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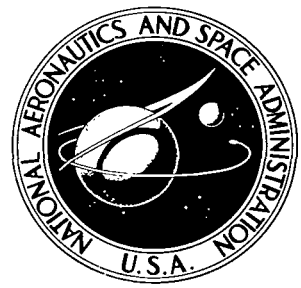

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SUMMARY

This investigation was conducted to gain some insight into the relation of friction to the adhesion or cohesion of metals in vacuum. Metal single crystals were used in an attempt to understand better the influence of basic metal properties such as orientation of planes, surface energy, work hardening, and crystal structure on friction and adhesion. The following characteristics were examined: (1) atomic plane matching across an interface, (2) the effect of plane atomic density, (3) orientation of coupled metals, (4) mutual solubility, and (5) the effect of crystal structure.

The metal couples examined included the copper plane pairs: (100) on (100), (110) on (110), and (111) on (111), all three pairs matched planes and directions; and (110) on (100) and (111) on (100). The (111) plane of copper was also examined in contact with planes (0001) of cobalt, (111) of nickel, and (110) of tungsten. The (0001) plane of cobalt was also studied in contact with itself.

The results of this investigation indicate that adhesion is markedly increased by small amounts of unidirectional sliding of the surfaces in contact (in some instances, an increase of a factor of 100). The adhesion measurements correlated with the friction coefficients; high friction coefficients were always accompanied by high adhesive forces.

With matched atomic planes of copper, very marked differences in friction and adhesion were observed. The {100} planes exhibited adhesion coefficients, after sliding, in excess of 130, which was the limiting force that could be measured by the apparatus. In contrast, adhesion coefficients as low as 10.5 were observed for the {111} planes in contact. Mismatched orientations of copper required less force to separate than matched atomic planes. Measurements for copper on cobalt and on nickel revealed adhesion of copper to both nickel and cobalt. With sliding, shear took place in the copper. When copper contacted tungsten, transfer and shear of copper were noted. Crystal structure influences adhesion and friction behavior. Very low friction and adhesion were observed with the (0001) plane of hexagonal cobalt sliding on itself, while very high values were obtained for face-centered cubic copper.

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INTRODUCTION

The friction and/or adhesion characteristics for some metals in vacuum have been measured by many investigators (refs. 1 to 7, among others). Further, the relation of friction to adhesion has been reported (refs. 1 to 8). The results of these investigations were obtained for the polycrystalline form of the metals in contact with themselves or with other polycrystalline metals. The studies of references 9 and 10 indicate that orientation of individual crystallites (single crystals) may markedly influence the friction behavior of metals in vacuum. With the hexagonal metals, beryllium and titanium, marked anisotropic friction behavior was observed. In fact, the friction results correlated with crystallographic slip behavior for these metals. Similar effects have been observed for face-centered cubic metals such as copper in a hydrogen atmosphere (refs. 11 to 13) and body-centered cubic metals such as tungsten (ref. 3). A summary observation of the data presented in these references indicates that, for body-centered and face-centered cubic metals, as well as for close-packed hexagonal metals, the lowest friction coefficients usually are observed on the preferred slip planes (those with greatest atomic density) with sliding in the preferred slip direction (that with closest packing of atoms).

Polycrystalline materials are used in most mechanical applications where adhesion, friction, and wear might be involved; this use does not, however, necessarily preclude the use of materials in single-crystal form. It is certainly recognized that grain boundaries influence the behavior of materials; thus, single-crystal observations cannot be extrapolated directly to polycrystalline materials. Grain boundaries influence deformation in a number of ways: they act as barriers to the motion of slip dislocations, they have higher surface energies than crystallite faces, and they are sites on the surface for accelerated reaction and diffusion rates. The effects of boundaries can be more fully understood if the basic element of polycrystalline structures, namely, the single crystal, is better understood.

This investigation was conducted to determine, in vacuum, the influence of the following properties on the friction and adhesion of single crystals: (1) crystal orientation, (2) mutual solubility, and (3) crystal structure. Studies were conducted with single-crystal and polycrystalline copper as well as single crystals of cobalt, tungsten, and nickel. The following experiments were made: (1) simple contact adhesion, (2) sliding friction, and (3) adhesion after sliding. Hemispherical single crystals were loaded against single-crystal flats under a 50-gram load. Sliding velocity in friction experiments was 0.001 centimeter per second. All specimens were cleaned by electron bombardment. The ambient pressure of the experiments was 10^{-11} torr.

MATERIALS

The metals used in this investigation were all 99.99 percent pure with the exception of copper, which was 99.999 percent pure. All specimens were electropolished with orthophosphoric acid with the exception of tungsten, which was electropolished with sodium hydroxide. Laue back reflection was used to determine all single-crystal orientations. Specific orientations of single crystals were maintained within $\pm 2^{\circ}$. All specimens were rinsed in acetone and alcohol prior to insertion into the vacuum chamber.

