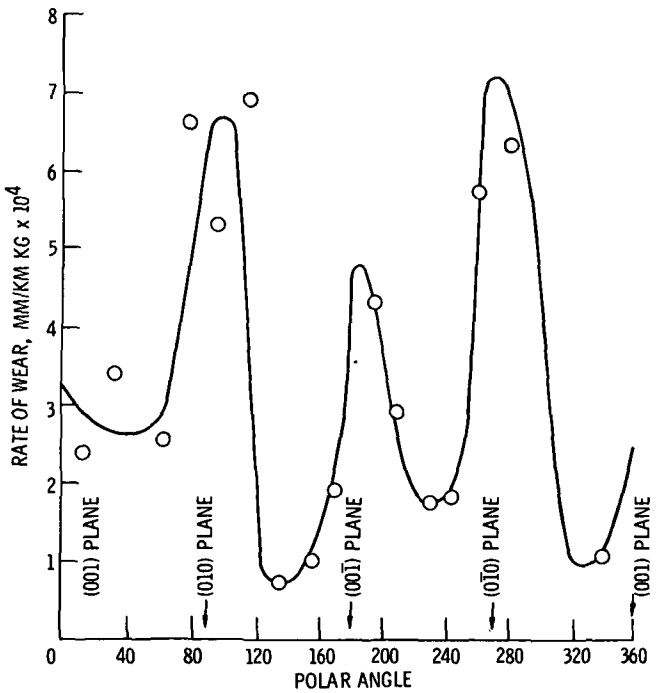

Figure 5. - Rate of wear of a rutile single-crystal sphere on a great circle in the plane of the a- and c-axes. The c-axis is normal to plane of sliding at 0 and 180°. Slide direction in plane of the great circle.

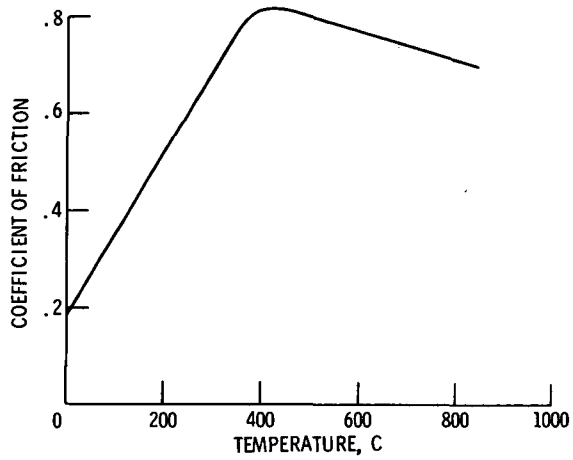

Figure 6. - Effect of temperature on friction coefficient of Al_2O_3.

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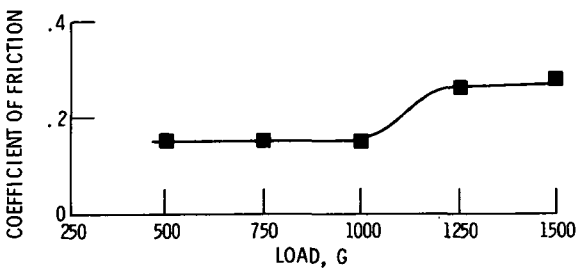

Figure 7. - Coefficient of friction as a function of load for sapphire sliding on sapphire in air (760 torr). Sliding velocity, 0.013 cm/s; ambient temperature, 25^0 C.

