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**A FUNDAMENTAL REVIEW OF THE FRICTION
AND WEAR BEHAVIOR OF CERAMICS**

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TECHNICAL PAPER proposed for presentation at
American Ceramic Society Meeting
Washington, D. C., May 8, 1972

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ABSTRACT

The basic concepts associated with the friction and wear of materials are discussed as they relate to ceramics. Properties of ceramics such as crystal structure, crystallographic orientation, mechanical deformation and surface chemistry are reviewed as they influence friction and wear. Both adhesive and abrasive wear of ceramics are discussed. The friction and wear of ceramics are examined in contact with themselves and when in contact with metals. The influences of environmental constituents such as water and hydrocarbons on friction and wear are reviewed. Materials discussed, by way of example, include aluminum oxide, rutile, calcium fluoride, and lithium fluoride.

INTRODUCTION

The greatest amount of effort in fundamental studies of adhesion, friction and wear has been put into metals. In recent years the increasing potential for the use of ceramics as components in lubrication systems has focused attention upon these materials. Adhesion, friction and wear studies have been conducted with these materials in order to better understand the physical and chemical properties of these materials which will effect their behavior when in contact with themselves, other ceramics or metals.

Metals generally deform plastically very readily, whereas

ceramics, while having high strength, are normally brittle and fracture with little or no evidence for plastic flow. At the contacting interface between two ceramics in solid state contact under load and relative motion, plastic flow has been observed in the surficial layers of some ceramics. Plastic flow has been observed with magnesium oxide⁽¹⁾ and aluminum oxide,⁽²⁾ for example, under relatively modest conditions of rubbing.

Those factors which influence the mechanical behavior of materials when plastic flow occurs such as dislocations, vacancies, stacking faults, and crystal structure will therefore influence the friction and wear behavior of ceramics. From the analogous slip behavior between certain ceramics (i.e., Al_2O_3) and metals⁽³⁾ comparisons can be made between anisotropic friction behavior of ceramics and metals.

The presence of surface films such as adsorbates markedly influences the adhesion, friction and wear behavior of metals and ceramics as well. Further, with ceramics and other ionic solids, the presence of surface films such as water and surface active organics can influence adhesion, friction and wear by altering the amount of plastic deformation that will occur during sliding or rubbing contact.^(4,5)

The objectives of this paper are to review the adhesion, friction and wear of ceramics, anisotropic friction and wear behavior and the effect of surface films and ceramic-metal interactions. Analogies to metals will be made where applicable. Both ceramics and other ionic solids will be discussed.

ADHESION

When surfaces are mechanically finished, they contain irregularities called asperities. These asperities are peaks or mounds of material that project up from the surface (fig. 1(a)); between asperities are valleys or grooves. When two such surfaces are placed into contact under load, contact is generally initially made between surface asperities as indicated in figure 1(b).

The real contact area, because of asperity contact, may be a small portion of the apparent area of contact. Under an applied load, these asperities will deform initially elastically and then plastically until the load is supported.

With ceramics and other ionic solids, relatively atomically flat surfaces can be generated by cleavage. But cleavage generally results in the formation of cleavage steps, as indicated in figure 1(c). When two surfaces containing such steps are brought into contact, unless there is a perfect mating of two halves of the same specimen, the real contact area will still be less than the apparent area.

The fact that strong adhesive forces can develop in ionic solids has been very aptly demonstrated with single crystals of rock salt.⁽⁶⁾ When two slabs of freshly cleaved rock salt are placed into contact with their [100] axis parallel and they are subject to compression, the surface at the points of contact deform. If the compressive force is increased so as to result in a doubling of the contact area and the force is then removed, the two crystals remain adhered. Subjecting the junction to a tensile

test, it withstood a stress of 0.4 Kg/mm^2 . This is of the order of the tensile strength of rock salt crystals and is good evidence for the development of strong adhesive forces between ionic crystals.

Crystallographic orientation influences the adhesive forces developed between ionic solids as it does with metals.⁽⁷⁾ With the rock salt crystals, a mismatch in the orientation of the crystals results in a lower adhesive force. When the [100] direction of one crystal is matched with the [110] direction of the second crystal, the force of adhesion is very small.

FRICITION

The friction force for two solids in contact is a function of the real contact area and the shear, or fracture strength in the case of ceramics of the materials in contact. As the load is increased, the true contact area increases and the friction force should increase. The fact that the friction force increases with an increase in load for ceramics is demonstrated by the data of figure 2. In figure 2, friction force is plotted as a function of load for rutile (TiO_2). The friction was measured on the (110) crystal face.⁽⁸⁾ One set of data was obtained sliding parallel to the C-axis while the other when sliding perpendicular to that axis.

Examination of figure 2 indicates that ceramics behave much like metals in that an increase in applied load results in an increase in the friction force. The data of figure 2 do not indicate anisotropic behavior with a change in crystallographic direction. Rutile does exhibit anisotropy in its friction and wear behavior and this will be discussed later.

Ceramics generally exhibit lower coefficients of friction than do metals. The coefficient of friction being the measured friction force between two surfaces divided by the normal applied load. In figure 3 the coefficient of friction for sapphire is plotted as a function of applied load. The prismatic plane of sapphire ($10\bar{1}0$) was sliding on a basal plane (0001). The coefficient of friction had a minimum value of 0.15 and a maximum value of 0.25 at higher loads. With metals, friction coefficients of 0.5 to 1.5 are generally observed under similar conditions.