ORIENTATIONS AND DEFINITIONS

The term matched planes and directions is used to describe the relative orientations of crystal faces in adhesion and friction experiments. Figure 1 is provided to assist in understanding the term; it represents in essence the matching of the direction on one surface with that on another crystal face of the same orientation. All sliding friction experiments were conducted in the preferred crystallographic slip direction for the particular plane under consideration. Further, where dissimilar metals were in contact, the greatest atomic density plane was used, even where differences in crystal structure existed.

In the initial adhesion experiments, a load was applied normal to the planar surfaces in contact. The adhesion coefficient is, then, the force required to separate the specimens divided by the applied force or load. The friction coefficients reported are all dynamic values obtained during sliding. After sliding was stopped, the force required to separate the two crystal surfaces in contact was measured. This force divided by the applied load during contact sliding, is termed "adhesion coefficient*." The asterisk is used to differentiate this value from those obtained in standard adhesion measurements.

There are a number of terms that have been used in the literature, particularly in regard to friction, to describe solid solubility of metal couples. Therefore, the following terms are used herein in order to avoid confusion: (1) complete solubility, (2) partial solubility, and (3) insolubility. Complete solubility characterizes those systems where the Hume-Rothery rules of electronegativity, valence, atomic size factor, and crystal structure are obeyed (100 percent solubility). An example of such a system is the copper-nickel system of this investigation. Partial solubility refers to those systems where solubility may not cover the entire phase diagram (less than 100 percent). In these systems, one or more of the Hume-Rothery rules may not be obeyed. The copper-cobalt system of this investigation is an example of such a system; they differ in crystal structure below 400° C. Insoluble couples are those in which no phase diagram exists and the solubility of which, if any, is normally considered to be insignificant. In

this investigation, the copper-tungsten couple represents such a system.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is described in reference 7 and is shown in figure 2. The basic elements of the apparatus were the specimens (a 1/2-in.-diam flat disk mounted in a $2\frac{1}{2}$-in.-diam disk holder and a 3/16-in.-rad rider) mounted in a vacuum chamber. The disk specimen was driven by a magnetic-drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The extended driver magnet was coupled to an electric motor. The driven magnet was shrouded completely with a nickel-alloy housing (cutaway in fig. 2) and was mounted on one end of the shaft within the chamber. The other end of the shaft supported the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was mounted from a gimbal and sealed to the chamber with a bellows. A linkage at the end of the restraining arm farthest from the rider specimen was connected to a strain-gage assembly that 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 forepump. 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 the ionization gage was a diatron-type mass spectrometer (not shown in fig. 2) for determination of gases present in the vacuum system. A 20-foot, 5/16-inch-diameter stainless-steel coil was used for liquid-nitrogen or liquid-helium cryopumping of the vacuum system.

The specimens used in the friction and wear experiments were finished to size. They were then electropolished and X-ray patterns obtained for orientation. Before each experiment, the specimens were rinsed with acetone followed by ethyl alcohol.

After the specimens were placed in the vacuum chamber, the system was thoroughly purged with dry nitrogen gas. The system was then evacuated with sorption forepumps to a pressure of 10^{-3} torr, and the ion pump was started. The vacuum chamber was baked out overnight. After the chamber was cooled to room temperature, the specimens were electron bombarded for 3 hours. Bulk specimen temperatures at this time were 400° C. The specimens were cooled to room temperature, and the experiments were started.

The contact time under load for simple adhesion experiments was 10 seconds. The total sliding distance was held at a constant 0.735 centimeter at a speed of 0.001 centimeter per second. Breakaway force after sliding was measured immediately after slid-

TABLE I. - PROPERTIES OF SINGLE-CRYSTAL AND POLYCRYSTALLINE COPPER (99.999 PERCENT PURE)

Copper form and orientation	Young's modulus,[a] $(10^{11}$ dynes/cm$)^2$	Surface energy, ergs/cm^2	Adhesion coefficient before sliding[b]	Friction coefficient during sliding[c]	Adhesion coefficient* after sliding[d]
Single crystal (100); matched planes and directions	6.67	2892	1.02	>40.0	>130
Single crystal (110); matched planes and directions	13.1	----	.61	>40.0	50.0
Single crystal (111); matched planes and directions	19.4	2499	.30	21.0	10.5
Polycrystal	12.0	1100 to 1350	1.00	>40.0	100

[a]Ref. 16.
[b]Load, 50 g; vacuum, 10^{-11} torr.
[c]Load, 50 g; sliding velocity, 0.001 cm/sec; vacuum, 10^{-11} torr.
[d]Load, 50 g; sliding distance in preferred slip directions, 0.735 cm; vacuum, 10^{-11} torr.

ing had ceased. When the specimens were broken more than once a 10-second contact time interval was used.

RESULTS AND DISCUSSION

The cohesion of polycrystalline copper has been examined (refs. 2, 6, and 8). The data reported in references 2 and 6 were obtained in vacuum. Single-crystal-copper cohesion has been examined in a hydrogen atmosphere (refs. 11 and 13). The results obtained in hydrogen indicated that the (100) planes of copper in sliding contact exhibited markedly higher friction coefficients than the (111) planes of copper in sliding contact.

