NASA TECHNICAL NOTE

NASA TN D-4143
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1967

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SUMMARY

An investigation was conducted with sliding friction experiments to determine the influence of recrystallization and texturing of various metals in sliding on friction coefficients. The metals examined in this investigation included copper, nickel, iron, tungsten, beryllium, and titanium. These metals were examined in their single-crystal and polycrystalline forms. The mating surface in sliding friction experiments was polycrystalline aluminum oxide. Experiments were conducted at a sliding velocity of 0. 001 centimeter per second with no external heating of the specimens. A change in release of interface frictional energy to produce recrystallization for the various metals in sliding contact with polycrystalline aluminum oxide was achieved by changing the load. All experiments were conducted in a vacuum of 10^{-11} torr (1.33×10^{-9} N/m^2) with specimens which had been electron bombarded to clean their surfaces.

The results of the investigation indicate that, at relatively modest loads, recrystallization and texturing will occur for some of the highest melting point metals. For example, tungsten, which has a recrystallization temperature of 1200° C, recrystallized and textured at the surface with a load of 3500 grams. The process of recrystallization and texturing produces very marked changes in friction coefficients. The higher the recrystallization temperature of a metal, the higher is the load at a constant sliding velocity needed to produce recrystallization. Prior to recrystallization, all metals exhibited lower friction coefficients for single-crystal orientations than for the metals in their polycrystalline form.

INTRODUCTION

There are many physical changes that can take place in metallic structures which markedly influence friction behavior. Crystal transformations (ref. 1), order-disorder

reactions (ref. 2), and recrystallization (the formation of a strain-free grain structure from that existing in cold worked metal (ref. 3)) have been shown to influence friction coefficients. Recrystallization of surfaces is extremely important to the friction properties of metals. It has been shown, for example, that a metal such as copper can exhibit a nearly twofold change in friction with surface recrystallization. Even relatively modest loads and surface speeds are sufficient to cause recrystallization (ref. 3).

The parameters important to the process of metallic recrystallization are an inherent part of the sliding process for metals in contact. Some plastic deformation is needed to initiate recrystallization; and deformation occurs with metals in sliding at their surfaces. Further, some recrystallization temperature must be achieved. This temperature will be a function of the materials in contact and the amount of plastic deformation that has occurred at the interface. Severe plastic deformation appreciably reduces the recrystallization temperature. Thus, while the recrystallization temperature for some metals may be extremely high (e.g., 1200° C for tungsten), it may be reduced by deformation to one which may be achieved at a sliding interface as a result of frictional heating.

The process of recrystallization is often followed by a preferred orientation of crystallites (texturing). This orientation occurs in drawing, rolling, and compression operations as well as in sliding friction experiments (ref. 3). Randomly oriented crystallites in a polycrystalline material may be expected to exhibit different friction behavior than that of textured surfaces. Further, for single crystals, surface recrystallization followed by texturing not only introduces grain boundaries but also crystallite orientation which may differ markedly from the original crystal orientation. All these interfacial changes will influence the shear process and, therefore, friction at a sliding interface.

The objective of this investigation was to determine, in vacuum sliding friction experiments, the influence of surface recrystallization on the friction coefficient for various metals in single-crystal and polycrystalline form. The metals examined in this study included copper, iron, nickel, titanium, beryllium, and tungsten. Friction experiments were all conducted with the metals in sliding contact with polycrystalline aluminum oxide. The sliding velocity in all experiments was held constant, and no external heating of the specimens was used. The only means used for changing interface frictional energy was that of changing load. All experiments were conducted in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2) with surfaces cleaned by electron bombardment to minimize the effects of surface contaminants.