An increase in friction coefficient occurs in figure 3 when the load was increased from 1000 to 1250 grams in an air atmosphere. This occurs with the desorption of adsorbed species as a result of the increased interfacial energies associated with the heavier loads.

Increasing the ambient temperature can frequently result, with ceramics, in an increase in friction coefficient. In figure 4 friction coefficient is plotted as a function of temperature for aluminum oxide. At room temperature the friction coefficient for aluminum oxide is 0.25. With an increase in temperature to 400° C the friction coefficient increases to a value of 0.8.⁽⁹⁾ This notable increase is due to the desorption of adsorbed species, principally water vapor. The experiments of figure 4 were conducted in dry air. If moisture was added to the dry air, a reduction in friction coefficient was immediately observed.

Aside from the effects of desorption which results in higher friction for ceramics at increased temperatures, the effect of increasing surface temperature is very commonly to reduce the fric-

tion. This decrease with increase in temperature is seen in figure 4 beyond 400° C.

Another method for the removal of adsorbates from ceramic surfaces is to outgas the material in a vacuum environment. A friction experiment conducted with sapphire in a vacuum as a function of load is presented in figure 5. These data were obtained under the same mechanical conditions used in figure 2 and with the same orientations. A comparison of the friction data of figure 2 with that of figure 5 indicates the marked influence exhibited by adsorbates on the friction properties of sapphire. Mass spectrometer analysis of the gases liberated by the surfaces in figure 5 indicate the principal species to be water vapor.

The data of figures 3, 4, and 5 indicate that adsorbates can be removed from ceramic surfaces in a variety of ways and the result is an increase in sliding friction. In a strict sense the adsorbates act as lubricants to reduce friction.

WEAR

In general there are two types of wear encountered with ceramics. These are adhesive and abrasive wear. Adhesive wear occurs when adhesion takes place across an interface between two ceramic surfaces or a ceramic surface and a metal. With tangential motion, that is sliding or rubbing one surface over the other, if fracture occurs in the ceramic, adhesive wear has taken place. In order for this type of wear to exist, adhesion must first occur. Secondly, the fracture strength of one of the two materials in contact must be less than that of the interfacial junction. If bond-

ing in the interfacial junctions is less than that in either of the two materials, fracture will occur at the interface with theoretically no wear occurring.

The presence and location of subsurface defects such as dislocations, vacancies, impurities, and micro-cracks in the surficial layers of the materials in contact will generally dictate the zones from which wear particles are generated. The extent and distribution of such defects will to a large extent determine the size of the wear particles generated.

Generally, the adhesive wear rate of ceramics such as aluminum oxide in air or when lubricated is extremely low. The excellent wear resistance of such materials make them extremely useful in mechanical applications requiring a minimum in wear, such as bearing surfaces in instruments and watches.

Abrasive wear occurs when two surfaces are brought into contact and one of the two surfaces is considerably harder than the other. Where free particles of the harder material are generated and imposed at the interface between the two surfaces, these particles can cut into and remove material from the softer surface.

Abrasive wear can also occur when a third particle harder than one or both of the surfaces in contact becomes trapped in the interface. It can then operate to remove material from one or both surfaces.

ANISOTROPY

Much like metals, ceramics exhibit anisotropic behavior in many of their mechanical properties. Friction and wear behavior

of ceramics are also anisotropic. Rutile is anisotropic in its friction characteristics both with respect to the crystallographic plane examined and the direction of sliding as indicated by the data of table I.⁽¹⁰⁾

On the (010) crystal face of rutile, friction is higher in the [001] and $[00\bar{1}]$ than in the [100] and $[\bar{1}00]$ directions. With the (110) face, friction is higher in the $[1\bar{1}0]$ and $[\bar{1}10]$ directions than in the [001] direction. These differences exist even when the surface is lubricated with a solid film lubricant as indicated by the data of table I.

Sapphire much like rutile exhibits anisotropic friction behavior. This effect is shown by the data of table II. These data were obtained in vacuum. The lowest friction coefficient was obtained on the preferred or basal slip plane⁽¹¹⁾ when sliding in the preferred $[1\bar{1}\bar{2}0]$ slip direction. Similar results have been obtained with metals. The lowest friction coefficients for metals are generally obtained when sliding on the highest atomic density or preferred slip plane when sliding in the preferred slip direction.⁽¹²⁾

The anisotropic differences in the friction behavior of sapphire are maintained over a range of loads as indicated by the data of figure 6. The friction coefficients for both the basal and prismatic orientations decrease with increasing load to approximately 1000 grams.

The wear rate of rutile is anisotropic both with respect to atomic plane and sliding direction.⁽¹³⁾ The variation of wear rate with plane can be seen from the data of figure 7. A seven fold

difference in wear rate exists with a change in plane from that exhibiting the minimum wear to that having the highest rate of wear.

In figure 8 the effect of changing direction on the (001) plane is seen to influence wear rate. The least amount of wear occurs when sliding in the $\langle 100 \rangle$ directions.

The wear rate of sapphire also varies with changes in crystallographic direction.⁽¹⁴⁾ The schematic of figure 9(a) shows the direction of sliding on the sapphire surface. The angle between the basal sheets and the crystal axis is indicated by the angle θ . Wear rate is shown in figure 9(b) as a function of two sliding directions and variations in the angle θ .

