THE INFLUENCE OF CRYSTAL STRUCTURE, ORIENTATION AND SOLUBILITY ON THE ADHESION AND SLIDING FRICTION OF VARIOUS METAL SINGLE CRYSTALS IN VACUUM (10^{-11} TORR)

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TECHNICAL PAPER proposed for presentation at

Symposium on Adhesion sponsored by the
American Society for Testing and Materials and the
American Society of Lubrication Engineers
Toronto, Canada, May 1-2, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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E-3670

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ABSTRACT

Friction and adhesion characteristics were measured in vacuum (10^{-11} Torr) for various metal single crystals. The (100), (110) and (111) planes of copper, the (111) plane of nickel, the (0001) plane of cobalt and the (110) plane of tungsten were studied. Experiments were conducted with matched planes and directions in contact, as well as mismatched orientations of copper. The (111) plane of copper was also examined in contact with nickel, cobalt and tungsten crystals. Measurements included: adhesion before sliding, friction during sliding and adhesion after sliding. The results indicate that sliding markedly increases the adhesion of clean metals in contact. The friction and adhesion of copper is highly anisotropic. Adhesion was observed for the insoluable couple copper-tungsten after sliding. Crystal structure was found to influence adhesion and friction.

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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 other polycrystalline metals. The studies of references 9 to 11 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. 12 to 14), and body centered cubic metals such as tungsten (ref. 10). 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 (greatest atomic density) with sliding in the preferred slip direction (closest packing of atoms).

Polycrystalline materials are used, in most mechanical applications where adhesion, friction and wear might be involved; this 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; 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 effect of boundaries can be more fully understood if the building block of polycrystalline structures, namely the single crystal, is better understood.

The objectives of this investigation were 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 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 cm/sec. 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 in sodium hydroxide. Lave 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 in the vacuum chamber.

Orientations and Definitions

The term matched planes and directions will be used to describe the relative orientations of crystal faces in adhesion and friction experiments. In order to assist in understanding the term, figure 1 is provided. 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 to separate the two crystal surfaces in contact was measured. This latter force divided by the applied load during contact sliding, will be termed "adhesion* coefficient". The asterisk is used to differentiate this value from those obtained in standard adhesion measurements.

There are a number of terms which have been used in the literature, particularly in regard to friction, to describe solid solubility of metal couples. Therefore in order to avoid confusion the following terms will be used herein: (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 of this investigation. Partial solubility will refer 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 systems of this study is such a system. They differ in crystal structure below 400° C. Insoluble couples are those where no phase diagram exists and whose solubility if any is considered normally 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 $2\frac{1}{2}$ 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 deadweight 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 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 stainles-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 three hours. Bulk specimen temperatures at this time were 400° C. The specimens were cooled to room temperature and the experiments started.

The contact time under load for simple adhesion experiments was 10 seconds. In sliding, the total distance slid was held at a constant 0.735 cm and the speed was 0.001 cm/sec. Breakaway force after the sliding was measured immediately after sliding 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. 12 and 14). The results obtained in hydrogen indicated that the friction coefficient for the (100) planes of copper in sliding contact exhibited markedly higher coefficients of friction than the (111) planes of copper in sliding contact.

ORIENTATION EFFECTS

Adhesion and friction coefficients in this study were measured in vacuum at 10^{-11} Torr for copper contacting copper. Three single crystal orientations of copper were examined. The (100) plane contacting the (100) plane, the (110) plane contacting the (110) plane and the (111) plane contacting the (111) plane. In all experiments the planes and directions were matched. In these experiments a load of 50 grams was used. This particular load was selected because earlier experiments have shown that recrystallization of copper occurred in sliding contact at higher loads (ref. 15). For reference purposes, adhesion data were also obtained for polycrystalline copper. Examination of the data of column 3 of table I indicates that adhesion coefficients (breakaway load/applied load) of copper are dependent upon crystal orientation. The highest atomic density (111) plane exhibits the lowest coefficient of adhesion.

It is of interest to note the adhesion coefficients decrease as modulus of elasticity and the surface energies on these planes increases. The decrease in coefficient of adhesion 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 is also occurring 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 (110) and (100) orientations of copper. These effects would indicate that, for a given load, the true area of contact for the (111) orientation might be less than for the (110) and (100) orientations.