Orientation Effects

Adhesion and friction coefficients in this investigation were measured in vacuum at 10^{-11} torr for copper contacting copper (table I). Three single-crystal orientations of copper were examined: the (100), (110), and (111) planes. In all experiments, the planes and directions were matched, and a load of 50 grams was used. This particular load was selected because earlier experiments had shown that recrystallization of copper

occurred in sliding contact at higher loads (ref. 14). For reference purposes, adhesion data were also obtained for polycrystalline copper. Examination of the data of table I indicates that adhesion coefficients (breakaway load/applied load) of copper are dependent upon crystal orientation. The (111) plane, which has the highest atomic density with the greatest distance between planes, exhibits the lowest adhesion coefficient.

The adhesion coefficients decrease as the modulus of elasticity on these planes increase. The decrease in adhesion coefficient with increase in elastic modulus might be related in part to differences in true contact area for the crystals at the interface. Since plastic deformation also occurs at the interface, the deformation behavior of the different crystal orientations must be considered. Examination of stress-strain curves for single crystals of copper indicate that, for a given stress, the amount of strain for the (111) plane is less than that for the (110) and the (100) orientations of copper. These effects indicate that, for a given load, the true area of contact for the (111) orientation might be less than that for the (110) and (100) orientations.

The resulting true contact area is the sum of elasticity and plasticity at the interface. The influence of elasticity and plasticity may therefore vary with orientation. Since the yield point also varies with orientation, the amount of plasticity shown for a given stress is greater for the (100) plane. The amount of elastic recovery, that is, the percent of elastic deformation to total deformation is greater for the denser (111) plane. It is shown in reference 15 that, for metals such as gold and silver, a temperature that is 0.4 that of the melting point must be reached before elastic recovery does not exert a noted influence on adhesion and the materials are plastic enough to ensure strong adhesion.

If atomic bonding occurs across the interface when two crystals of the same orientation are brought in contact under load, then, the interface may be considered to be analogous to a grain boundary. In these experiments, all possible attempts were made to match planes and directions. In any such attempts, it may be assumed that some mismatch of orientations will exist and perfect matching can occur only accidentally. Any bonding which occurs across the interface involves some elastic displacement of atoms near the surface. The interface then represents atomically displaced atoms connecting the individual crystals; that is, it represents a transitional region serving to link the two specimens much as a grain boundary links two grains. In these experiments the greater the mismatch at the interface the further into the parent crystals elastic stress may be expected to occur.

Examination of surface energies in table I, which are calculated values taken from the literature, indicates that the surface energies are least on the (111) plane and greatest on the (100) plane of copper. The adhesion data obtained would then appear to be in agreement with the surface-energy theory of adhesion and friction (ref. 17). However, when two surfaces are brought into contact, the interface formed has its own interfacial

energy. This energy is analogous to the energies associated with grain boundaries. Each crystal surface has its own characteristic; when two crystal surfaces are brought together, an interfacial energy is developed. The energy of this interface depends to a large extent on the degree of mismatch of the two crystallites; the greater the mismatch, the larger the energy (refs. 18 to 20). For two crystals in contact, the boundary energy must be considered, since with adhesion a new interfacial surface is created. In the literature, data exist which indicate the opposite effect of references 18 to 20, that is, that surface energy increases with increasing atomic density of planes (ref. 16).

Each of the adhesion-coefficient values before sliding (table I) represents a 10-second contact time under load. At room temperature, diffusion effects may not be expected to influence measured adhesion coefficients greatly. For longer periods of time, with plastic materials such as metal, creep may be expected to influence true contact area under a given load. The effect of contact time on the adhesion coefficient is shown in figure 3 for the three single-crystal orientations of copper. A marked increase in the adhesion coefficient occurred with time. Thus, with single crystals of copper, creep at the interface (with a corresponding relaxation of elastic strains) appears to influence the measured adhesion coefficients.

The adhesion coefficient before sliding (table I) for polycrystalline copper is interesting. The adhesion value obtained was 1.00, very near that of the (100) plane of single-crystal copper. Since the modulus of elasticity is nearly twice that of the (100) plane and the data of reference 19 indicate that a polycrystalline material is more resistant to plastic deformation than single crystals, the real area of contact on load removal might be anticipated to be markedly less for polycrystalline material. However, while the area of contact under a given load may be less than that of the (100) plane, the tensile strength of the junctions formed is greater. With deformation of polycrystals, grain boundaries act as barriers to the motion of slip-plane dislocations, and a high degree of strain-hardening of junctions formed must occur. This strain-hardening is even greater than that observed with single crystals so oriented that a high concentration of Lomer-Cottrell locks are generated. Thus, while a smaller true contact area may be anticipated for polycrystals for a given load, the tensile strength of junctions formed is greater than observed for single crystals. This fact accounts for the similarity in the two adhesion coefficients.

