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THE INFLUENCE OF THE ATOMIC NATURE OF CRYSTALLINE MATERIALS ON FRICTION

by Donald H. Buckley

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Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Lubrication Conference sponsored by the American Society of Lubrication Engineers and the American Society of Mechanical Engineers
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ABSTRACT

The arrangement of atoms in crystalline materials is discussed with reference to lattice, planes and crystal structure. The effect of atomic structure is considered in terms of its influence on mechanical properties with particular emphasis on those related to friction, namely deformation and shear. Friction data are presented for body centered cubic, face centered cubic and hexagonal metals, as well as for crystals of inorganic compounds. The data were primarily obtained in a vacuum environment where the effects of material structure on friction could be measured without the presence of contaminating surface films. The friction results presented are for various planes and for various directions on the planes of single crystals. Data are also presented to show the relation of observation with single crystals to those with polycrystalline materials. The data indicate that friction is anisotropic and is generally lowest on the greatest atomic density planes of crystalline materials when sliding in the direction of most closely packed planes. This relation appears to hold for many crystals of inorganic compounds as well as for various crystal forms of metals. Crystal structure, recrystallization and surface texturing as well as ordering of atoms in alloys are all shown to exert an influence on friction.

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INTRODUCTION

In recent years, considerable research has been conducted in the field of friction and wear with single crystals. Single crystals offer an advantage in that the influence of properties normally associated with planes and directions in the crystal can be studied more easily. Properties such as atomic density, spacing of atomic planes, influence of imperfections, surface energy, modulus of elasticity and hardness are all related to crystal orientation. While observations with single crystal cannot be related directly to those with polycrystalline engineering materials, they can furnish a closer insight into the fundamental or atomic nature of the friction and wear process. Further, single crystals are currently being considered for engineering applications (ref. 1).

Friction and deformation studies have been made by many investigators with a wide variety of single crystal materials. Studies have been conducted with a number of metallic structures. These includes (a) the face centered cubic metals, copper (2, 3 and 4) and brass (5); (b) the body centered cubic metals, iron (5) and tungsten (6) and (c) the hexagonal metals, cobalt (7), beryllium (8), rhenium (9) and titanium (10). The anisotropic nature of the friction process has been determined for a variety of salt structures (MgO, (11) LiF, NaCl etc. (5)) as well as for some of the most wear resistant materials such as sapphire (12, 13, 14, and 15) and diamond (16, 17, and 18).

Although considerable effort has been put forth in determining the friction behavior of single crystals on a variety of crystallographic planes and in various directions, no systematic study has been conducted to determine the relations of these observations to more fundamental properties. This has resulted in somewhat isolated results reported by various investigators. These independent studies have concerned themselves most frequently with the influence of sliding in a particular direction on a specific plane to friction and deformation.

The objective of this investigation was to examine friction behavior for single crystal materials and to attempt to relate these data to fundamental properties such as; (1) atomic density of planes (2) spacing between planes, (3) surface energy (4) elasticity of planes and (5) hardness. Data were taken from various sources as well as the authors work. The range of conditions (load, speed, temperature etc.) in these studies did not span a wide range because of the necessity of avoiding excessive interfacial heating which could cause recrystallization or surface texturing. In some of the data presented, materials were in sliding contact with themselves while in others they were in contact with a diamond or sapphire slider.

BACKGROUND

When the atomic theories were first used to calculate the strengths of materials on a theroetical basis, very marked discrepancies existed between calculated and measured strengths. The ratio of measured yield strengths to theoretical values for the body centered cubic form of titanium was 0.35 and for the hexagonal metal beryllium 0.03. The marked differences between calculated and observed values, as indicated by the ratios, are associated with the presence of imperfections (point defects such as vacancies but principally to dislocations) in real crystals. When real crystals are stressed, slip will occur (when the critical resolved shear stress is exceeded) in the crystals along well defined crystallographic planes. The presence of and generation of dislocations on the planes permit yielding well below the calculated strengths.

In the friction and deformation process, yeilding and shear strengths are of concern (yielding with respect to establishment of the true contact area and shear in determining friction force); dislocations and slip behavior must therefore, be of concern in friction studies. Table I summarizes the crystallographic planes along which deformation will occur for various structure and bond types. The slip planes are usually the atomically most densly packed planes (rock salt structure is an exception) which are also usually the most widely separated. A higher shear stress is required to initiate slip on planes of lower atomic packing density. When slip occurs, it will usually occur along the directions of the closest packing of atomic planes.

Some planes and directions of the three most commonly encountered metallic structures are presented in Fig. 1. Examination of Table I indicate that, for face centered cubic metals, there are four slip planes and three directions or twelve possible slip systems. With the body centered cubic there are forty-eight possible slip systems. It is interesting to note that the close packed hexagonal structure exhibiting basal slip have only three slip systems (Table 1).

The greater the number of slip systems the easier it is to initiate plastic deformation because of the greater probability that some of the slip systems will be favorably oriented for slip. With a large number os slip systems, however, the is a greater tendency to work-harden because of the intersection of slip plane and slip plane dislocations impeding further slip. This work hardening increases the shear strength of junction formed in sliding. Hexagonal metals exhibiting basal slip have, in their single crystalline form, the least tendency to work-harden.

For the metallic structures, yielding could be expected to occur least readily normal to basal planes of the hexagonal structure for a given stress. For example, the metal beryllium can be stressed in this direction until the crystal explodes with no evidence of slip along other planes. This limited ability to deform can be expected to limit the true contact area. Further since they do not workharden very readily, the shear strength (therefore friction force) should not increase markedly with sliding.