MATERIALS

All the single-crystal and polycrystalline metals used in this study had a minimum purity of 99.99 percent with the exception of beryllium (99.97 percent). The purity of

TABLE I. - ANNEALING TEMPERATURES AND

ELECTROPOLISHING REAGENTS USED

IN THIS INVESTIGATION

Metal	Polycrystalline annealing temperature, ^{o}C (time, 8 hr)	Electropolishing agent
Copper	400	Orthophosphoric acid
Nickel	500	Orthophosphoric acid
Iron	600	Orthophosphoric acid
Tungsten	Used as obtained from electron-beam melting	10-percent solution of NaOH
Beryllium	1100	Orthophosphoric acid
Titanium	1000	Chemical polish, 1 HF, 1 HCl, 4 H_2O

copper was 99.999 percent. Before friction experiments, the specimens were prepared as shown in table I. The orientations for all single crystals were determined by standard X-ray Laue back-reflection technique. The orientations are within $\pm 2^{o}$ of that stated. The planes on which sliding took place are shown in the figures. The planes indicated are parallel to the sliding interface. For single crystals, the crystallographic direction of sliding is the preferred slip direction (e.g., (100) face-centered cubic metals [110], (110) body-centered cubic metals [111], and (0001) close-packed hexagonal metals [$11\bar{2}0$]).

APPARATUS

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens (a 6.35-cm-diam flat disk and a 0.48-cm-rad. hemispherical rider) mounted in a vacuum chamber. The disk specimen was rotated by two 20-pole magnets 0.381 centimeter apart with a 0.076-centimeter diaphragm between magnet faces. The driver magnet that was outside the vacuum system was coupled to a hy-

draulic 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 strain-gage 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 6.0-meter-long stainless-steel coil of 0.787-centimeter-diameter tubing was used for liquid-helium cryopumping of the vacuum system.

In experiments where external heating of the specimens was required, an electron temperature was recorded. No attempt was made to record interface temperatures.

EXPERIMENTAL PROCEDURE

The polycrystalline disk and the rider specimens used in this study were machined to size and electropolished. They were then rinsed in acetone and alcohol before insertion into the vacuum chamber. The single crystals were prepared by spark discharge machining. They were electropolished, and orientations were determined using the Laue back-reflection X-ray technique. They were mounted in the specimen holder, orientation was rechecked, and they finally were 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 with sorption pumps and finally the ion pump. 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 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

Face-Centered Cubic Metals

Sliding friction experiments were conducted (ref. 3) with a single-crystal copper, (111) plane, sliding parallel to the interface on polycrystalline aluminum oxide. Experiments were also conducted with polycrystalline copper. The friction results are presented in figure 2.

The data of figure 2 indicate that marked differences exist in the friction properties with the various single-crystal orientations in contact with polycrystalline aluminum oxide at a load of 50 grams. The friction coefficient of polycrystalline copper was 1.2. With increase in loading, the friction coefficient decreases to approximately 0.9 at 200-gram load. The friction coefficient for the polycrystalline material remains unchanged with further increases in load. For the single crystals, however, the (111) plane exhibits the lowest friction coefficient at a load of 50 grams (0.4). With increased loading, the friction coefficient increases and continues to do so at loads up to 1000 grams.

The (100) plane of copper exhibits a friction coefficient of 0.6 at a 50-gram load or 0.2 higher friction coefficient than the (111) crystal plane of copper. With increasing load, the friction coefficient for the (100) plane single-crystal orientation increased from 0.6 at 50 grams to 0.9 at a load of 200 grams. This friction coefficient was essentially the same as that for the polycrystalline copper.

The friction coefficient for the (110) single-crystal orientation was 1.0 at a load of 100 grams and decreased with increasing load to a value of 0.9 at a load of approximately 500 grams. With further increases in load, no change in friction coefficient from 0.9 was observed for the (110) single-crystal orientation. This behavior was much like that observed for the polycrystalline and the (100) single-crystal orientation.

X-ray Laue patterns obtained on the crystal surfaces after loading to 1000 grams indicated recrystallization and texturing of the copper surfaces for both single-crystal and polycrystalline copper. It is interesting to note, however, that while the friction coefficients for the (100) single-crystal orientation of copper and polycrystalline copper were essentially the same at loads above 200 grams, this was not observed for the (110) and the (111) single-crystal orientations. Even with a 1000-gram load and a recrystallized and textured surface layer present, the friction coefficients for the (110) and the (111) single-crystal orientations were below the friction coefficients obtained for the (100) single-crystal orientations and polycrystalline copper.