In figure 9(b) the wear rate is higher when sliding with than when sliding against the basal sheet edges. When sliding against the edges a difference in wear rate exists with a change in θ . The differences in wear rates are, however, even greater with changes in θ when sliding is with the direction of the basal edges. This edge effect is not normally seen with metals.

SURFACE FILMS

The presence of water and organics on the surface of ceramics are known to influence 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 in-

crease in the ability of surfaces to deform plastically in the presence of surface active species is the Rebinder effect.

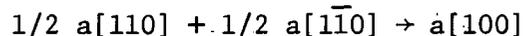
Sliding friction experiments have been conducted with the ionic solid lithium fluoride to determine the influence of surface films on friction and deformation. A sapphire ball was slid across a freshly cleaved lithium fluoride (100) surface. The lithium fluoride specimen was then cleaved normal to the sliding track and subsequently etch pitted. The subsurface deformation and the development of cleavage cracks is shown in figure 10(a). Examination of figure 10(a) 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 developed along the {011} slip bands and have their origin at the surface. Cracks can form in lithium fluoride at the intersection of {110} slip planes according to the equation:

$$1/2 a[011] + 1/2 a[101] = 1/2 a[110]$$

It is important to note from the etch pitted slip bands in figure 10(a) that a brittle material such as lithium fluoride will deform plastically in sliding.

In order 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. The track subsurface deformation is shown in figure 10(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 (fig. 10(a)) the crack formed at the surface along (110) planes rather than subsurface. With plastic deformation of lithium fluoride, cracks can develop along a (100) plane with the intersection of {110} slip bands in accordance with the equation:



The crack developed in figure 10(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 10(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 10(a) and (b). In figure 10(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 11 presents deformation data as a function of molar concentration of dimethylsulfoxide in water. The data indicate that with decreasing concentrations of dimethylsulfoxide or increasing concentrations of water, the width of the wear track increases. This increase in the width of the wear track may be attributed to an increase in the plasticity of the surface.

The foregoing discussion on the influence of surface films on the deformation and fracture of lithium fluoride and calcium fluoride indicate 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.

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. This impedement to motion is shown schematically in figure 12. The material ahead of the ball must be plowed. This results in an increase in friction force.

Plowing is extremely important when metals contact ceramics. The mark 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 the data of figure 13.

In figure 13 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 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. The manner of bonding is shown in figure 14.

With sliding of these metals across the sapphire surface, fracture took place in the sapphire along the basal cleavage plane. This resulted in the plucking out of 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 indicated in figure 14. 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. The friction results are presented in figure 15.

A number of metals were examined in sliding contact with polycrystalline aluminum oxide. Some metals had cubic structures while others had hexagonal crystal structures. The friction results obtained are presented in figure 15. 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 surficial 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 15 because of the differences in slip and the shear behavior of these metals. In general hexagonal metals have less operable slip systems, shear more readily, and do not work harden rapidly and as a consequence, they exhibit lower friction coefficients than cubic metals.⁽¹²⁾ Titanium exhibits complex slip making it behave more like a cubic rather than hexagonal metal accounting for its friction behavior in figure 15.

If a metal does not form a stable oxide the observed friction coefficient is less than that seen in figure 15. Both gold and silver were slid on sapphire in a vacuum. The friction results obtained in these experiments are presented in figure 16. With both gold and silver, the friction coefficient was 0.1 or half that obtained in figure 15 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.

CONCLUDING REMARKS

Ceramics like metals behave in accordance with the adhesion theory of friction. Interfacial adhesion is a large component of

measured friction forces. Ceramics in general exhibit lower friction coefficients than metals. The excellent resistance to wear characteristic of many ceramics can be attributed to the presence of surface films which minimize the formation of strong adhesive junctions and to their high elastic moduli minimizing the real contact area.

Anisotropy is observed in both the friction and wear behavior of ceramics. Both crystallographic plane and the direction of sliding on a crystal face exert an influence on friction coefficient. With sapphire frictional anisotropy is very analogous to that observed in hexagonal metals.

The presence of films on the surface of ionic solids effect the mechanical behavior of these materials during sliding. Surface active organics increase the deformability of the surface during sliding thereby arresting crack formation.

When metals contact ceramics, the ability of the metal to interact chemically with the ceramic surface plays an important role in observed friction and wear behavior. Friction forces and wear will be dictated by the zone of weakest bonding in the interfacial layers. It may occur in the ceramic, in the metal or at the interface.

REFERENCES

1. K. F. Dufrane and W. A. Glaeser, "Study of Rolling-Contact Phenomena in Magnesium Oxide," Battelle Memorial Inst., NASA CR-72295 (1967).
2. R. P. Steijn, "On the Wear of Sapphire," J. Appl. Phys., 32, 1951-1958 (1961).
3. M. L. Kronberg, "Plastic Deformation of Single Crystals of Sapphire: Basal Slip and Twinning," Acta Met., 5, 507-524 (1957).
4. D. H. Buckley, "Influence of Surface Active Agents on Friction, Deformation and Fracture of Lithium Fluoride," NASA TN D-4716 (1968).
5. D. H. Buckley, "Effect of Surface Active Media on Friction, Deformation and Fracture of Calcium Fluoride," NASA TN D-5580 (1969).
6. R. F. King and D. Tabor, "The Strength Properties and Frictional Behaviour of Brittle Solids," Proc. Roy. Soc., A223, 225-237 (1954).
7. R. P. Steijn, "Sliding and Wear in Ionic Crystals," J. Appl. Phys., 34, 419-428 (1963).
8. R. P. Steijn, "Friction and Wear of Single Crystals," Wear, 7, 48-66 (1964).