In Table I are also presented the slip planes, directions and systems for crystals having ionic and covalent structures. The rock salt structures are typically cubic ionic compounds while the ionic rhombohedral structure of aluminum oxide allows it to behave in the region of plastic deformation in a manner very analogous to hexagonal metals.

APPARATUS

The apparatus used in this investigation is shown in Fig. 2. The basic elements of the apparatus were the specimens (a $2\frac{1}{2}$-in.-diam. flat disk and a $\frac{3}{16}$- in.-rad. rider) mounted in a vacuum chamber. The disk specimen was driven by two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The driver magnet that was outside the vacuum system was coupled to a hydraulic motor or small instrument motor for slow speed experiments. The second magnet was completely covered with a nickel-alloy housing and was mounted on one end of the shaft within the chamber (fig. 1). The end of the shaft that was opposite the magnet held the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm, away from the rider specimen, was connected to a straingage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber was a 500-liter-per second ionization pump and a sorption pump. The pressure in the chamber was measured adjacent to the specimen with a cold cathode ionization gage. In the same plane as the specimens and ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases presented in the vacuum system. A 20-foot-long stainless steel coil of 5/16-inch-diameter tubing was used for liquid-helium cryopumping of the vacuum system.

In experiments where external heating of the specimens was required, an electron gun was used (fig. 2). A thermocouple was inserted in the rider and the bulk specimen temperature recorded. No attempt was made to record interface temperatures.

EXPERIMENTAL PROCEDURE

The polycrystalline disk and rider specimens used in this study were machined to size and electropolished. They were than rinsed in acetone and alcohol before insertion into the vacuum chamber. The single crystals were hemispherically tipped by spark discharge machining. They were electropolished and orientations were then determined using the Laue back-reflection X-ray technique. They were mounted in the specimen holder, orientation rechecked and finally rinsed with acetone and alcohol prior to insertion into the vacuum chamber. The vacuum system was purged with dry nitrogen gas after insertion of the specimens. The chamber was then evacuated, first, with vacsorption pumps and finally with ion pumps. After an overnight chamber bakeout, the specimen surfaces were cleaned with an electron gun. Sufficient energy could be obtained with the electron bombardment to evaporate the surface layer of most metals. After the specimens were cooled to room temperature, liquid helium cryopumping was then initiated. When the system was at operating pressure, the only gases which could be detected by the mass spectrometer were hydrogen and helium.

RESULTS AND DISCUSSION

Metallic Bonding

Face centered cubic structures. - The results obtained in Ref. 3 indicated the friction characteristics of copper to be highly anisotropic. In that investigation (3), it was found that friction coefficient was highly dependent on slip plane and slip plane direction. The experiments were conducted in air with a diamond or sapphire stylus sliding on the crystal surface. The deformation of the soft copper played a significant role in the observed friction behavior.

Friction experiments were conducted by the author with single crystals of copper sliding on single crystals of copper in air and vacuum. The planes and directions across the interface were matched to one another. The friction results obtained on three planes are presented in Table II. It is interesting to note that the lowest friction (either with contaminant surface films present or with clean surfaces in vacuum) were obtained with preferred slip planes (see Table I) for face centered cubic metals. These planes are, the greatest atomic density planes and possess the greatest spacing between planes.

It might be anticipated that the greatest atomic density planes would offer the greatest resistance to deformation. Examination of Table II indicates that the (111) plane does exhibit the highest elastic modulus. Further, because of the larger spacing between planes, shear can be expected to occur more readily between planes. With sliding, however, work hardening will occur and this will influence shear and friction. The rate of work hardening for the three planes of Table II are [111] > [100] > [110] (ref. 19).

Since friction involves interfacial energy and is somewhat dependent upon it, a relation between surface energy and friction would be anticipated. Surface energies are presented in Table II for two of the planes. These energies were obtained from Ref. 20. The energies appear to be in the order to what might be anticipated. It would appear from atomic bonding considerations that the greatest atomic density and preferred slip planes (111) should exhibit the least surface energy. Reference 21 also indicate that this should be the case. The author of reference 22, however, obtains a reverse relation. Because of the difficulty in measuring solid surface energies and including all the necessary parameters in calculations it is difficult to obtain good energy values. From the atomic nature of surfaces, it might be anticipated that the highest density planes would have the lowest surface energies. In air, the real significance of surface energy may be lost because of the presence of surface contaminants. In vacuum, when two clean metallic crystal surfaces are brought into contact the adhesion of the surfaces at the interface alters energy considerations. When complete adhesion occurs across an interface, the interface may be considered to be analogous to a twin or grain boundary (assuming some mismatch in orientations). The interface will then have its own characteristic energy which may be considerably different from that of the two crystals. This energy may well be more a function of mismatch in crystallite orientations (as it is for grain boundaries) than parent surface energies. Of greater significance under this condition would be the crystal lattice energy at the interface.

In addition to a difference in atomic density of various crystallographic planes within the face centered cubic metals, there are atomic density variations on planes. For example, for the face centered cubic metal copper, the preferred slip direction is the $\langle 110 \rangle$. This is the greatest atomic density direction on the (100) plane and, if friction is influenced by sliding direction on a plane, it might be expected that this direction would exhibit the lowest friction coefficient. Data with a diamond pyramid sliding on the (100) face of copper (ref. 2) did in fact exhibit lower friction in the $\langle 1\bar{1}0 \rangle$ than in the $\langle 100 \rangle$. Static friction data obtained for copper single crystals in contact (Ref. 4) also showed the friction to be lowest in the $\langle 110 \rangle$ direction. Results with a hemispherical stylus, (Ref. 2) however, showed just the opposite result, that is lower friction in the $\langle 100 \rangle$ on the (100) plane than in the $\langle 110 \rangle$ direction. The work of Ref. 5 with a hemispherical stylus has shown similar results friction is lowest in the $\langle 100 \rangle$ for other face centered cubic metals.