After adhesion measurements were completed, the crystals listed in table I were slid a distance of 0.735 centimeter, and the friction coefficients were observed during sliding. All the copper specimens exhibited friction coefficients in excess of 40.0 with the noted exception of the (111) plane, which had a friction coefficient of 21.0. Those specimens with friction coefficients in excess of 40.0 (the limit of the indicator) exceeded it in the first few tenths of a centimeter of sliding.

The adhesion coefficients were again measured immediately after sliding was stopped. These adhesion coefficients* are presented in table I. In all cases, a drastic increase in adhesion coefficient was observed after sliding. This increase may be attributed to two factors associated with the sliding of clean metals in contact: First, a marked increase in true contact area occurs with sliding, and second, the area in contact represents metal which has work hardened in the process of sliding. Thus, not only the area of contact but also the tensile strength of the junctions increases with sliding. When a tensile load is applied to the cold-welded junction, rupture must occur over the larger true contact area where work hardening has increased the strength of the interfacial layer.

The adhesion and friction coefficients observed in table I for polycrystalline copper are markedly greater than those given in reference 3. In reference 3, the load employed was 1000 grams and the sliding velocity was 198 centimeters per second. Recrystallization of copper at the interface is known to occur at this high load and speed (ref. 14). Thus, the type and the nature of the surface under the two sets of experimental conditions were markedly different. At the higher loads and speeds of the study reported in reference 3, however, such effects were not noted. It is quite natural, therefore, to expect differences in friction and adhesion results when the interface is different.

The results in table I indicate that differences in adhesion coefficients exist for different crystallographic planes of copper and that sliding markedly increases adhesion of two surfaces in contact. The only friction coefficient which could be measured was that for the (111) plane, the orientation exhibiting the lowest adhesion coefficient. If the others could have been measured, a correlation of friction with orientation might have been observed, as was the correlation of adhesion with orientation. Slip lines outside the contact area are shown in figure 4 for the (100) and (111) copper riders. It is of interest that slip lines on the (100) surface appear at about 90°, while on the (111) surface, they appear at about 60°. These slip lines might well correlate with observed slip directions which also correlate with these angles.

Adhesion and friction measurements were made with the (100), (110), and (111) planes of copper contacting a (100) plane. In all three experiments, sliding was in the [110] direction. The results obtained are presented in table II. The data indicate, as anticipated, that pairs of matched planes exhibit higher adhesion coefficients before sliding than pairs of unmatched planes; that is, the greater the tendency for atomic matching across the interface, the less the lattice strain and the stronger the adhesion. In all three experiments, the friction coefficient during sliding exceeded 40.0.

TABLE II. - ADHESION AND FRICTION COEFFICIENTS FOR VARIOUS SINGLE-CRYSTAL ORIENTATIONS OF COPPER

[Load, 50 g; vacuum, 10^{-11} torr; ambient temperature, 20° C.]

Planes in contact	Adhesion coefficient before sliding	Friction coefficient during sliding[a]	Adhesion coefficient* after sliding
(100)/(100)	1.02	>40.0	>130
(110)/(100)	.25	>40.0	32.5
(111)/(100)	.20	>40.0	40.0

[a]Sliding velocity, 0.001 cm/sec; sliding distance in [110] direction, 0.735 cm.

TABLE III. - ADHESION AND FRICTION COEFFICIENTS FOR VARIOUS SINGLE-CRYSTAL METAL COUPLES

[Load, 50 g; vacuum, 10^{-11} torr.]

Metal couples and orientations	Adhesion coefficient before sliding	Friction coefficient during sliding[a]	Adhesion coefficient* after sliding	Solubility	Crystal structure
Copper (111) / Copper (111)	0.30	21.0	10.5	Complete	Face-centered cubic / Face-centered cubic
Copper (111)[110] / Nickel (111)[110]	.25	4.0	2.0	Complete	Face-centered cubic / Face-centered cubic
Copper (111)[110] / Cobalt (0001)[11$\bar{2}$0]	.10	2.00	.5	Partial	Face-centered cubic / Hexagonal
Copper (111)[110] / Tungsten (110)[111]	<.05	1.40	.5	None	Face-centered cubic / Face-centered cubic

[a]Sliding velocity, 0.001 cm/sec; sliding distance, 0.735 cm.

Solubility

A subject of much interest, related to adhesion, is that of the relative importance of solid solubility (refs. 5, 8, 21, and 22) and crystal structure (ref. 8) on the adhesion of metal couples. Four experiments were selected to determine the influence of solubility and crystal structure on adhesion and friction (table III). In all these experiments, the (111) plane of copper was the rider surface. The results of the cohesion experiments for the (111) plane of copper on itself represent the first set of results as presented in table I. The second set of experiments represent the (111) plane of copper on the (111) plane of nickel with sliding in the preferred slip direction. Both nickel and copper have a face-centered cubic structure, and they are completely soluble (100 percent).

The data of table III indicate that the adhesive forces of copper to nickel are less than those of copper to copper. The sliding friction coefficient was also less. These results might be anticipated since a difference (2 percent) in lattice parameters for the two crystal faces exists. Therefore, bonding across the copper-nickel interface could be expected to involve considerably more lattice strain than for matched copper poles.