The resulting 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 plastic shown for a given stress will be greater for the (100) plane. The amount of elastic recovery for the (111) plane will be greater. That is the percent of elastic deformation to total deformation is greater for the denser (111) plane. It has been shown in reference 17 that, for metals such as gold and silver, a temperature 0.4 of 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 insure strong adhesion.

Since two crystals of the same orientation are brought in contact under load, if atomic bonding occurs across the interface, then, the interface may be considered to represent an interface which is 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 only occur accidently. Any bonding which occurs across the interface will involve some elastic displacement of atoms near the surface. The interface then represent atomically displaced atoms connecting the individual crystals, that is they represent a transitional region serving to link the two specimens much as in a grain boundary. The greater the mismatch, the further into the parent crystals elastic stress may be expected to occur.

Examination of surface energies of table I which are calculated values taken from reference 18 indicate that the surface energies are greatest on the (111) plane and least on the (100) plane. The adhesion data obtaine would then appear to be in conflict with the surface energy theory of adhesion and friction (ref. 19). It should be indicated, however, that when two surfaces are brought into contact the interface formed will have 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 on interfacial energy is developed. The energy of this interface will depend to a large extent on the degree of mismatch of the two crystallites. The greater the mismatch the larger the energy. For two crystals in contact the boundary energy must be considered since with adhesion a new interfacial surface is created.

Each of the adhesion coefficient values reported in column 3 of table I represent a 10 second contact time under load. At room temperature, diffusion effects may not be expected to greatly influence measured adhesion coefficients. At larger periods of time, with plastic materials such as metal, creep may be expected to influence this 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 coefficient of adhesion 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 of table I, column 3 for polycrystalline copper is interesting. The adhesion value obtained was 1.00 or very near that of the (100) plane of copper. Since the modulus of elasticity is nearly twice that of the (100) plane and the data of reference 20 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 junctions formed will be 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 will be even greater than that observed with single crystals oriented such that a high concentration of Lomer-Cottrell locks may be generated. Thus while a smaller true contact area may be anticipated for polycrystals for a given load, the tensile strength of junctions formed will be greater than observed with single crystals. This may then account for the similarity in the two adhesion coefficients.

After completing adhesion measurements, the crystals of table I were slid a distance of 0.735 cm and the friction coefficients observed during sliding are reported in column 4 of table I. 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 having 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 coefficients of adhesion were again measured immediately after sliding was stopped. The measured coefficients of adhesion are presented in colume 5 of 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 the true contact area will occur with sliding and secondly, the area in contact will represent metal which has work hardened in the process of sliding. Thus not only will the area of contact have increased with sliding but also the tensile strength of the junctions will have increased.

The adhesion and friction coefficients observed in table I for polycrystalline copper are markedly greater than those observed in reference 3. Some explanation is therefore in order. In reference 3, the load employed was 1000 grams and the speed was 198 cm/sec. At this high load and speed, recrystallization of copper at the interface is known to occur (ref. 15). Thus the type and nature of the surface under the two sets of experimental conditions were markedly different at the higher loads and speeds. At the higher loads and speeds of the study reported herein, 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 of table I indicate that differences in adhesion coefficients exist for different crystallographic planes of copper. Further, the results show 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 (100) and (111) copper riders. It is interesting to note that slip lines on the (100) surface appear at about 90°. On the (111) surface they appear at about 60°. These 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 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 might be anticipated, that pairs of matched planes exhibit higher adhesion coefficients before sliding than pairs of unmatched planes across the interface or boundary differ. In all three experiments, the friction coefficient during sliding was in excess of 40.0.

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. In all of these experiments the (111) plane of copper was the rider surface. The results of the cohesion experiments for (111) copper on (111) copper represent the first set of results as they were presented in table I. The second set of experiments represent the (111) of copper on the (111) 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 the cohesive forces 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 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 $[11\bar{2}0]$ direction on cobalt. It is interesting to note that while cobalt is next to nickel in the periodic table and many of its properties are similar, they differ in crystal structure. Cobalt and copper are partially soluble. Examination of the data of table III would indicate that while both cobalt and nickel are soluble in copper, significantly lower friction and adhesion was 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 will be brought out again later in this paper. 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 if adhesion would occur and what effect sliding has on adhesion. The results obtained are presented in table III, figures 5(c), and 6.

In table III the initial coefficient of adhesion for copper to tungsten was less than 0.05, that is, less than that which could be detected with 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. Friction data are included in figure 6 for copper sliding on nickel. With copper sliding on nickel the friction started high and decreased to some lower value after about one 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 latter friction points of figure 6.