At some load, beyond 1000 grams, it might be anticipated that, with a thicker recrystallized layer present, the friction coefficients for all three single-crystal orientations and for polycrystalline copper would become essentially the same. This sameness

in friction occurs because the surface layers are essentially the same (recrystallized and textured).

It is interesting to note that the polycrystalline material exhibits the highest coefficient of friction (1.2) at a load of 50 grams. The (100) single-crystal orientation exhibits one-half that friction coefficient (0.6), while the (111) single-crystal orientation exhibits only a third of the friction coefficient of polycrystalline copper at a load of 50 grams. Since adhesion of the metal to the polycrystalline aluminum oxide occurs in all these sliding friction experiments and shear takes place in the metal, the low shear strengths for the single-crystal material account for the marked differences in friction coefficients observed.

At a 100-gram load, the lowest friction coefficient for the single crystals of copper was observed with the (111) single-crystal orientation. The (100) single-crystal orientation exhibited intermediate friction values, and the (110) single-crystal orientation exhibited the highest friction coefficient for the three single-crystal orientations of copper. These friction results are in the same order observed for the work hardening characteristics of the three orientations. The (111) orientation exhibits the greatest tendency to work harden, and the (110) single-crystal orientation exhibits the least tendency to work harden for the three orientations indicated. These friction results are the reverse of what might be anticipated. The metal with the least tendency to work harden would be expected to exhibit the lowest friction coefficient since it did have the least tendency to produce an increase in shear strength near the interface.

Not only is shear strength increasing during sliding friction experiments but the yield strength is increasing which results in a reduction in the real contact area (shear area) with the application of a normal load. The (111) plane, in addition to being the plane with the greatest tendency to work harden, is also the plane of highest atomic density. As a consequence, the deformation on this plane would (for an equivalent load) be expected to be less than for the (100) or the (110) crystal orientations. Elastic modulus data obtained on these three crystallographic planes for copper, in fact, substantiate that the deformation is least for the highest atomic density plane.

After sliding at a load of 1000 grams, the (111) orientation of copper was examined at a load of 50 grams in contact with the aluminum oxide disk surface. The reduction in load from 1000 to 50 grams resulted in no change in friction coefficient, as indicated by the data point in figure 2. A friction coefficient of essentially 0.8 was obtained at the two loads. The friction coefficient did not return to its original value of 0.4 indicating that the change which had taken place at the sliding interface was irreversible. This permanent change is to be expected since recrystallization and texturing are permanent changes in the structure of the metal.

The type and the nature of texturing normally obtained for face-centered cubic metals

under various conditions of mechanical deformation are discussed in detail in references 6 and 10.

The sliding friction properties of another face-centered cubic metal, namely nickel, were examined in experiments at various loads. These experiments were conducted with both single-crystal, (111) crystallographic plane parallel to the sliding interface, and with polycrystalline nickel sliding on aluminum oxide. The results obtained in these sliding friction experiments at various loads are presented in figure 3. At a load of 50 grams, a fourfold difference in friction coefficient existed for the preferred crystallographic slip plane of single-crystal nickel and the polycrystalline nickel. The friction coefficient for the single crystal was approximately 0.4, and that of polycrystalline nickel was 1.6. With increased loading, the friction coefficient of the polycrystalline nickel decreased to a value of 1.2 and remained at that value as load was increased to 1200 grams. The friction coefficient of the single crystal of nickel also increased with increasing load. Loads in excess of 300 grams, however, produced no further changes in the friction coefficients for the single-crystal orientation. X-ray Laue patterns obtained on the interface surface for the single-crystal and polycrystalline nickel after sliding indicated the presence of a recrystallized textured surface film.

It is interesting to note that with the recrystallized and textured surface layer, the original form of the nickel is not important. Following recrystallization and texturing, the interfaces are essentially the same for the two different forms of nickel. Recrystallization and texturing result in essentially a common friction coefficient of 1.2 at the higher loads. Nickel, with a higher shear strength than copper, exhibits a higher coefficient of friction after recrystallization and texturing has occurred for the two forms of this metal. The friction coefficient for recrystallized copper was 0.9 whether the starting material was single-crystal or polycrystalline copper. The corresponding value for nickel was 1.2.