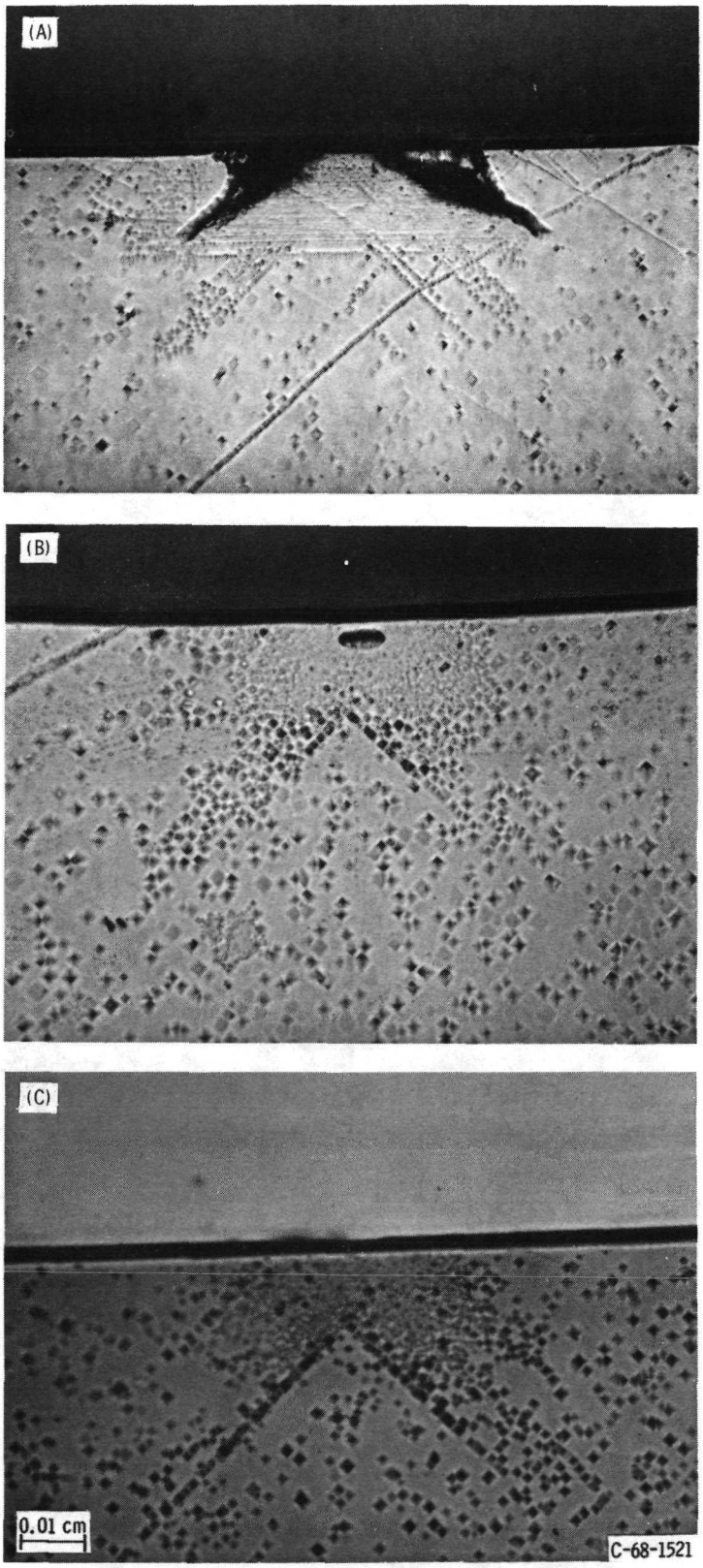

Figure 8. - Cross section of wear tracks on LiF in sliding friction experiments. Load, 200 g; rider, 1.6-mm-diameter sapphire ball; temperature, 20° C; sliding velocity, 0.005 mm/s. Ball made a single pass across surface covered with (A) dry air, (B) water and (C) water with myristic acid.

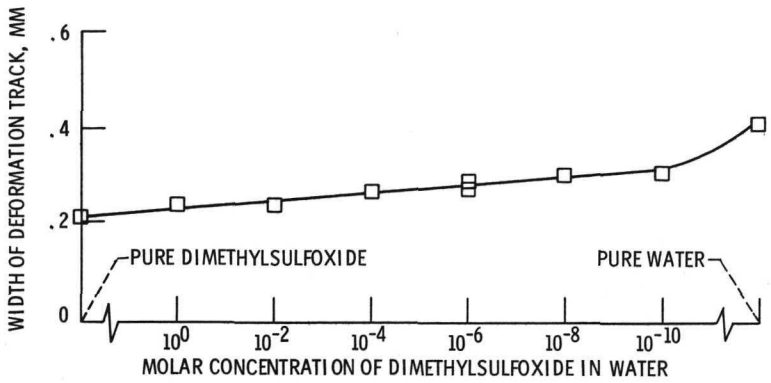

Figure 9. - Dislocation track width for sapphire ball sliding on (111) cleavage surface of CaF_2 in various concentrations of dimethylsulfoxide in water. Sliding velocity, 0.005 cm/s; load 300 g (2.9 N); ambient temperature, 20^0 C.