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

The effect of solubility on adherence of copper may be seen further in the data of figure 7. With copper contacting nickel (completely soluble) the initial breakaway force is high after sliding. With a subsequent number of contacts and breaks, it decreases to some relatively constant value. These results are as might be anticipated. Due to sliding both work-hardening and increase in true contact area has occurred. On the initial separation the area in contact will be greater than in subsequent contacts. The adhesion does not decrease to the value obtained before sliding because the junction 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

In order to gain a fuller understanding of the influence crystal structure has an adhesion and friction of metals, a set of experiments were conducted with cobalt sliding in contact on cobalt in the $[11\bar{2}0]$ slip direction. The results obtained in these experiments are presented in table IV, together with the minimal adhesion and friction obtained with copper matched planes and directions. (These are the results obtained with the (111) plane 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. Cobalt was selected because of its close proximity to copper in the periodic table. These results would 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 8. Similar twinning has been observed with compressive loading of the hexagonal metal (ref. 24).

SUMMARY OF RESULTS

Based upon the friction and adhesion data for various single crystal couples in vacuum the following summary remarks are made:

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

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

3. After sliding adhesion was found to occur for mutually insoluble couples (Cu-W) as well as for the mutually soluble couples (Cu-Ni).

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

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

Copper form and orientation	Young's modulus $(10^{11}\ \mathrm{dynes/cm})^2$ Ref. 18	Surface energy, $\gamma_{hk1} = \frac{E_{hk1}}{\gamma_{hk1}}\left(\frac{a_o}{\pi}\right)^3$ Ref. 18	Adhesion coefficient before sliding[a]	Coefficient of friction[b] (during sliding)	Adhesion* coefficient after sliding[c]
Single crystal (100) matched planes and directions	6.67	590	1.02	>40.0	>130
Single crystal (110) matched planes and directions	13.1	820	0.61	>40.0	50.0
Single crystal (111) matched planes and directions	19.4	2980	0.30	21.0	10.5
Polycrystal	12.0	1100-1350	1.00	>40.0	100

[a] Load 50 gms, 10^{-11} Torr.

[b] Load 50 gms, sliding velocity 0.001 cm/sec, 10^{-11} Torr.

[c] Load 50 gms, distance slid in preferred slip directions 0.735 cm, 10^{-11} Torr.

TABLE II. - COEFFICIENTS OF ADHESION AND FRICTION FOR VARIOUS SINGLE CRYSTAL ORIENTATIONS OF COPPER (10^{-11} TORR, 20° C, 50 GMS)

Matched planes	Adhesion coefficient before sliding	Coefficient of friction[a] (during sliding)	Adhesion* coefficient after sliding
(100)/(100)	1.02	>40.0	>130
(110)/(100	0.25	>40.0	32.5
(111)/(100)	0.20	>40.0	40.0

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

TABLE III. - COEFFICIENT OF ADHESION AND FRICTION FOR VARIOUS SINGLE CRYSTAL METAL COUPLES IN VACUUM (10^{-11} TORR) (50 GMS)

Metal couples and orientations	Adhesion before sliding	Friction coefficient[a] (during sliding)	Adhesion* coefficient after sliding	Solu-able	Crystal structures
Cu(111) Cu(111)	0.30	21.0	10.5	S	F.C.C. F.C.C.
Cu(111)[110] Ni(111)[110]	0.25	4.0	2.0	S	F.C.C. F.C.C.
Cu(111)[110] Co(0001)[11$\bar{2}$0]	0.10	2.00	0.5	S	F.C.C. Hex
Cu(111)[110] W(110)[111]	less than 0.05	1.40	0.5	INS	F.C.C. F.C.C.