Friction is determined by two parameters, shear of junctions at the interface and plowing. While plowing may not markedly affect friction, where the slider and the surface upon which it is sliding are the same material, it may have a marked influence where the slider is very much harder as was the case in Refs. 2 and 5. The nature of deformation and plowing has been examined by the authors of Refs. 23 and 24. In general, plowing and work hardening contribute to the observed results. Thus the effect of plowing may overshadow any affects due to differences in shear strengths for the two directions. For example, with sapphire sliding on a copper single crystal, shear effects accounted for only 13 percent of the observed friction and plowing the balance (Ref. 25).

The reason the authors of Ref. 3 observed friction results with diamond pyramid as predicted from the atomic nature of surfaces is that the pyramid plows with minimum amount of material at the apex. Thus the plowing effect may not be marked with the pyramid while with a hemisphere a considerable bulge of displaced material may have to be plowed (frontal bulge of Ref. 24). With work-hardening, this material offers even greater resistance to sliding. Where materials slide on themselves, and consequently plowing is less of an influence (that of Ref. 4 for copper on copper) as will be discussed later in reference to hexagonal metals, ionic and covalent crystals, friction is lowest in the greatest atomic density (preferred slip) directions.

Body centered cubic structures. - Of metallic structures one which it might be anticipated would exhibit the least amount of anisotropic behavior are the body centered cubic metals. Further, one of the least anisotropic of body centered cubic metals is tungsten (26). Friction data were obtained for tungsten on various planes and in various directions with a sapphire slider in contact with a large grained polycrystalline tungsten disk, the orientations of each grain known (ref. 6). Friction data obtained in three directions on one of the grains ((100) plane) are presented in Table III. It is interesting to note that anisotropic friction behavior exists for even the least anisotropic of metals. The coefficient of friction was least in the greatest atomic density direction $\langle 100 \rangle$ for the (100) face of the body centered cubic metal. The hardness values of Table III indicate anisotropic hardness behavior. Friction is lowest and hardness greatest in the direction of closest packing of atomic planes. It should be indicated, however, that the data of Table III were obtained in vacuum and the presence of surface film with their preferred affinity for certain atomic sites and planes could reduce observed friction values disproportionality on various planes and in different directions.

Hexagonal structures. - The metallic structure which exhibits the least tendency to deform plastically is that associated with the hexagonal metals having near ideal lattice ratios. This limited deformability is due essentially to the limited number of slip systems which can operate in the structure (see Table I) under an applied stress. In their single crystal form, these metals exhibit very little tendency to work harden and have extended regions of easy glide where dislocations on the basal slip plane may move readily out of the crystal. This is in contrast to the cubic structures, such as the face centered cubic metals, where intersection of ⟨111⟩ slip planes produce sessile dislocations (e.g. Lomer-Cottrell locks) impeding slip and increasing shear stress (work hardening). Thus, it might be anticipated that hexagonal metals with near ideal atomic stacking would exhibit lower shear strength under a given stress or load and, accordingly, friction would be less for this structure than for cubic metals.

The above predictions based upon atomic structure considerations are borne out by experimental results. Adhesion of hexagonal metals is markedly less than for cubic metals (Ref. 27) and their friction and wear are also markedly less (Refs. 7, 9, 25, and 28). Further, in the process of friction welding it has been found extremely difficult to friction weld hexagonal metals (ref. 29). It therefore can be said with reasonable certainty that crystal structure of metals influences adhesion, friction and wear behavior.

In contrast to the body centered cubic metals such as tungsten, the hexagonal metals are extremely anisotropic in their various properties. It is reasonable, therefore, to assume that their friction properties are also anisotropic and are dependent upon atomic density of planes and directions on atomic planes. The data obtained for various hexagonal metal single crystals in Table IV confirm the anisotropic friction characteristics of hexagonal metals. The three hexagonal metals, cobalt, beryllium and rhenium which exhibit basal slip primarily are shown to have the lowest coefficients of friction on the basal (0001) rather than prismatic $(10\bar{1}0)$ plane. Further, for beryllium and rhenium, friction is lowest in the preferred or closest packing of atomic planes direction. Thus the preferred slip plane, the basal plane (greatest atomic density) exhibits the lowest friction coefficient. Further it is lowest over that plane when sliding in the preferred (greatest atomic density) direction (see Table I).

Since the friction is dependent upon direction of sliding on a plane, and on the basal plane, there are three equivalent directions, it might be anticipated that the friction coefficient should repeat itself with every sixty degrees of change in direction on the basal plane. The results obtained with sliding on the basal plane of beryllium confirm this relation (Fig. 3). The friction coefficient is reproduced every sixty degrees through a 180 degrees arc; friction is lowest in the $\langle 11\bar{2}0\rangle$ slip directions.