9. M. B. Peterson and S. F. Murray, "Frictional Behavior of Ceramic Materials," Met. Eng. Quart., 7, 22-29 (1967).
10. R. P. Steijn, "Friction and Wear of Rutile Single Crystals," ASLE Trans., 12, 21-33 (1969).
11. D. H. Buckley, "Friction Characteristics in Vacuum of Single and Polycrystalline Aluminum Oxide in Contact With Themselves and With Various Metals," ASLE Trans., 10, 134-145 (1967).
12. D. H. Buckley and R. L. Johnson, "The Influence of Crystal Structure and Some Properties of Hexagonal Metals on Friction and Adhesion," Wear, 11, 405-419 (1968).
13. E. J. Duwell, "Wear Rates of Rutile and Spinel Single Crystals in Water-Lubricated Slide Interfaces," ASLE Trans., 12, B4-35 (1969).
14. E. J. Duwell, Discussion on "Friction Characteristics in Vacuum of Single and Polycrystalline Aluminum Oxide in Contact With Themselves and With Various Metals," by D. H. Buckley, ASLE Trans., 10, 143-144 (1967).
15. A. R. C. Westwood and D. L. Goldheim, "Occurrence and Mechanism of Rebinder Effect in CaF_2 ," J. Appl. Phys., 39, 3401-3405 (1968).

16. A. R. C. Westwood, D. L. Goldheim, and R. G. Lye, "Rebinder Effects in MgO," Phil. Mag., 16, 505-519 (1967).
17. A. R. C. Westwood, D. L. Goldheim, and R. G. Lye, "Further Observations on Rebinder Effects in MgO," Phil. Mag., 17, 951-959 (1968).
18. P. Reh binder and V. Lichtman, "Effect of Surface Active Media on Strains and Rupture in Solids," Elec. Pheno. and Solid/Liquid Interface, Proc. 2nd Intern. Cong. on Surface Activity, 563-578 (1957).
19. J. H. Westbrook, Environment-Sensitive Mechanical Behaviour, Gordon and Breach, Science Publ., New York, 1966.
20. A. R. C. Westwood, "The Rebinder Effect and the Adsorption-Locking of Dislocations in Lithium Fluoride," Phil. Mag., 2, 633-649 (1961).
21. P. A. Reh binder, L. A. Schreiner, and K. F. Zhigach, "Hardness Reducers in Rock Drilling," C.S.I.R.O., Melbourne, (1948).

TABLE I. - FRICTION ON DRY AND LUBRICATED^a (110)
 AND (010) PLANES 1/16-INCH-DIAMETER RUBY
 SLIDER; 6000 g LOAD⁽¹⁰⁾

Crystal face	Sliding direction	Coefficient of friction	
		Dry	Lubricated
(010)	[001]	0.11	0.061
	[00 $\bar{1}$]	0.11	
	[100]	0.10	0.069
	[$\bar{1}$ 00]	0.10	
(110)	[001]	0.13	0.052
	[00 $\bar{1}$]	0.12	
	[$\bar{1}$ 10]	0.15	0.055
	[$\bar{1}$ 1 $\bar{0}$]	0.16	

^aLubricated with commercial resin-bonded MoS₂ film. The film was applied by spraying the solid lubricant dispersion from an aerosol can followed by drying in air for 18 hours.

TABLE II. - THE INFLUENCE OF CRYSTALLOGRAPHIC
DIRECTION ON THE COEFFICIENT OF FRICTION
FOR SAPPHIRE SLIDING ON SAPPHIRE IN
VACUUM (10^{-10} MM Hg)^a

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

^aLoad 1000 gm, sliding velocity 0.013 cm/sec.

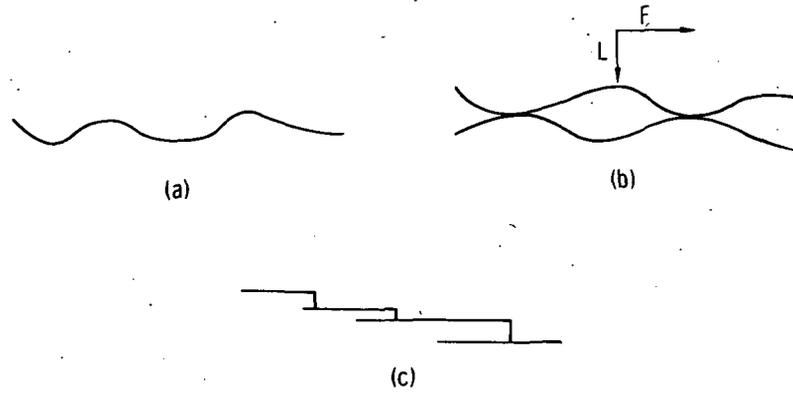


Figure 1. - Nature of surfaces and surface interactions.