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

TABLE IV. - COEFFICIENTS OF ADHESION AND FRICTION FOR COPPER AND COBALT SINGLE CRYSTALS IN VACUUM (10^{-11} TORR) (50 GMS)

Metal couples (matched poles)	Adhesion coefficient before sliding	Friction coefficient[a] (during sliding)	Adhesion* after sliding
$\frac{\mathrm{Cu(111)[110]}}{\mathrm{Cu(111)[110]}}$	0.30	21.0	10.5
$\frac{\mathrm{Co(0001)[11\bar{2}0]}}{\mathrm{Co(0001)[11\bar{2}0]}}$	<0.05	.35	<0.05

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

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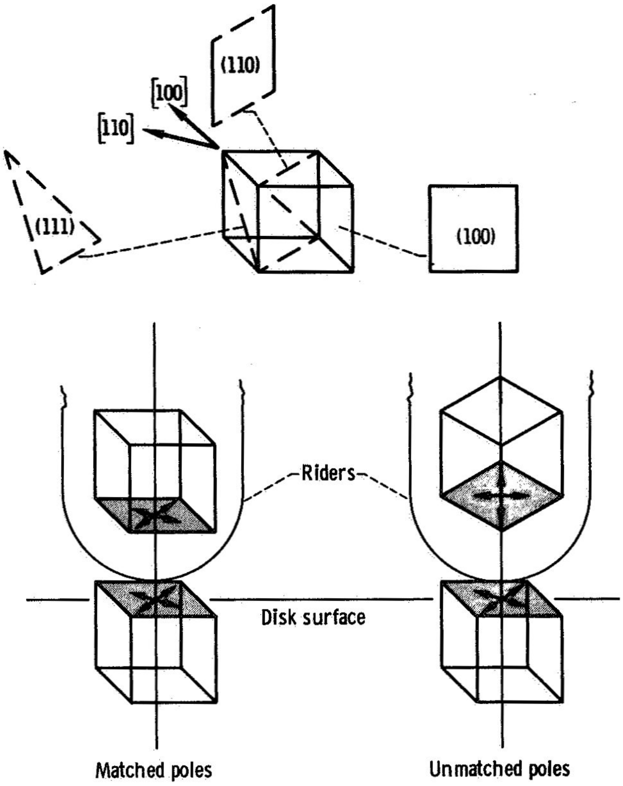

Figure 1. - Orientations; planes and crystallographic directions.

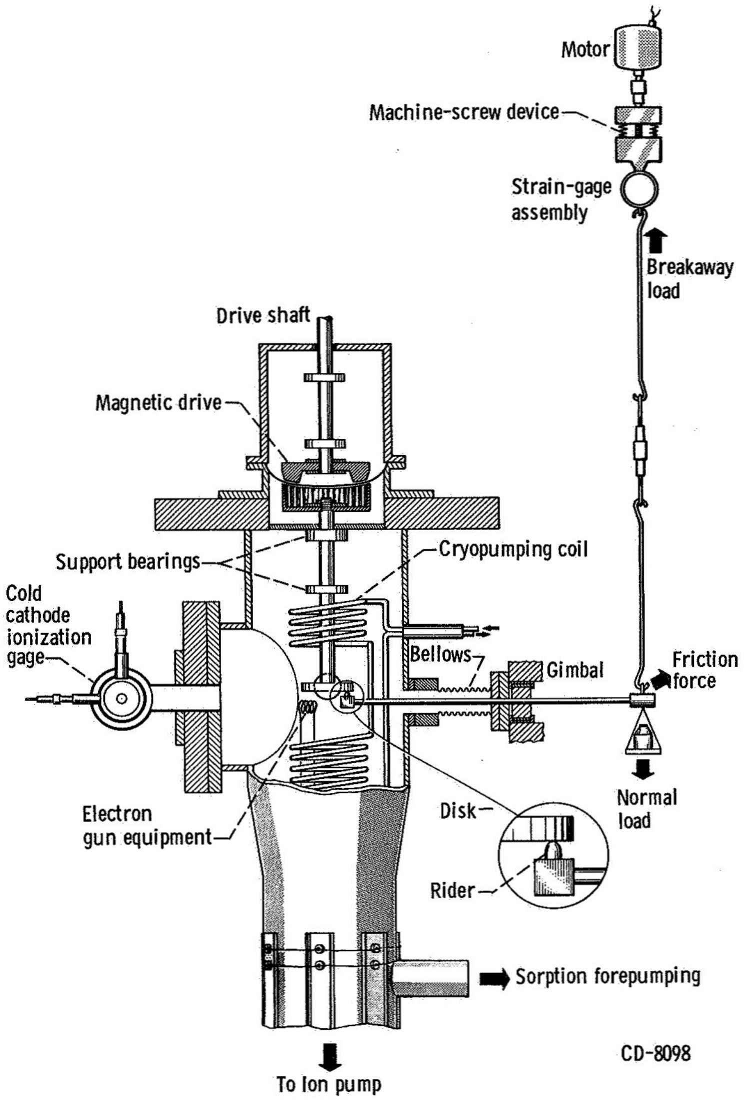

Figure 2. - Vacuum friction apparatus.