In contrast to simple mechanical tests for determining the shear stress associated with various slip systems, with friction studies one of the two surfaces in contact is in motion relative to the other. The relative orientation of a crystallographic plane with reference to the mating surface may be extremely important to the observed friction. For example, with the basal plane in a metal like beryllium, changing the orientation of the plane with respect to the mating surface is going to change the shear stresses acting on the slip plane. This results from the two forces acting on the crystal, namely the normal load applied to the specimens in contact and the tangential shearing or friction force.

Friction experiments were therefore conducted with the basal plane of the hexagonal metal beryllium inclined at various angles with respect to the mating surface (Ref. 8). The results presented in Fig. 4 show that the friction coefficient was greatest when sliding was normal to the basal plane. It is interesting to note that friction was not lowest with the basal plane parallel to the interface but rather when the basal plane was inclined into the sliding direction at an angle of 135° to the sliding mating surface. This is very analogous to water skiing where mimimal friction resistance is offered by the water to the motions of the ski when the tips are elevated out of the water. The very hard crystallite edges of the basal planes give a smaller true projected contact area for a given load and the normal applied load assists in apply forces to shear between planes thereby reducing friction force. While this in true for both the 45° and 135° case, the sciving action of the plane edges to the mating surface will increase friction in the 45° case (see Fig. 4).

The data of Table IV indicate lower friction on the prismatic $(10\bar{1}0)$

plane of the metal titanium than on the basal (0001) plane or results just the reverse of what was obtained for the other three hexagonal metals. In titanium the preferred slip plane is not the basal plane (see Table I). The prismatic $\{10\bar{1}0\}$ planes are of greater atomic density and are therefore, the preferred slip planes with pyramidals also slipping to a lesser degree with deformation. Because of the greater number of possible slip systems which can operate in titanium (see Table I) it might be anticipated that polycrystalline titanium would behave more like cubic than ideal hexagonal metals with respect to friction.

Ionic Bonding

Considerable discussion has been devoted to metallic structures because of their use in mechanical systems involving friction and shear. There are, however, other types of structures which also show a dependence in their friction properties on orientation, such as ionic compounds. The ionic structures are produced by combining highly electropositive metallic ions with highly electronegative elements such as oxygen and the halogens. In such structures, chemistry is extremely important and bonds strengths will determine many of the physical properties of such materials. Cohesive energy is a measure of the bond strength in such crystals.

Rhombohedral structure. - An ionic crystal structure of considerable interest because of its use in mechanical systems is aluminum oxide which in its single crystal form, is sapphire. Sapphire has been observed to deform plastically in sliding studies (12). Under such conditions it behaves in a manner analogous to that for hexagonal metals (30). Its anisotropic friction behavior is demonstrated by the data of Table V, (25). The friction coefficient is lowest on the preferred slip plane when sliding in the preferred slip direction. These results are very analogous to friction results obtained with the hexagonal metals.

In hexagonal metals sixfold directional symetry exists on the basal plane and friction is the same in a forward or reverse direction. With a trigonal crystal, however, there is only threefold symetry and friction will not be the same in the forward and reverse direction. It is like the sliding of cards in a deck over one another only with saw teeth between. Sliding is easier in one direction than in the reverse direction.

Rock salt structure. - Those ionic crystals having a cubic structure analogous to the structure of sodium chloride are classified as having the rock salt structure. The preferred slip plane and direction in these crystals is shown in Table I along with some examples. Although the greatest atomic density planes in the rock salt structure are the {100} the preferred slip or glide planes are the {110}. In metals the greatest density planes are always the slip planes. In rock salt the reason for preferred glide or slip on the {110} planes may be associated with ionic bonding and electrostatic repulsion at midglide positions on the {100} resulting in large increases in shear energy with slip. As a consequence the shear stress on the {100} is four times that for the {110} in NaCl and six times for LiF at 100° C (ref. 31). Friction and deformation studies have been conducted with various crystals of this type by a number of investigators. The most detailed study of any one compound has probably been done with magnesium oxide (Refs. 11 and 18). The most comprehensive friction measurements on them as a group probably is the work of Ref. 12. Friction data as well as other data for some rock salt type crystals are presented in Table VI. It is interesting to compare friction data for the various compounds with various other properties. The cohesive energies were taken from Ref. 33. The cohesive energy of the crystal determines the atomic bond strength. Modulus of elasticity and hardness are related to bond strength. Data of Table VI would tend to support that they are. Further, elastic modulus and hardness are certainly related to friction as indicated. The data for friction, elastic modulus, hardness and surface energy are all for the (100) plane. As cohesive energy, elastic modulus, hardness and surface energy decrease, the coefficient of friction increases.

Covalent Structure

Elements crystallizing in the diamond structure are usually described as being held together by highly directional covalent bonds. Each atom is tetrahedrally coordinated by four like atoms and the structure is most readily pictured as a stacking of sheets composed of continuously linked "puckered" hexagonal rings of carbon atoms parallel to the {111} planes of the cubic crystal. The slip planes in diamond are then the {111} and the direction is the ⟨110⟩ (see Table I). Some elements having the diamond structure in addition to diamond itself are silicon and germanium.

Diamond. - Friction data for diamond are presented in Table VII on two atomic planes the (100) and (111) planes together with elasticity and surface energy for these two planes. The data indicate that diamond the hardest of materials also exhibits anisotropic properties. The data of Table VII indicate that friction for diamond is lowest on the highest atomic density plane. On the (100) it is lowest in sliding in the direction of closest packing of atomic planes.

Recrystallization

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. The greater the mismatch in adjacent orientations, the greater will be the number of atoms serving to link the two orientations. Grain boundaries in addition to having Read-Shockley dislocation of their own, serve as a barrier to the motion of dislocations of the crystallites. Such a structure could be expected to offer greater resistance to shear and higher friction coefficients than single crystals.