The third set of experiments involved the contact of the (111) plane of copper on the (0001) basal plane of cobalt. Sliding was in the preferred slip or [1120] direction on cobalt. It is interesting that while cobalt is next to nickel in the periodic table and many of its properties are similar, the metals differ in crystal structure. Cobalt and copper are partially soluble. Examination of the data of table III indicates that while both cobalt and nickel are soluble in copper, significantly lower friction and adhesion were obtained with copper contacting cobalt, which has only partial solubility. This difference may be related in part to crystal structure. The relation of adhesion and friction to crystal structure is discussed in the section Crystal Structure. The adhesion of copper to nickel and cobalt crystals is shown in the photomicrographs of figures 5(a) and (b). Copper and tungsten are insoluble, and therefore adhesion of copper to tungsten should not occur. Experiments were conducted to determine whether adhesion would occur and what effect sliding has on adhesion. The results obtained are presented in table III and in figures 5(c) and 6(a).

In table III, the initial adhesion coefficient for copper to tungsten was less than 0.05, that is, less than that which could be detected by the system. With sliding, the friction coefficient was 1.40 and was relatively constant over the entire sliding period as indicated by the data of figure 6(a). Friction data are included in figure 6(a) for copper sliding on nickel. With copper sliding on nickel, the friction started high and decreased to some lower value after about 1 minute of sliding. This initially high friction coefficient is believed to reflect the adhesion of copper to nickel during the adhesion experiments. As sliding commences, the copper is still in contact with adhered copper and the friction is high. As sliding progresses, the copper continues to slide on a greater and greater

amount of nickel. Finally, copper is sliding over nickel, as represented by the friction points on the right side of figure 6(a).

During sliding, adhesion of copper to tungsten occurred as shown in figure 5(c). When sliding was terminated and the force required for separation was again measured, an adhesion coefficient of 0.5 was obtained. This value is further evidence for the adherence of copper to tungsten.

The effect of solubility on adherence of copper may be seen further in the data of figure 6(b). With copper contacting nickel (completely soluble), the initial breakaway force is high after sliding. With a subsequent number of contacts and breaks, the force decreases to some relatively constant value. These results are as might be anticipated. Because of sliding, both work hardening and increase in true contact area occurred. On the initial separation, the area in contact is greater than in subsequent contacts. The adhesion does not decrease to the value obtained before sliding because the junctions have work hardened as a result of sliding and thus exhibit a higher tensile strength.

With copper contacting tungsten, a continuous decrease in adhesion coefficient was observed with subsequent breaks. This decrease is believed to reflect the nature of the interfacial bond. The work of reference 23 indicates a possible surface interaction in vacuum with copper contacting the (110) face of tungsten.

Crystal Structure

A set of experiments was conducted with cobalt sliding in contact with cobalt in the $[11\bar{2}0]$ slip direction in order to gain a fuller understanding of the influence crystal structure has on adhesion and friction of metals. The results obtained in these experiments are presented in table IV, together with the minimal adhesion and friction obtained with

TABLE IV. - ADHESION AND FRICTION COEFFICIENTS FOR COPPER AND COBALT SINGLE CRYSTALS

[Load, 50 g; vacuum, 10^{-11} torr.]

Metal couples with matched poles	Adhesion coefficient before sliding	Friction coefficient during sliding[a]	Adhesion coefficient* after sliding
Copper (111)[$\bar{1}10$] Copper (111)[$\bar{1}10$]	0.30	21.0	10.5
Cobalt (0001)[$11\bar{2}0$] Cobalt (0001)[$11\bar{2}0$]	<.05	.35	<.05

[a]Sliding velocity, 0.001 cm/sec; sliding distance, 0.735 cm.

copper matched planes and directions. (These results are the ones obtained with the (111) plane of copper contacting itself.) The adhesion coefficients for cobalt before and after sliding were too low to measure. The friction coefficient was the lowest recorded in all sets of experiments. These results indicate that crystal structure does influence adhesion and friction behavior of metals.

Hexagonal metals are extremely prone to twinning with mechanical deformation. Evidence for such twinning was observed on the basal plane of cobalt adjacent to the sliding track as shown in figure 7. Similar twinning has been observed with compressive loading of other hexagonal metals (ref. 24).

SUMMARY OF RESULTS

In an investigation of the influence of crystal structure, orientation, and solubility on the adhesion and sliding friction of various single-crystal couples in vacuum, the following results were obtained:

1. The adhesion of metal couples was markedly (100 fold in some instances) increased by sliding. High friction coefficients were accompanied by high adhesion coefficients.

2. The adhesion and friction characteristics of copper single crystals in contact with themselves were highly orientation dependent. Adhesion and friction were least on planes with the greatest atomic density.

3. After sliding, adhesion occurred for mutually insoluble couples (copper and tungsten) as well as for mutually soluble couples (copper and nickel).

4. Crystal structure markedly influenced friction and adhesion of metals. The lowest friction and adhesion coefficients were observed for matched planes (0001) and directions of cobalt.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 30, 1967,
129-03-13-02-22.