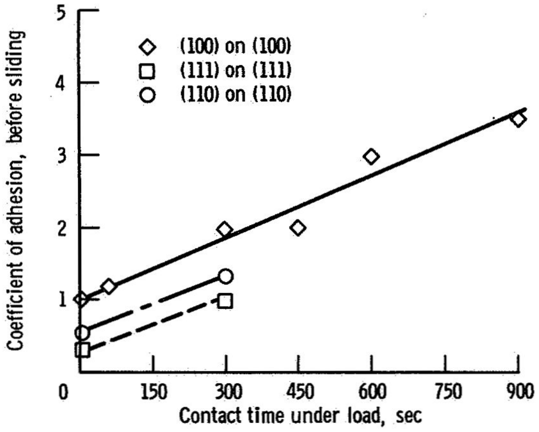

Figure 3. - Coefficient of adhesion before sliding for copper on copper with matched planes and directions in vacuum (10^{-11} torr). Simple touch contact under a 50 gram load.

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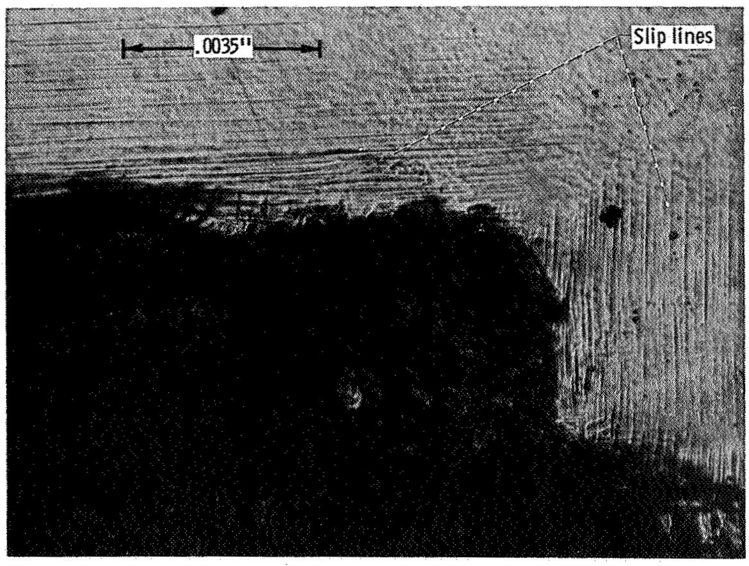
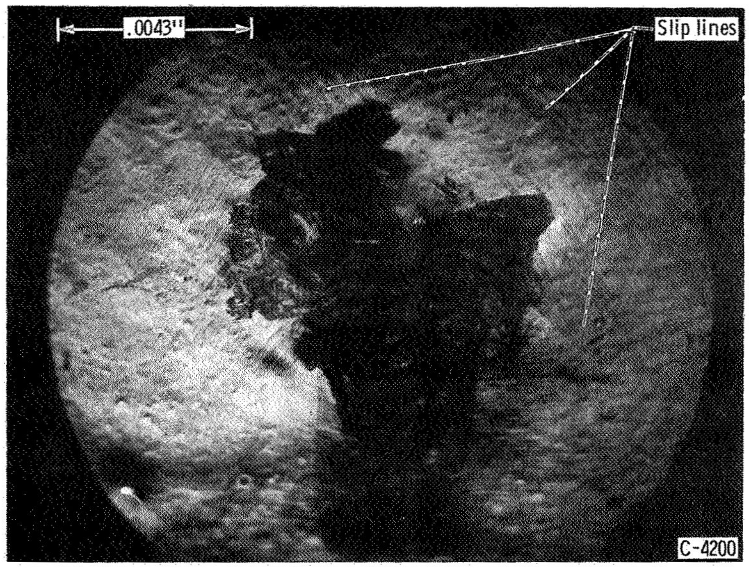


(a) (100) rider wear area.



(b) (111) rider wear area.

Figure 4. - Photomicrographs of wear scars on copper single crystal rider specimens. Disks were of the save orientation. Load, 50 gms; sliding distance, 0.735 cm.