Data obtained for single and polycrystalline copper at various loads in sliding contact with polycrystalline aluminum oxide are presented in Fig. 5. Aluminum oxide was selected as a mating surface because adhesion of the copper to aluminum oxide occurs with shear subsequently taking place in the copper. The results indicate marked differences in friction for the two forms of copper. As load is increased, the interface temperature increases and recrystallization occurs on the copper surface. This condition represents then, an increase in friction for the single crystal. Although the surface at the interface is textured, it contains grain boundaries which act as barriers to dislocation motion. It represents a decrease in friction for the polycrystalline metal because recrystallization is followed by texturing which reduces shear stress. At higher loads the friction coefficients should be the same because the interfacial surface films are the same.

Order-Disorder

The arrangement of atoms is not only important to pure metals as discussed earlier but it is also important to the friction behavior of alloys. It has been found that certain intermetallic compounds will exhibit different distribution of atoms A in a lattice of B atoms. When A atoms take up regular sites such that they are uniformly distributed throughout the lattice as shown in Fig. 6 for (Cu_3Au) the structure is said to be ordered. The effect of this orderly arrangement of atoms on friction and two properties (elasticity and hardness) related to friction, are shown in Fig. 7. Friction is lowest when the alloy is in the ordered state. Transformation to the disordered atomic state results in a decrease in hardness, elasticity and an increase in friction coefficient.

SUPPLEMENTAL DISCUSSION

Anisotropic friction properties might normally be expected to be such that those atomic planes and directions of planes exhibiting the highest hardness, greatest elastic modulus and lowest surface energy would exhibit the lowest coefficients of friction. Some data in the literature substantiate this thesis. Other results are, however, in conflict with this concept.

Where differences exist, analysis of data presented indicate that severe plastic deformation has resulted in plowing of the crystal surface. Unfortunately, many investigators have adapted a specimen configuration and material combination conducive to plowing. Since friction is the sum of plowing and shear components, shear effects may be masked by severe plowing effects thereby altering any simple relations which may be found between friction and the atomic nature of surfaces. This is true because, with severe plowing, friction is no longer a simple function of the atomic nature of the surface but rather is dependent upon many subsurface effects. The analysis of resolved shearing stress and which planes are contributing to the deformation and work-hardening of plowed material becomes quite involved. The fact that these conditions exist is well substantiated.

In contrast, however, if the specimen configuration and material combination are such as to emphasize the shear rather than the plowing component of friction, a simple correlation between atomic planes, directions, mechanical properties (e.g. hardness, elastic modulus) and friction can be drawn. Thus, for example, in friction experiments in vacuum with hexagonal metals or inorganic crystals sliding on themselves, the plowing component of friction becomes less important and with adhesion shear at the interface becomes the prime friction determinant.

When a specimen configuration is chosen which emphasizes the plowing effect, the real significance of the atomic plane and direction is somewhat lost because of the marked influence of the orientation of so many other planes in the crystal on friction. Thus the difference in friction behavior for the same orientations of the same crystals in the literature can be attributed to whether the investigator is measuring shear or plowing. With brittle inorganic crystals, the problem is not quite so severe as with pure soft metals such as copper as can be seen from the data presented. For example, on the (100) of magnesium oxide, lithium fluoride and diamond friction is lowest in the preferred ⟨110⟩ slip direction and greatest in the ⟨100⟩ direction (ref. 18). A face tissue is sufficient, however, to scratch a annealed pure copper crystal. It is difficult, therefore, to envision that a diamond photograph needle under even the lightest of loads is going to have anything but plowing as its principal resistance to motion on the metal crystal.

Regarding surface energy considerations and their possible relation to friction, it might normally be anticipated that the lowest energy planes in crystals would exhibit the lowest friction coefficients. While this condition may exist whenever minimal adhesion occurs across an interface as with basal planes of aluminum oxide (layer of oxygen atoms facing a layer of oxygen atoms across the interface) it may not in metals. In metals where marked adhesion can occur for clean surfaces, a new energy is created, namely the energy of the interface. The difference between this energy and that of the two crystals in contact can be considered similar to that of two crystallites and an included grain boundary. Further measurements of the surface energy of solids is difficult and therefore reliable data are hard to obtain. Therefore it would be difficult to establish fundamental relations between friction and surface energy until more data is available.

CONCLUDING REMARKS

The friction data presented for various structures of metallic, ionic and covalent crystals at loads, speeds and temperature not conducive to texturing or recrystallization indicate that:

1. The friction coefficients for metals in sliding contact with metals are lowest on the preferred slip or glide planes when sliding in the preferred slip direction. For metals these planes and directions represent the greatest atomic density planes and directions of closest atomic packing on a plane.

2. The covalent crystal diamond appear to exhibit similar friction behavior to metals. Friction is lowest on the preffered (greatest atomic atomic density) plane.

3. With ionic crystals (such as Al_2O_3) the friction coefficient is also lowest on the preferred slip plane (greatest atomic density) when sliding in the preferred slip direction. The rock salt structures because of the nature of the ionic bonding across slip planes have the {110} as the preferred slip planes rather than the greater atomic density {100}. The friction would therefore be expected to be lowest on the {110} because of a lower shear strength.

4. When specimen configuration is such as to contribute to the marked plowing of surfaces rather than principally shear for friction force measurements in various crystallographic directions, friction may not be the lowest in the greatest atomic density direction of a plane because of the marked influence of subsurface effects.