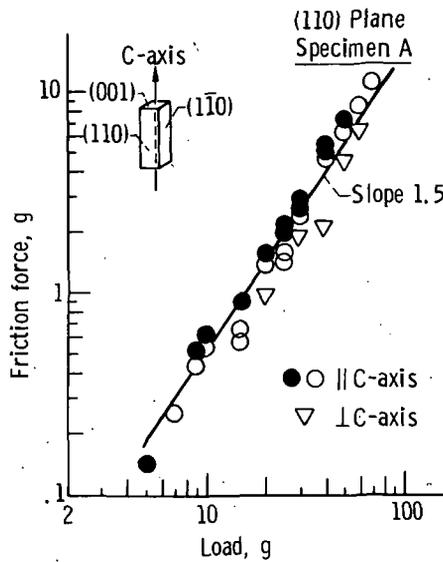


Figure 2. - Friction as a function of load-1.0-mil diamond tip. (10)

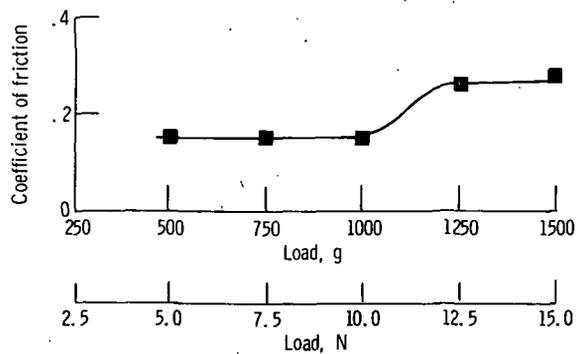


Figure 3. - Coefficient of friction as function of load for sapphire sliding on sapphire in air (760 torr). Sliding velocity, 0.013 centimeter per second; ambient temperature, 25° C (298 K).

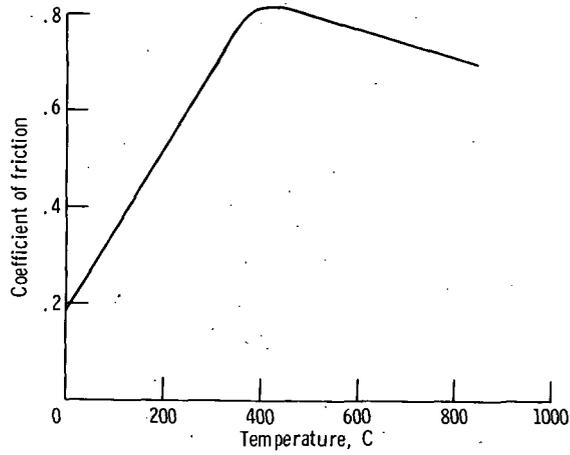


Figure 4. - The effect of temperature on the friction coefficient of aluminum oxide.

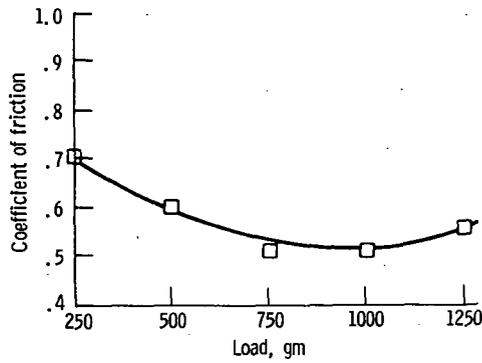


Figure 5. - Coefficient of friction as function of load for sapphire sliding on sapphire in vacuum, 10^{-10} mm Hg. Sliding velocity, 0.013 cm per second; temperature, 25 C; specimen outgassing with electron gun at 300 C. Disk specimen was (0001) plane parallel to sliding interface.

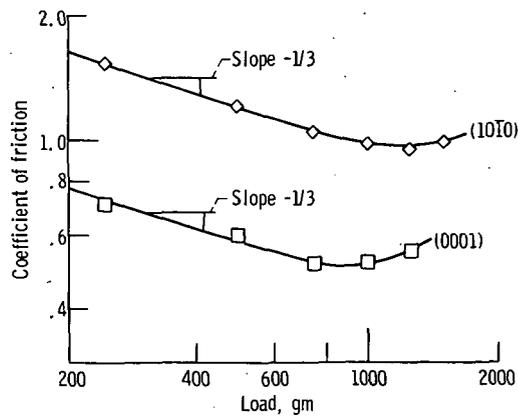


Figure 6. - Friction for two orientations of sapphire with load.

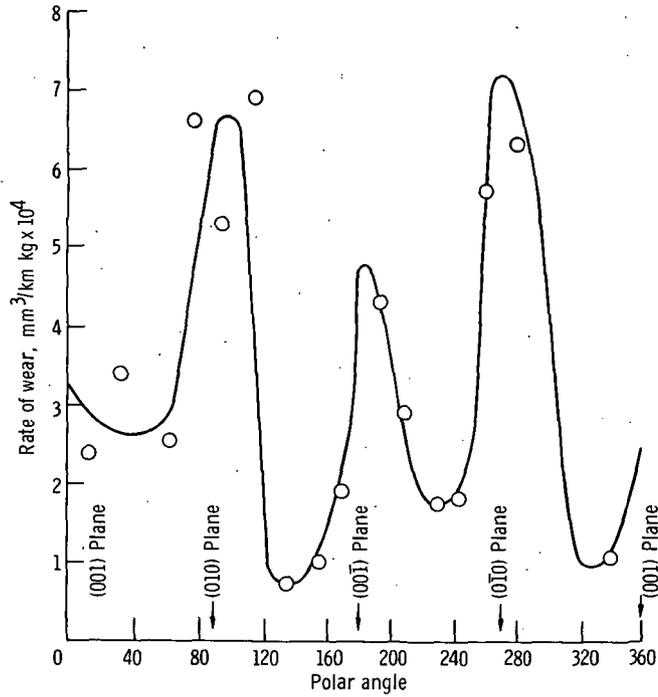


Figure 7. - Rate of wear of a rutile single crystal sphere on a great circle in the plane of the a and c-axes. The c-axis is normal to the plane of sliding at 0 and 180°. The slide direction was in the plane of the great circle. (13)