Body-Centered Cubic Metals

Iron and tungsten were examined in sliding friction experiments to determine the influence of recrystallization on friction coefficients for body-centered cubic metals. The two body-centered cubic metals examined were iron and tungsten in sliding contact with polycrystalline aluminum oxide. In the first set of experiments, the (110) plane of single-crystal iron, the preferred crystallographic slip plane in iron, and polycrystalline iron were in sliding contact with polycrystalline aluminum oxide. These two forms of iron were examined at various loads to 2000 grams at a sliding velocity of 0.001 centimeter per second. The results obtained in these sliding friction experiments are presented in figure 4.

At a 50-gram load, the friction coefficient for polycrystalline iron was 1.6 while that for the single-crystal (110) iron was 0.8 or half the polycrystalline value. With increasing load, the friction coefficient for polycrystalline iron, much as for nickel and copper, decreased to 1.3 at a load of approximately 400 grams. With further increases in load to 2000 grams, no further marked change in friction properties for polycrystalline iron was observed.

With single-crystal iron, an immediate change in friction coefficient was observed when the load was changed from 50 to 100 grams. The friction coefficient increased from 0.8 to 1.0. With an increase in load to 200 grams, the friction coefficient rose to 1.12 and ultimately at 500 grams to a value of 1.3 or essentially the same friction coefficient as was obtained for the polycrystalline iron. Further increases in load to 2000 grams produce no further changes in the friction properties of single-crystal iron. Again Laue back-reflection X-ray patterns obtained for the single-crystal and the polycrystalline iron indicated that essentially the same interfacial surface layers were present for the two orientations. This recrystallized and textured layer accounted for the same values in friction coefficient. After sliding under a load of 2000 grams, the load was reduced to 50 grams for the single-crystal and the polycrystalline iron resulting in a common friction coefficient of 1.3. This friction value is indicated by the completely shaded data points of figure 4. These results indicate that the recrystallization and the texturing, which had taken place at the sliding interface, were permanent changes.

In these sliding friction experiments, the speeds were so low that it was difficult to obtain appreciable wear debris or deformed and recrystallized surface material. In some earlier experiments, however, at higher sliding velocities, an appreciable amount of deformed surface material was obtained in the form of wear debris for polycrystalline iron sliding on the aluminum oxide. Photomicrographs obtained for some of these specimens after the sliding friction experiments are presented in figure 5. There were essentially no grain boundaries within the debris material. In contrast, examination of the rider body indicates a very large-grained structure. The grain boundaries are clearly evident in the photomicrographs of figure 5.

Detailed X-ray analysis, however, of the wear debris in the form of a trailing edge of metal, from the rider specimen shown in figures 5(a), (b), and (c) and the surface layer in the sliding contact zone of figure 5(d), revealed the material to be essentially crystalline. The crystallites were extremely small in size so as not to be readily evident in the metallographic photomicrographs.

Tungsten is a body-centered cubic metal with a very high melting point and extremely high recrystallization temperature. Tungsten recrystallizes normally at a temperature of 1200° C (dependent upon the amount of plastic deformation in the specimen). Sliding friction experiments were conducted in vacuum with polycrystalline, and (100) and (110) single-crystal orientations of tungsten in sliding contact with polycrystalline aluminum