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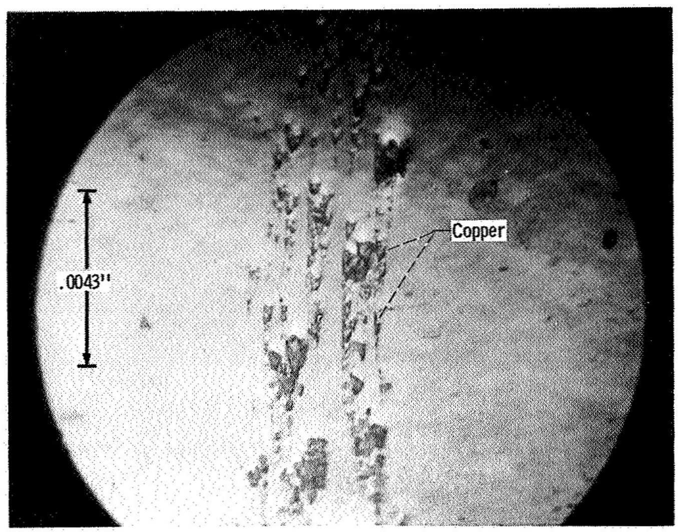
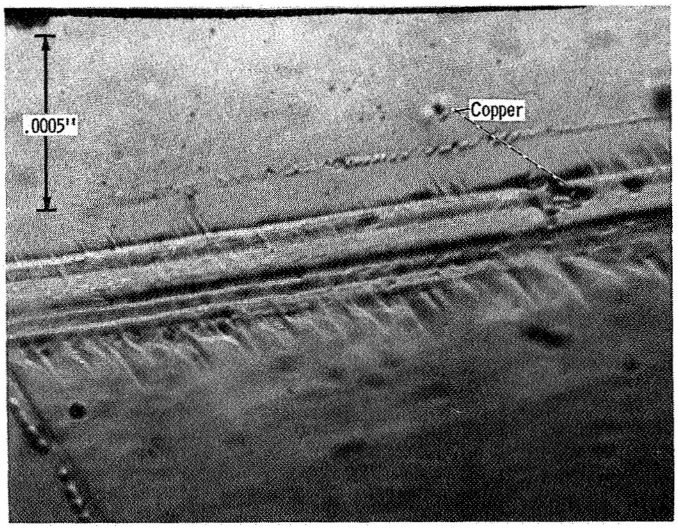
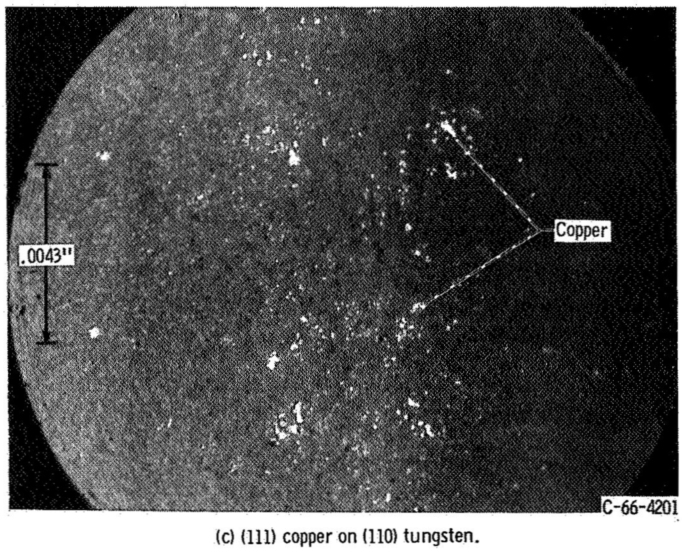


(a) (111) copper on (111) nickel.



(b) (111) copper on (0001) cobalt.



(c) (111) copper on (110) tungsten.

Figure 5. - Photomicrographs of wear tracks for (111) [110] copper sliding on various substrates in vacuum.