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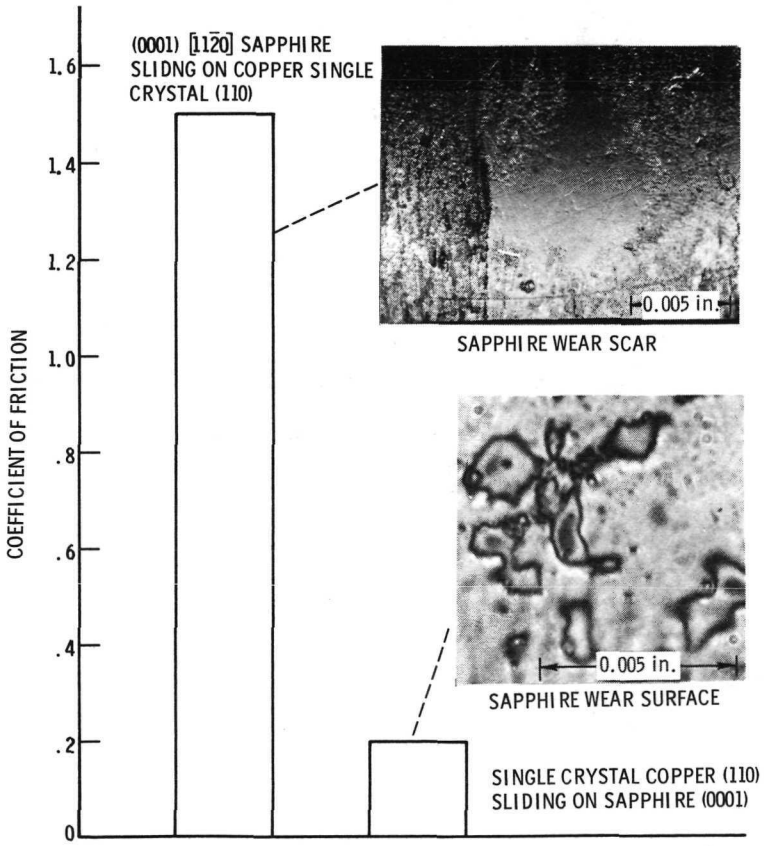


Figure 10. - Coefficient of friction for copper in sliding contact with sapphire in vacuum (10^{-10} torr). Load, 100 g; sliding velocity, 0.013 cm/s.

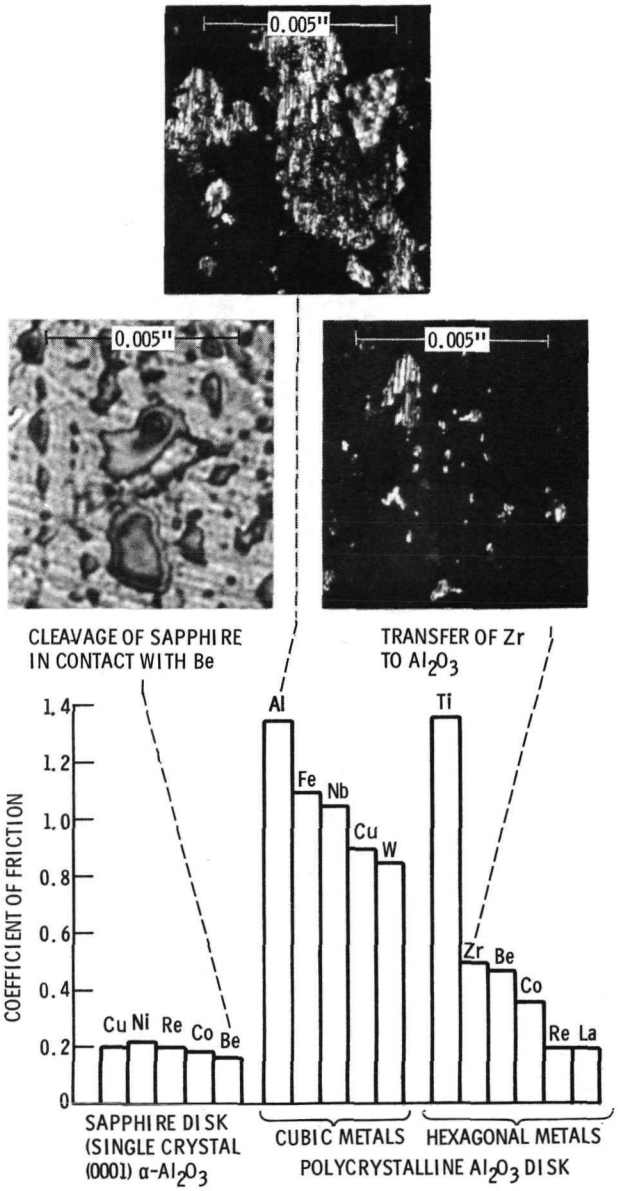


Figure 11. - Coefficient of friction for various metals sliding on Al_2O_3 in vacuum (10^{-10} torr). Load, 1000 g; sliding velocity, 0.013 cm/s; duration of experiment, 1 h.