oxide. The sliding conditions were the same as those used in previous experiments. The results obtained in sliding friction experiments with tungsten in single-crystal and polycrystalline form at loads to 3500 grams are presented in figure 6. The data of figure 6 indicate that for single-crystal and polycrystalline tungsten the differences in friction coefficients are not as marked as was observed for the metals, copper, nickel, and iron. The (110) single crystal of tungsten exhibited a friction coefficient of 0.8 while polycrystalline tungsten exhibited a friction coefficient of 1.2 or approximately a 50-percent increase in friction coefficient for the polycrystalline material. An increase in load from 50 grams resulted in a decrease in friction coefficient for polycrystalline tungsten. At loads from 50 to approximately 1000 grams, changes in friction were observed. No further marked changes in friction coefficients at loads from 1000 to 3500 grams were observed. The two single-crystal orientations of tungsten also exhibited changes in friction properties with change in load. The (110) single-crystal orientation, which is a preferred slip plane in tungsten, exhibited the lowest friction coefficient, much as was observed for copper (111). With increase in load, however, the friction coefficient continually increased to a load of approximately 3500 grams. At 3500 grams, the friction coefficients for single-crystal (110) tungsten and polycrystalline tungsten were essentially the same. With the (100) single-crystal orientation of tungsten, the friction coefficient started at 1.0 and decreased with increased loading again reaching a common value with the polycrystalline tungsten at a load of 3500 grams. At 3500 grams, the friction coefficient was the same for all three forms of tungsten. X-ray Laue patterns obtained on all three specimens at 3500-gram load reveal the presence of a recrystallized textured surface layer. The Laue pattern obtained for the (110) specimen is shown in figure 7.

Examination of figure 7 for the single crystal (110) reveals that one can still detect the Laue spots obtained for the various crystallographic planes of the single crystal. The bulk of the specimen which is diffracting X-rays is still essentially the single-crystal material. On the surface, however, a thin recrystallized textured layer is present, as indicated by the partial arcs shown on the photograph. Thus, at a sliding velocity of 0.001 centimeter per second and at a load of 3500 grams, it is possible to achieve sufficient interface frictional energy to produce recrystallization in tungsten. Tungsten has a normal recrystallization temperature of approximately 1200° C.

Plastic deformation at a sliding interface markedly reduces the recrystallization temperature for a metal. It is not uncommon with a 90-percent deformation or strain of metal to experience a reduction in recrystallization temperature of 60 percent. It is well known that at a sliding interface the metal undergoes very severe plastic deformation. Thus, it is not difficult to understand recrystallization occuring even in some of the highest melting point metals.

Hexagonal Metals

Another crystal form of metals of interest because of their inherent low friction properties are the hexagonal metals. Beryllium is a typical hexagonal metal. In order to gain some insight into the possible behavior of a hexagonal metal, sliding friction experiments were conducted in vacuum with beryllium sliding on polycrystalline aluminum oxide at various loads, under the same mechanical conditions at which the other metals were examined. Results obtained in these friction experiments are shown in figure 8. Two single-crystal orientations of beryllium, (0001) and $(10\bar{1}0)$, and polycrystalline beryllium were examined. The polycrystalline beryllium exhibited a friction coefficient of approximately 0.8 at a load of 50 grams. The friction coefficient decreased appreciably with increased loading. It ultimately reached a value of approximately 0.5 at a load of 4000 grams. The preferred crystallographic slip plane, the (0001) slip plane, for beryllium also exhibited a decrease in friction coefficient with increase in load. The friction coefficient decreased to a value of approximately 0.48 at a load of 1000 grams with no further changes in the friction coefficient at loads to 4000 grams. The $(10\bar{1}0)$ single-crystal orientation of beryllium exhibited a higher friction coefficient than the (0001) single-crystal orientation. With increasing load, however, the friction coefficient decreased, and at a load of 3500 grams the friction coefficient for the three orientations became essentially the same. Electron diffraction patterns obtained for the three forms of beryllium indicated that a recrystallized textured surface film was obtained on all three surfaces.

For the hexagonal metals, much as with the face-centered cubic and body-centered cubic metals, relatively modest loads are needed to produce recrystallization and texturing of metal surfaces.

The results obtained thus far in this investigation with the body-centered cubic, face-centered cubic, and close-packed hexagonal metals indicate, in fact, that metals in general recrystallize in the process of sliding at relatively modest conditions of load and speed. The sliding velocity in this investigation was only 0.001 centimeter per second. The only means used to provide changes in interface frictional energy was that of changing load. At a load of 3500 grams, recrystallization of a metal such as tungsten could be achieved with relative ease, indicating the extreme amount of energy involved in a sliding friction process.