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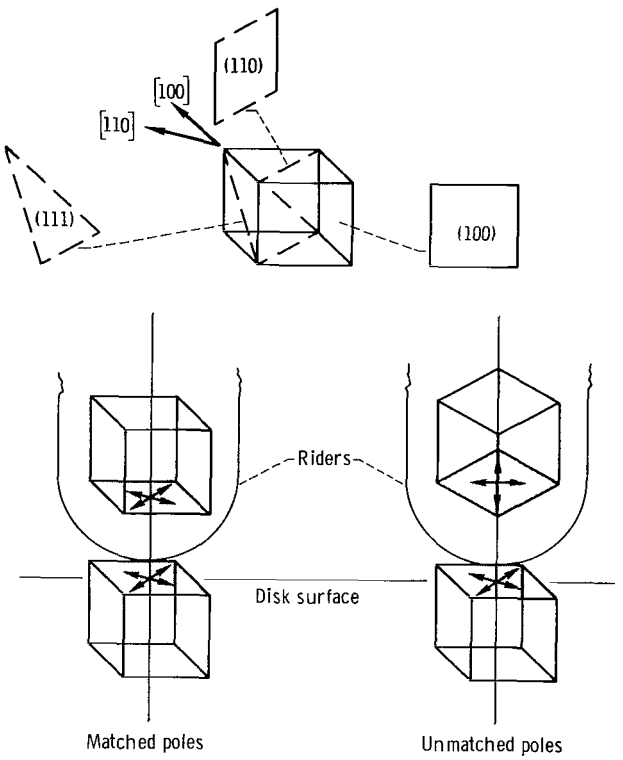


Figure 1. - Orientations; planes and crystallographic directions.

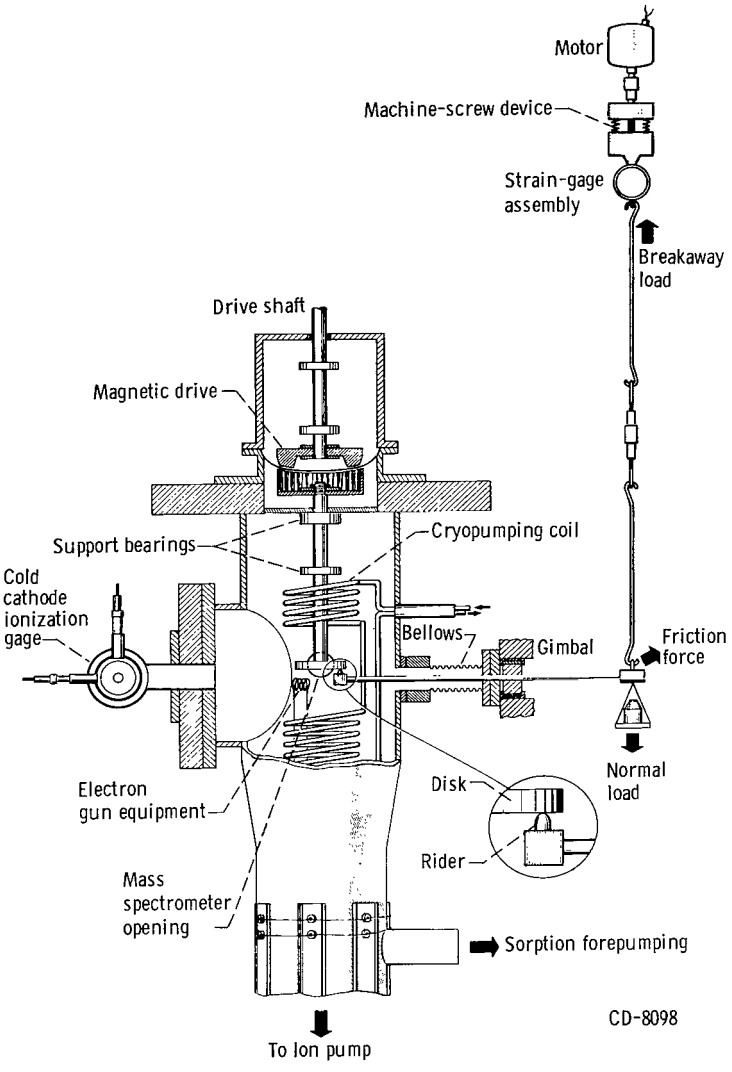


Figure 2. - Vacuum friction apparatus.