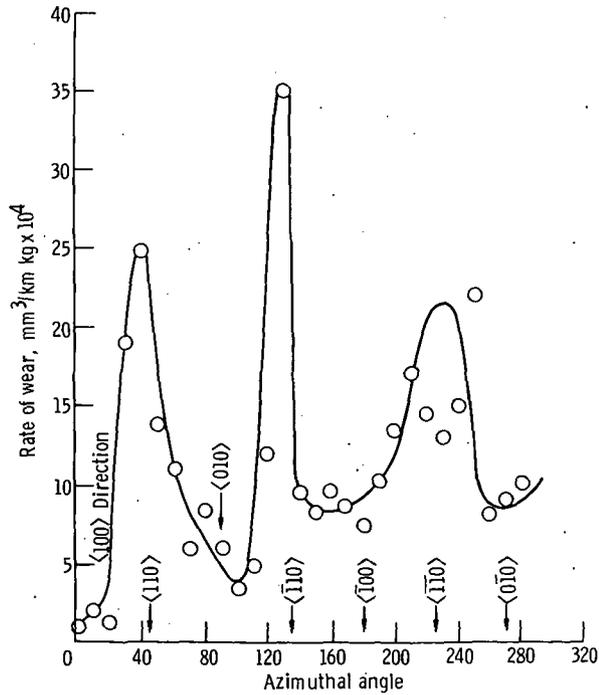


Figure 8. - Rate of wear of a rutile single crystal sphere as a function of slide direction on the (001) plane. The slide direction is parallel to an a-axis at 0, 90, 180, and 270°. (13)

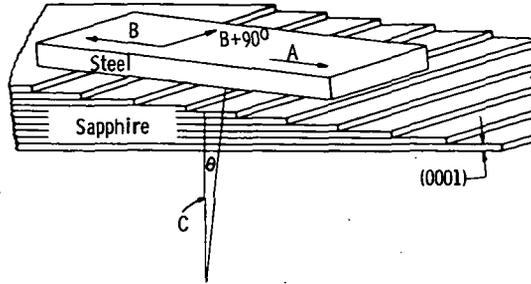


Figure 9(a). - Schematic diagram of Al_2O_3 -Fe slide interface. The sapphire surface consists of successive emerging basal sheets (0001). The c-axis, which is normal to the basal sheets, makes an angle θ with the slide interface. Slide direction A: high wear rate of sapphire; slide B: low wear rate of sapphire; slide direction $B + 90^\circ$: intermediates wear rate. Slide directions A and B are in opposite directions and perpendicular to the edges of the basal sheets. (14)

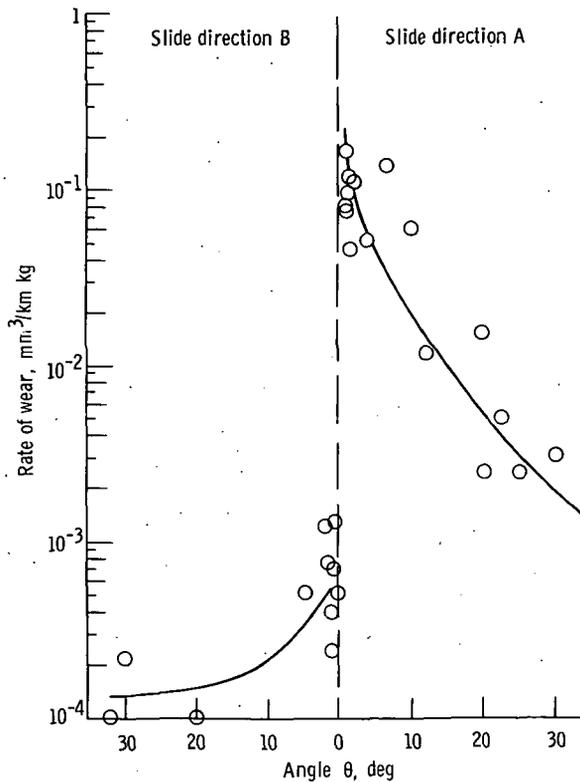
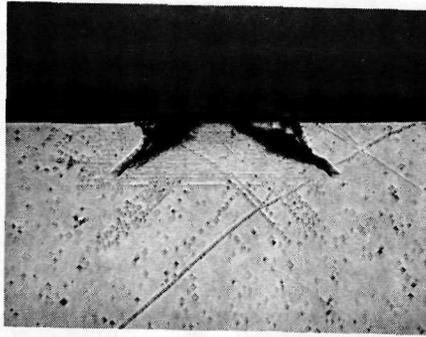
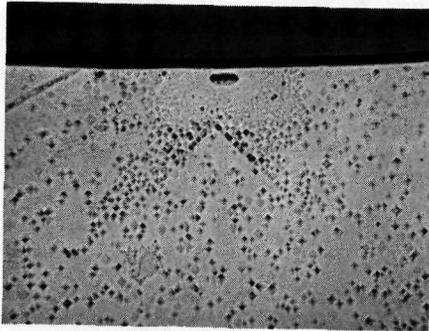


Figure 9(b). - Rate of wear as a function of angle θ . Slide directions A and B and angle θ are defined in figure 9(a). Load: 650 gm; H_2O lubricated; sliding speed: 100-140 m/minute; circular track experiments. (14)



(a) Dry air.