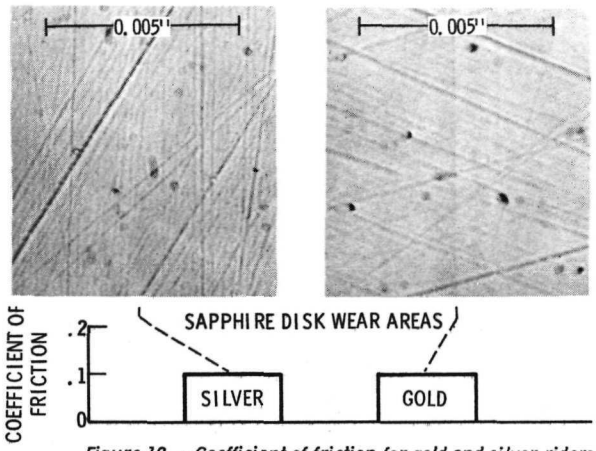
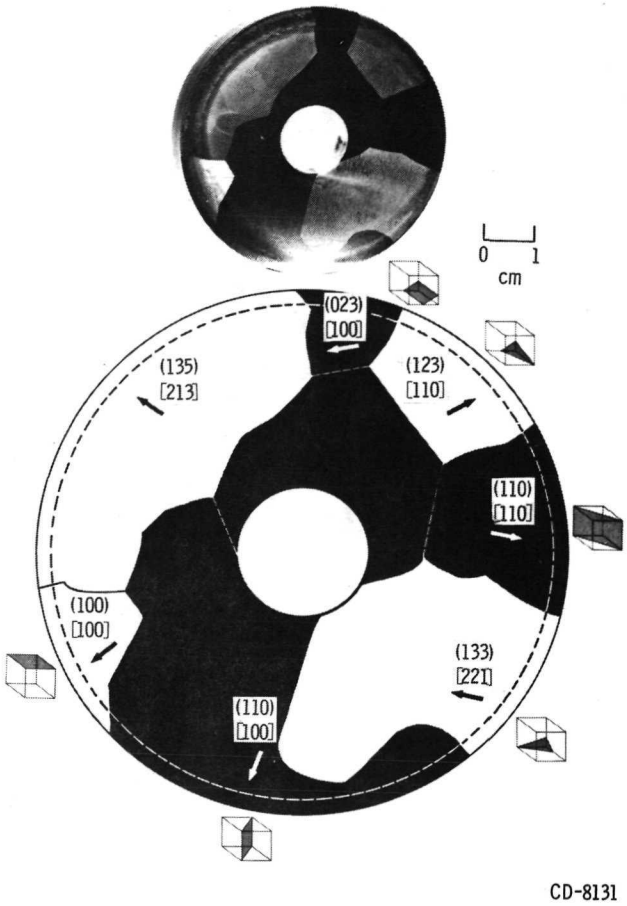
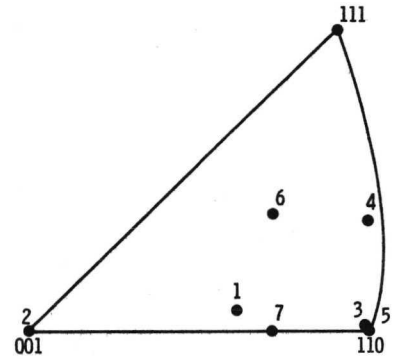