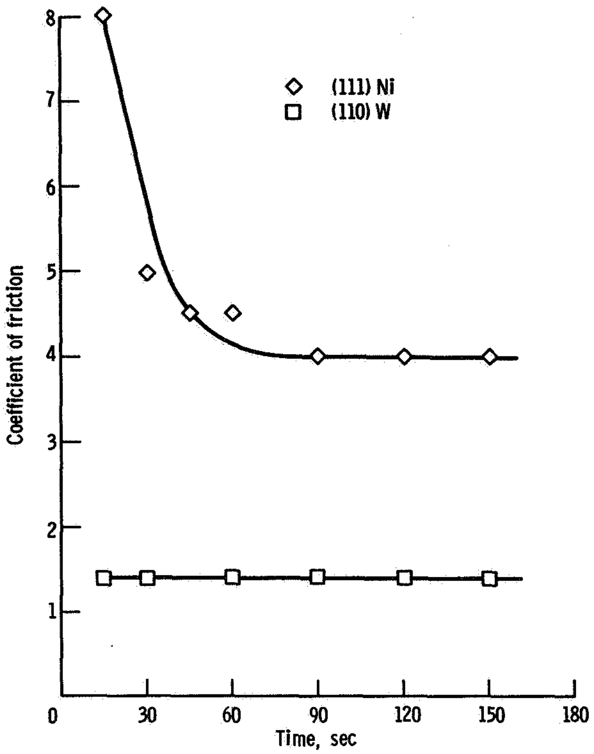


Figure 6. - Coefficient of friction for (111)[110] copper sliding on single crystal nickel and single crystal tungsten in vacuum (10^{-11} torr). Sliding velocity, 0.001 centimeter per second; load, 50 grams; and ambient temperature, 20° C.

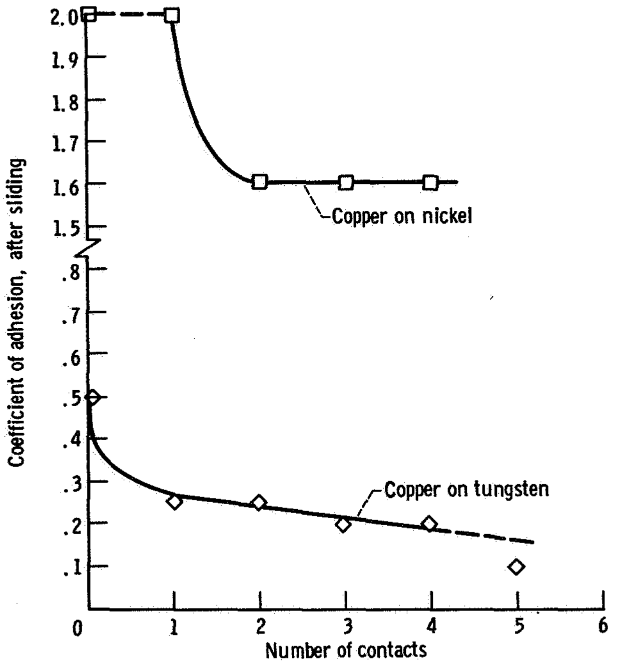


Figure 7. - Coefficient of adhesion of (111) copper to (111) nickel and to (110) tungsten after sliding in vacuum (10^{-11} torr). Sliding velocity, .001 millimeter per second; load, 50 grams; and ambient temperature, 20° C.

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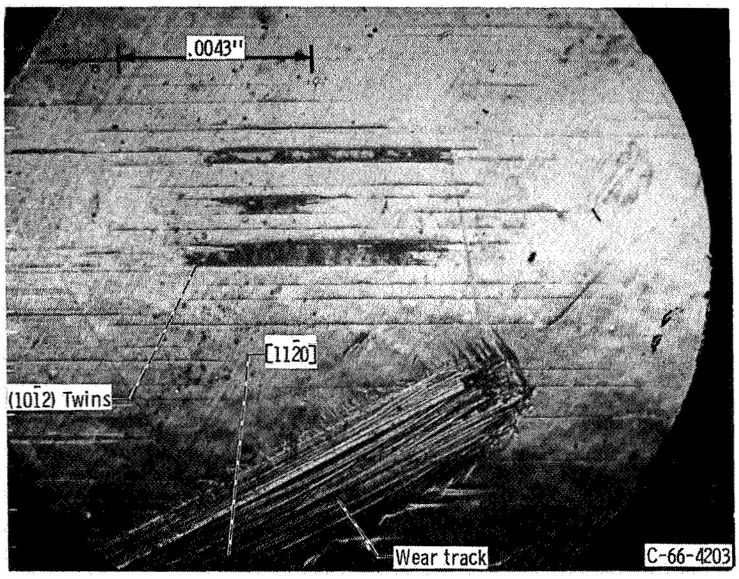

Figure 8. - Photomicrograph of sliding track on cobalt single crystal disk specimen (0001). Rider specimen (0001) single crystal cobalt.