(b) Water.

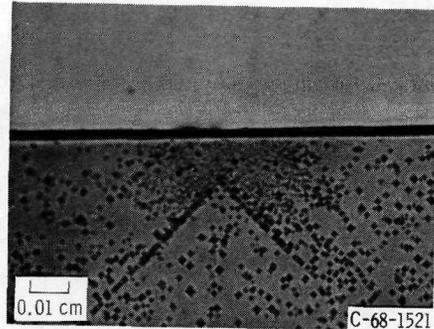
(c) Water and 5.0×10^{-6} N myristic acid.

Figure 10. - Cross section of wear tracks on lithium fluoride in sliding friction experiments. Load, 200 grams (2.0 N); rider, 1.6-millimeter-diameter sapphire ball; temperature, 20° C (293 K); sliding velocity, 0.005 millimeter per second. Ball made a single pass across surface covered with three different media: air, water, and water with myristic acid.

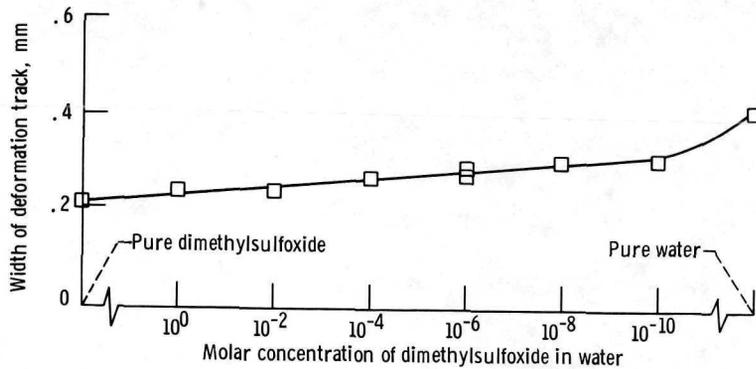


Figure 11. - Dislocation track width for sapphire ball sliding on (111) cleavage surface of calcium fluoride in various concentrations of dimethylsulfoxide in water. Sliding velocity, 0.005 centimeter per second; load, 300 grams (2.9 N); ambient temperature, 20° C (293 K).

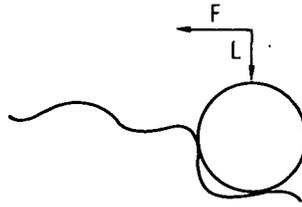


Figure 12. - The nature of plowing in friction.

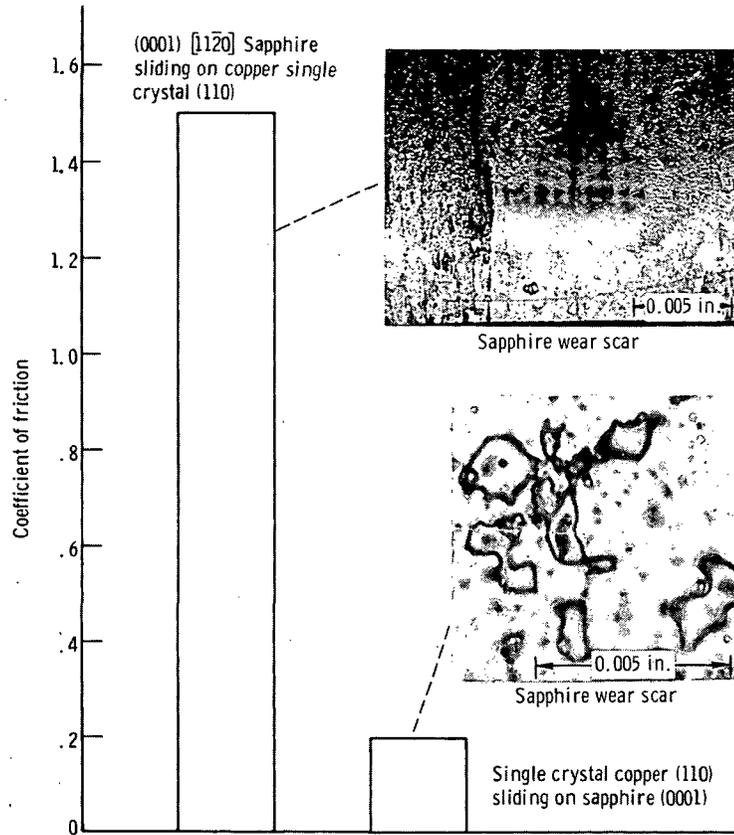


Figure 13. - Coefficient of friction for copper in sliding contact with sapphire in vacuum (10^{-10} torr). Load, 100 grams, sliding velocity, 0.013 centimeter per second.