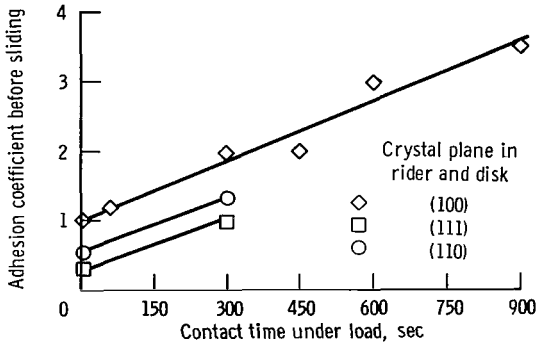
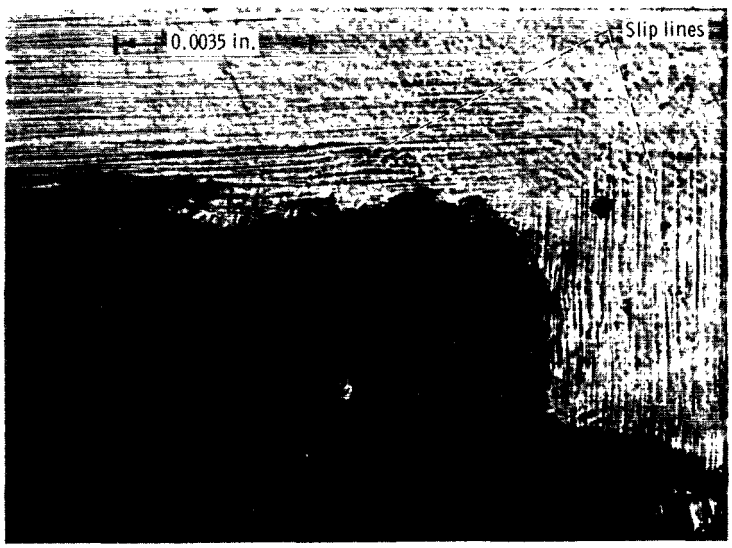
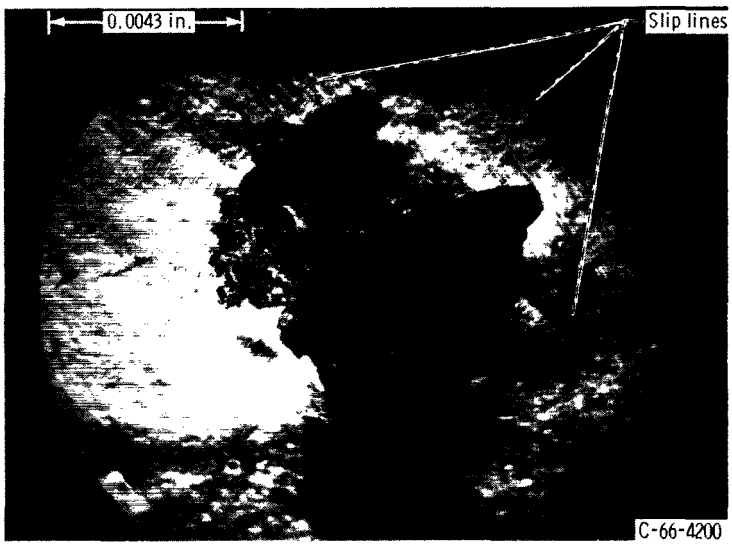


Figure 3. - Adhesion coefficient before sliding for copper on copper with matched planes and directions in vacuum (10^{-11} torr). Simple touch contact under 50-gram load.



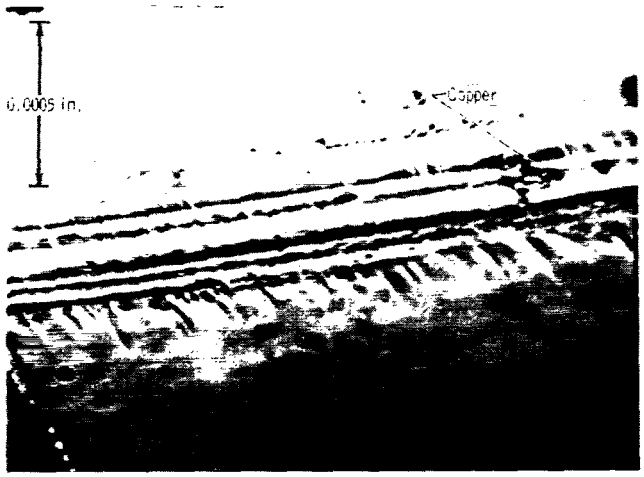
(a) (100) plane.



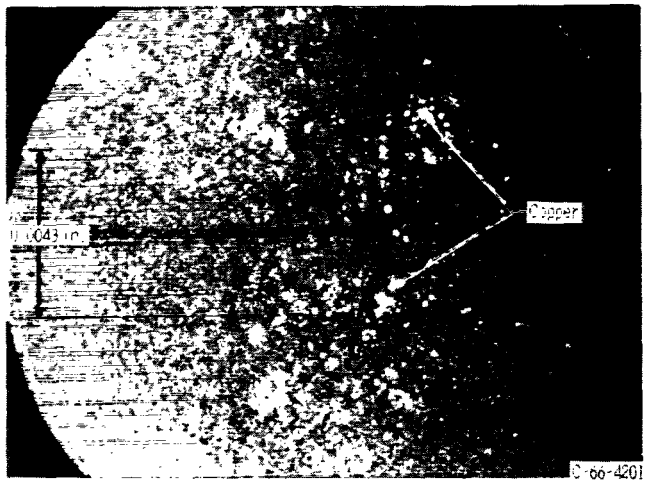
(b) (111) plane.