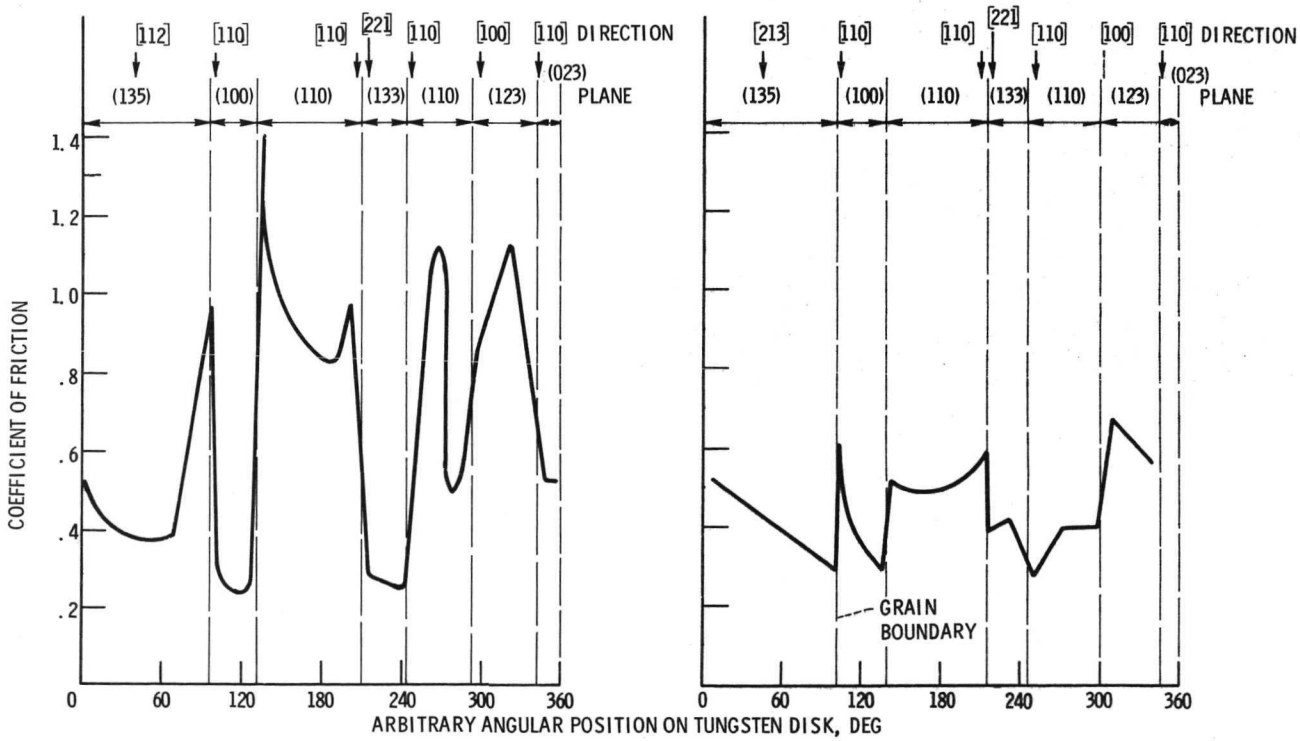
Figure 12. - Coefficient of friction for gold and silver riders sliding on sapphire in vacuum (10^{-10} torr). Sliding velocity, 0.013 cm/s; ambient temperature, 25° C; duration, 1 h.



(a) TUNGSTEN DISK



(b) UNIT TRIANGLE.



(c) IN VACUUM (10^{-10} MM Hg).

(d) IN AIR (760 MM Hg).

Figure 13. - Coefficient of friction of sapphire $(10\bar{1}0)$ plane sliding [0001] direction on polycrystalline tungsten. Load, 500 g; sliding velocity, 0.013 cm/sec.

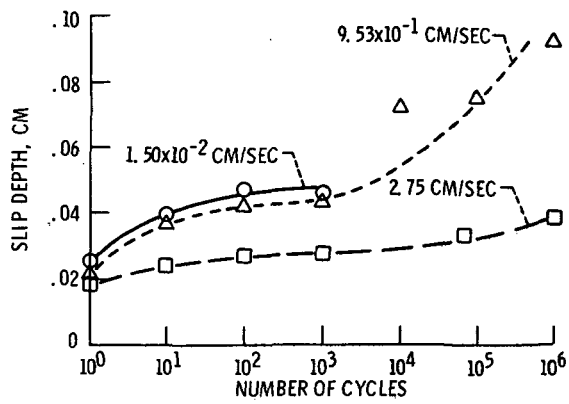


Figure 14. - Variation of slip depth with rolling-contact cycles at three rolling velocities for a steel ball on magnesium oxide.

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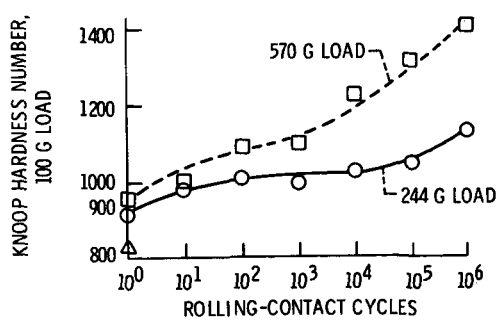

Figure 15. - Variation of track hardness with rolling-contact cycles under dry conditions in 100 rolling direction on a magnesium oxide single crystal surface.