5. The presence of grain boundaries in crystalline materials influence the coefficient of friction.

6. Ordering of atoms in intermetallic structures results in a reduction in their friction.

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TABLE I. - PRIMARY SLIP SYSTEMS ASSOCIATED WITH VARIOUS CRYSTALLINE MATERIALS

Type of structure	Slip plane	Slip direction	Number of systems	Examples
Metallic Structure				
Face centered cubic	(111)	$\langle 1\bar{1}0 \rangle$	12	Cu, Ni, Al, Ag, Au
Body centered cubic	(110) (112) (123)	$\langle \bar{1}11 \rangle$ $\langle \bar{1}11 \rangle$ $\langle \bar{1}11 \rangle$	12 12 24	α Fe, W, Mo
Close packed hexagonal				
basal slip	(0001)	$\langle 11\bar{2}0 \rangle$	3	Co, Be, Re, Cd, Zn, La
prismatic and	$(10\bar{1}0)$	$\langle 11\bar{2}0 \rangle$	3	Ti, Zr, Hf
pyramidal	$(10\bar{1}1)$	$\langle 11\bar{2}0 \rangle$	6	
Ionic Structure				
Rock salt (cubic)	(110)	$\langle 1\bar{1}0 \rangle$	12	MgO, LiF, NaCl, KBr
rhombohedral	(0001)	$\langle 11\bar{2}0 \rangle$	3	Al_2O_3(sapphire)
Covalent Structure				
Diamond	(111)	$\langle 1\bar{1}0 \rangle$	12	Si, Ge, Diamond

TABLE II. - PROPERTIES OF THE FACE CENTERED CUBIC METAL COPPER

Crystallographic plane	Atomic density, $\frac{\text{atom}}{\text{unit area}}$	Spacing between planes, A°	Elastic modulus, $\frac{10^{11}\ \text{dynes}}{\text{sq cm}}$	Surface energy, $\frac{\text{ergs}}{\text{sq cm}}$	Coefficient of friction[a]	
					Air 760 Torr	10^{-11} Torr
(100)	0.1527	1.28	6.67	2892	0.60	> 40
(110)	.1080	1.805	13.1	----	.40	> 40
(111)	.1722	2.08	19.4	2499	.21	21.0
Reference	calc	calc	22	20	---	7

[a] 50 Gms load, 0.001 cm/sec, 20° C, mating surface same as rider (plane and direction).

TABLE III. - PROPERTIES OF THE BODY CENTERED CUBIC METAL TUNGSTEN

Atomic plane	Direction	Knoop hardness	Coefficient of friction[a], 10^{-10} Torr
(100)	⟨100⟩	420	0.70
	⟨120⟩	395	.98
	⟨110⟩	370	1.23

[a] Sapphire rider, 500 Gms load, 0.013-cm/sec, 20° C.

TABLE IV. - COEFFICIENT OF FRICTION FOR HEXAGONAL METALS

Metal	Coefficient of friction[a]				
	(0001) Atomic plane		$(10\bar{1}0)$ Atomic plane		Reference
	$\langle 11\bar{2}0\rangle$ Direction	$\langle 10\bar{1}0\rangle$ Direction	$\langle 11\bar{2}0\rangle$ Direction	⟨0001⟩ Direction	
Cobalt	0.38	----	0.80	----	28
Beryllium	.48	0.51	----	0.70	8
Rhenium	.28	.38	.50	.80	9
Titanium	.56	----	.36	----	10

[a] 10^{-9} - 10^{-11} Torr, 250 Gms load, 20° C, 0.001 - 2 cm/sec

TABLE V. - PROPERTIES OF THE IONIC STRUCTURE ALUMINUM OXIDE

Plane	Direction	Coeficient of friction[a]
(0001)	$\langle 11\bar{2}0\rangle$	0.50
	$\langle 10\bar{1}0\rangle$	.96
$(10\bar{1}0)$	$\langle 1120\rangle$	.93
	$\langle 0001\rangle$	1.00

[a] Load 1000 gms, 0.013 cm/sec, 20° C (ref. 25).

TABLE VI. - PROPERTIES OF IONIC BONDED CRYSTALS WITH ROCK SALT STRUCTURE

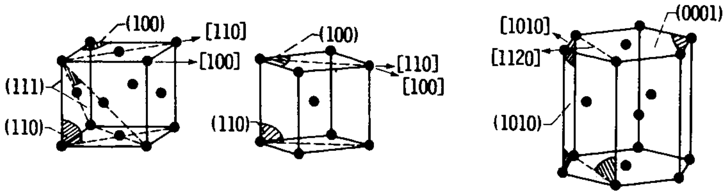
Crystal	Cohesive energy, $\frac{\text{k cal}}{\text{mole}}$	Elastic modulus, $\frac{10^{11}\text{ dynes}}{\text{sq cm}}$ (100)	Relative hardness, $\frac{\text{kg}}{\text{sq mm}}$	Surface energy, $\frac{\text{ergs}}{\text{sq cm}}$	Coefficient of friction[a], (100)⟨110⟩
MgO	940.1	24.5	400⟨100⟩ 700⟨110⟩	1310	0.07
LiF	240.1	7.35	100	374	.24
KCl	164.4	4.80	18	318	.71
NaCl	153.1	4.37	17	310	0.47 - 0.70
KBr	140.8	3.70	7	306	.85
References	33	22	20	22	5

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

TABLE VII. - THE PROPERTIES OF THE COVALENT STRUCTURE DIAMOND

Atomic plane	Direction	Young's modulus, $\frac{10^{11}\ \text{dynes}}{\text{sq cm}}$	Surface energy, $\frac{\text{ergs}}{\text{sq cm}}$	Coefficient of friction,	
				760 Torr	10^{-10} Torr
(100)	⟨100⟩	105.0	7050	0.15	----
	⟨110⟩	-----	----	.05	----
[a](111)	-----	120.0	3500	.05	0.9
References	-----	22	22	16 and 18	17

[a] Direction on the (111) appears to have no effect on friction.