Figure 4. - Wear scars on copper single-crystal rider specimens. Disks were of same orientation. Load, 50 grams; sliding distance, 0.735 centimeter.

(a) Nickel, {111} plane.

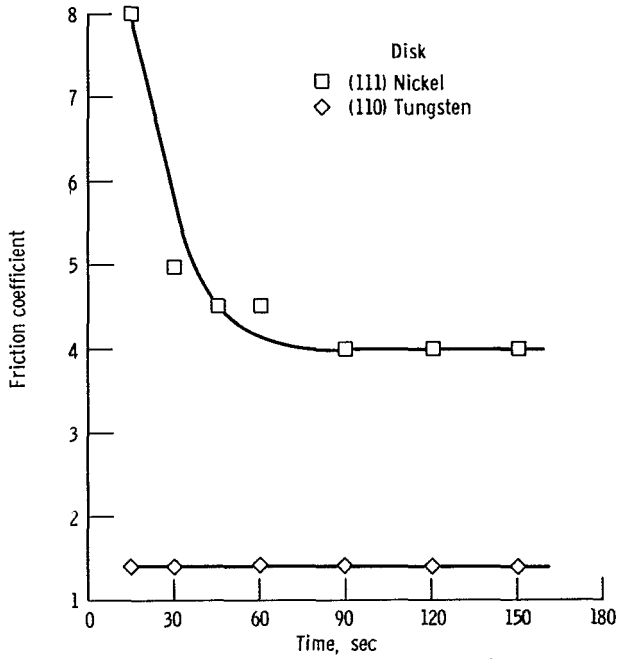


(b) Cobalt, {0001} plane.

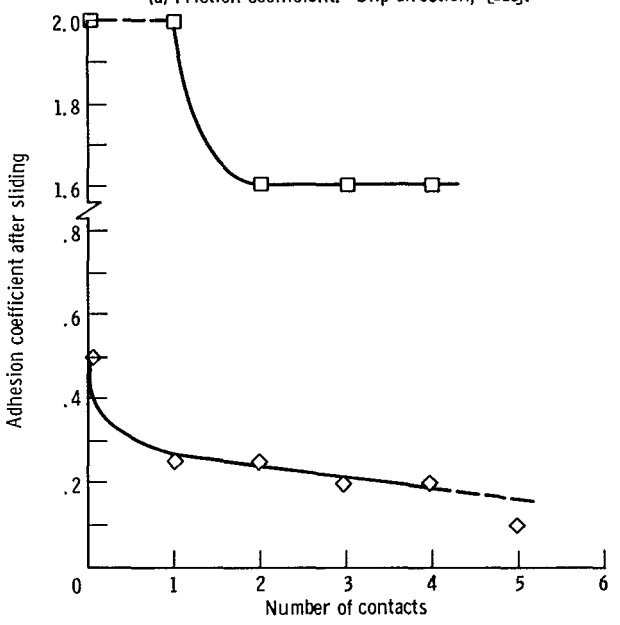


(c) Tungsten, {110} plane.

Figure 5. - Wear tracks for {111} plane of copper sliding in the [110] slip direction on various substrates in vacuum.



(a) Friction coefficient. Slip direction, [110].



(b) Adhesion coefficient*.

Figure 6. - Copper ((111) plane) on single-crystal nickel and tungsten in vacuum (10^{-11} torr). Load, 50 grams; ambient temperature, 20° C. Sliding velocity, 0.001 centimeter per second.

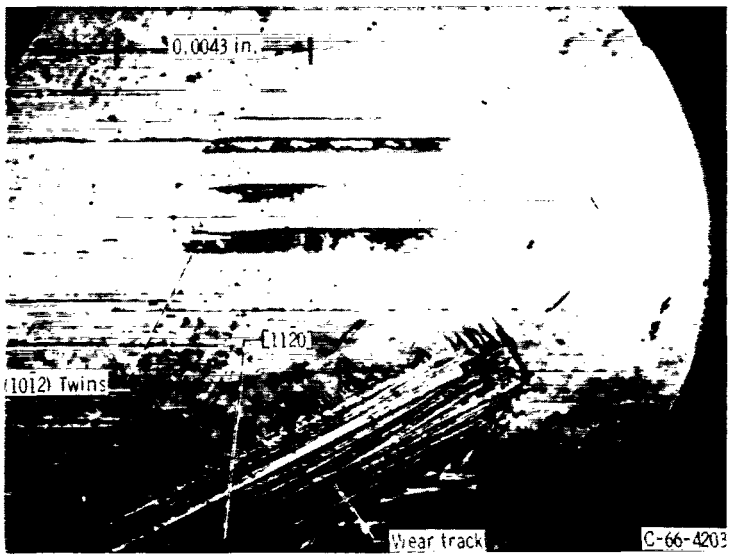


Figure 7. - Sliding track on disk. Disk and rider of {0001} plane single-crystal cobalt.

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