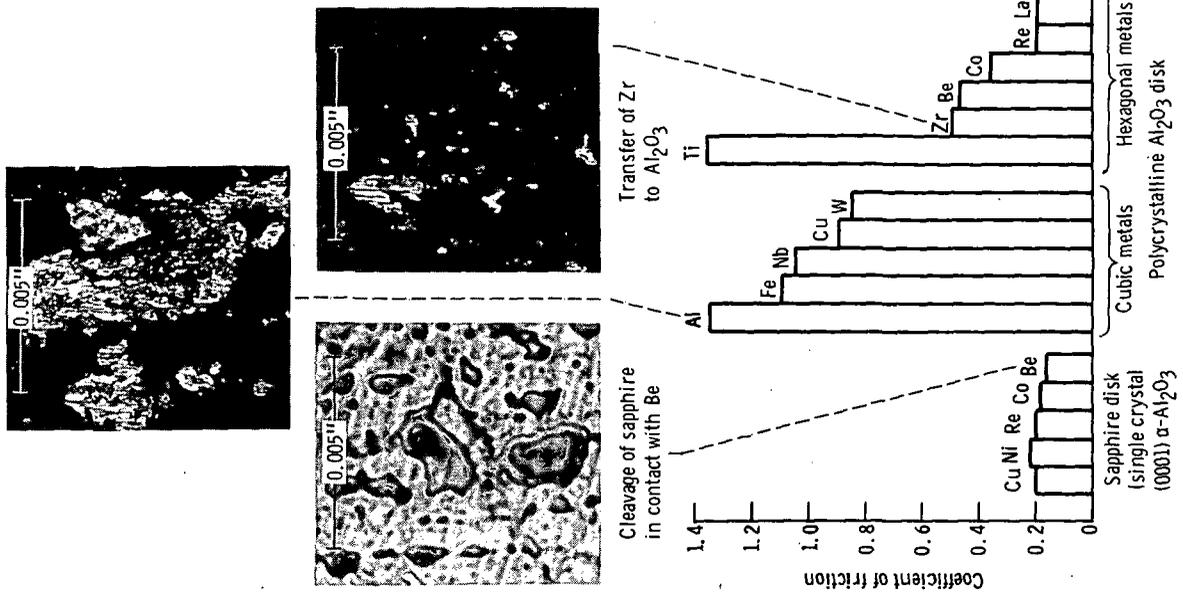


Figure 15. - Coefficient of friction for various metals sliding on aluminum oxide in vacuum (10-10 torr). Load, 1000 g; sliding velocity, 0.013 cm/sec; duration of experiment, 1 hr (from ref. 15).

- Al³⁺ in first subsurface layer and arranged in octahedral array
- Surface covered by layer of O²⁻
- ⊙ Sites for chemical bonding of metals with oxygen when in contact with surface
- ⊙ Sites for van der Waals interaction with metals sliding on surface

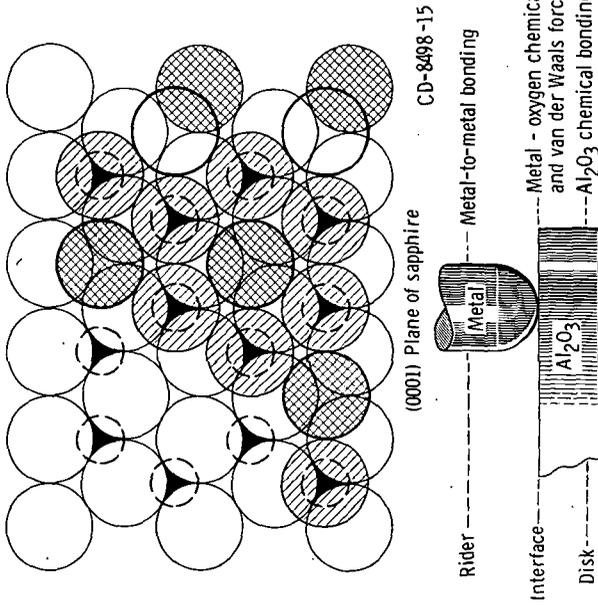


Figure 14. - Nature of surface interaction and bonding of metal to aluminum oxide.

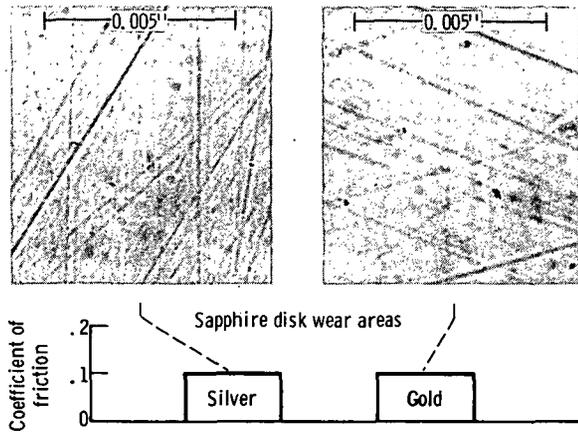


Figure 16. - Coefficient of friction for gold and silver riders sliding on sapphire in vacuum (10^{-10} mm Hg). Sliding velocity, 0.013 centimeter per second; ambient temperature, 25° C; duration, 1 hour.