Face centered cube Body centered cube Close-packed hexagon

Figure 1. - Crystal structures with various planes and directions.

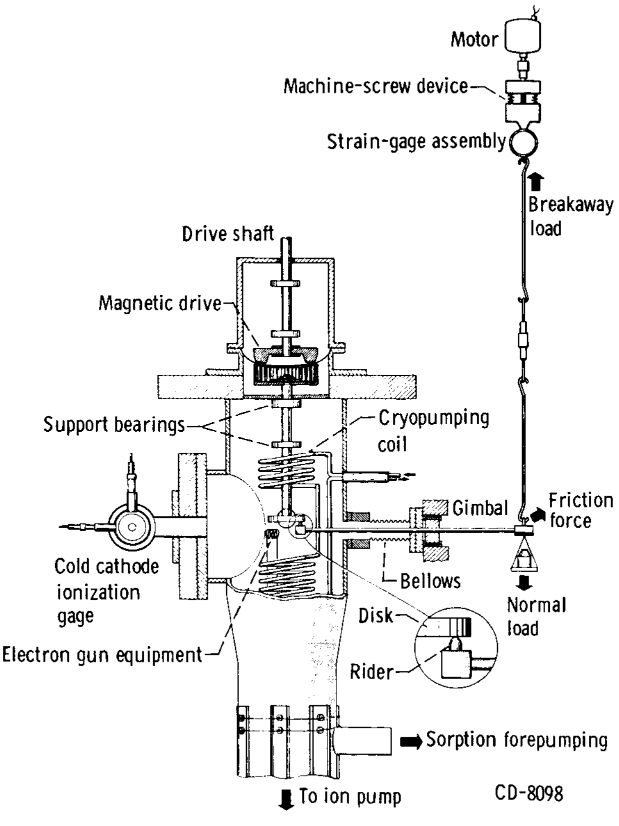


Figure 2. - Vacuum friction apparatus.

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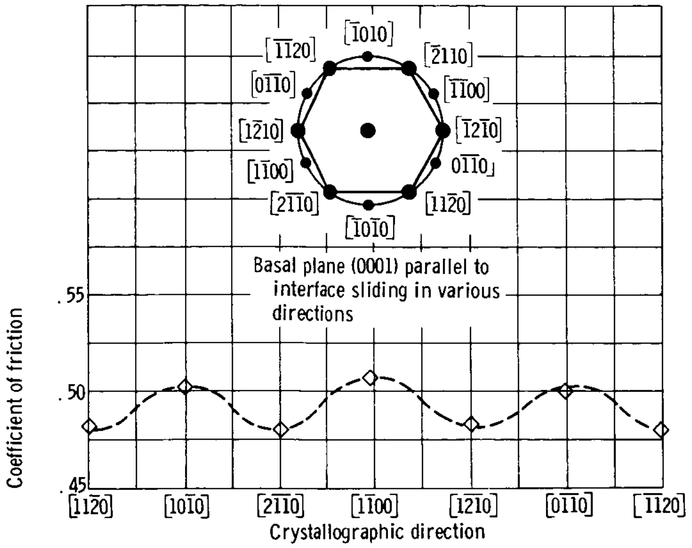

Figure 3. - Coefficient of friction for single-crystal beryllium rider sliding on polycrystalline disk with basal plane of rider in various crystallographic directions. Load, 250 grams; sliding velocity, 0.013 centimeter per second; ambient pressure, 10^{-10} millimeter of mercury; no external heating of specimens (ref. 8).

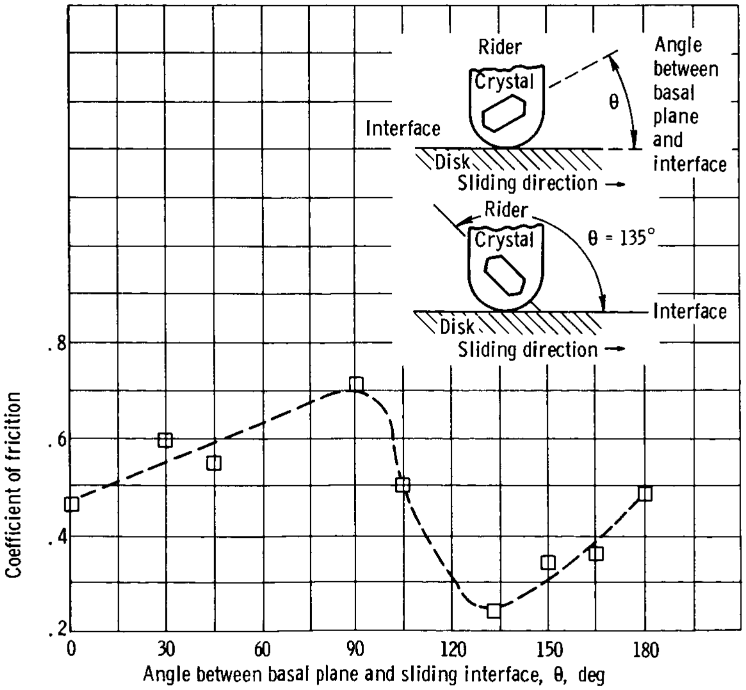

Figure 4. - Coefficient of friction for single-crystal beryllium sliding on polycrystalline beryllium in vacuum with various basal-plane orientations with respect to sliding interface. Load, 250 grams; sliding velocity, 0.013 centimeter per second; ambient pressure, 10^{-10} Torr; no external heating of specimens (ref. 8).

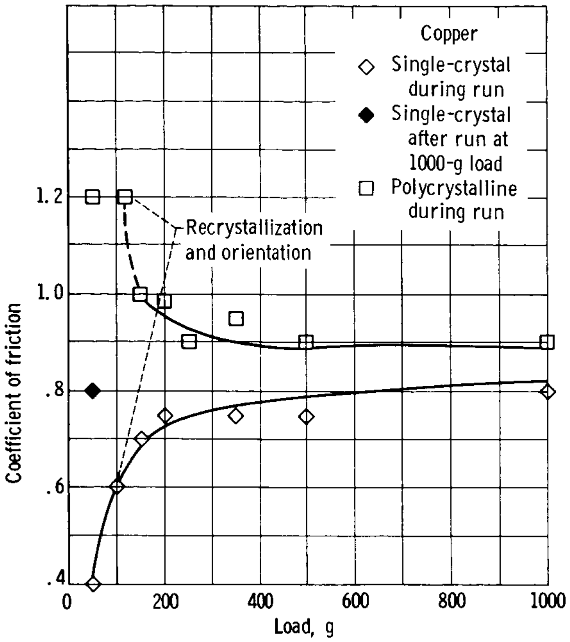

Figure 5. - Coefficient of friction for single-crystal and polycrystalline copper sliding on polycrystalline aluminum oxide in vacuum (10^{-11} torr). Copper oriented with (111) plane parallel to sliding interface; sliding velocity, 0.001 centimeter per second; no external specimen heating.

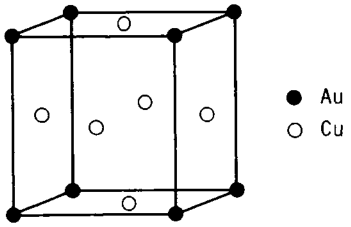

Figure 6. - The Cu_3Au superlattice structure.

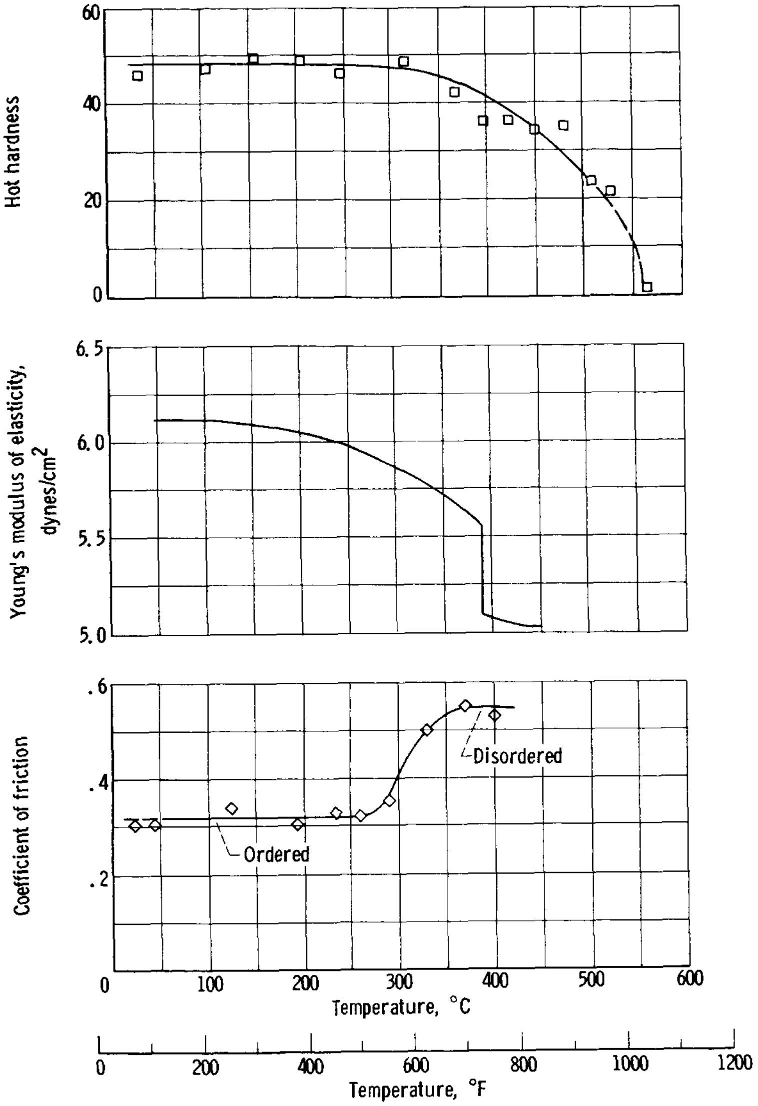

Figure 7. - Hardness, Young's modulus, and coefficient of friction for Cu_3Au (75 atomic percent copper - 25 atomic percent gold) sliding on 440-C stainless steel at various temperatures. Load, 1000 grams; ambient pressure, 10^{-9} Torr (ref. 31).