The recrystallization temperatures of metals are markedly dependent on the amount of prior deformation that occurred for the metals. As mentioned earlier severe deformation of metals can readily reduce the recrystallization temperatures by 60 percent. In order to gain some insight into a possible correlation between recrystallization temperatures for metals and their sliding friction behavior, the recrystallization temperature obtained for various metals from the literature together with friction coefficients obtained in the sliding friction studies are presented in table II.

TABLE II. - RECRYSTALLIZATION TEMPERATURES AND LOADS AT WHICH EQUIVALENT FRICTION COEFFICIENTS WERE OBTAINED FOR SINGLE-CRYSTAL AND POLYCRYSTALLINE METALS

Metal	Experimental load at which friction is approximately equivalent for single-crystal and polycrystalline metal, g	Approximate[a] recrystallization temperature, °C
Copper	200	100
Nickel	300	350
Iron	400	450
Titanium	500	700
Beryllium	3500	900
Tungsten	3500	1200

[a]These temperatures taken from refs. 7, 8, and 10 are only approximate because amount of deformation will influence this value.

Examination of table II indicates approximate recrystallization temperatures for the various metals examined in this investigation, as well as that of titanium examined in reference 7. The approximate load at which the friction was equivalent for the single-crystal and the polycrystalline metallic forms of each of the various metals correlates with the recrystallization temperatures for these metals. That is, the higher the recrystallization temperature, the greater the load necessary to achieve surface recrystallization and to produce a marked change in friction properties. These results are extremely interesting in light of the fact that marked differences exist in the thermal conductivity characteristics of the various metals and in their abilities to deform.

It is well known that heat dissipation at the sliding interface is extremely important in the removal of frictional heat generated in the process of sliding. It might be anticipated that good thermal conductivity metals, such as copper, might exhibit a greater tendency to carry away frictional heat from the sliding interface thereby resulting in a higher load required for recrystallization than for a metal, such as nickel, which does not have the good thermal conduction characteristics of copper. Examination of table II indicates that while a 250° C temperature difference exists in the recrystallization temperatures for these two metals, a difference of only 100 grams in load necessary for recrystallization exists. This difference indicates that the loads for recrystallization are closer than what might be anticipated from the marked difference in recrystallization temperatures. Tungsten has a recrystallization temperature of approximately 1200° C. The load at

which recrystallization was the same for the three forms of tungsten was 3500 grams. Beryllium has a recrystallization temperature of 900° C. The sameness in friction and load for producing recrystallization in sliding friction, and the difference in recrystallization temperature between beryllium and tungsten may be accounted for by the differences in crystal structure for beryllium and tungsten. Single-crystal beryllium has a markedly lower tendency to work harden than tungsten. A lesser tendency to work harden will influence recrystallization in metals. Further, differences in friction coefficients for the two metals will be accompanied by differences in heat generated at the interface.

From the results obtained in this investigation in many sliding friction experiments, recrystallization and texturing must be considered in interpretation of friction data. The recrystallization and texturing process markedly influences the friction properties for metals in sliding contact.

Marked differences exist in the friction characteristics for single-crystal and polycrystalline forms of metals, with the single-crystal forms exhibiting lower friction coefficients in each and every case. These results would seem to indicate that large-grained structures might exhibit lower friction than fine-grained metallic structures. With recrystallization and texturing, the friction coefficients become essentially the same for polycrystalline and single-crystal forms of the same metal.

CONCLUSIONS

Based on the friction coefficients measured in this investigation for copper, nickel, iron, tungsten, and beryllium in their single-crystal and polycrystalline forms, the following concluding remarks are made:

1. Recrystallization and texturing occur for metals in sliding contact at relatively modest loads and sliding velocities. This process results in a notable change in friction coefficients. For single crystals oriented on preferred slip planes, it represents an increase in friction while for polycrystalline metals it represents a decrease in friction coefficients.

2. The higher the recrystallization temperature of a metal, the higher is the load needed to produce recrystallization.

3. Prior to recrystallization, all single-crystal metals oriented to slide on the preferred slip plane exhibit lower friction coefficients than in their polycrystalline form.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 11, 1967,
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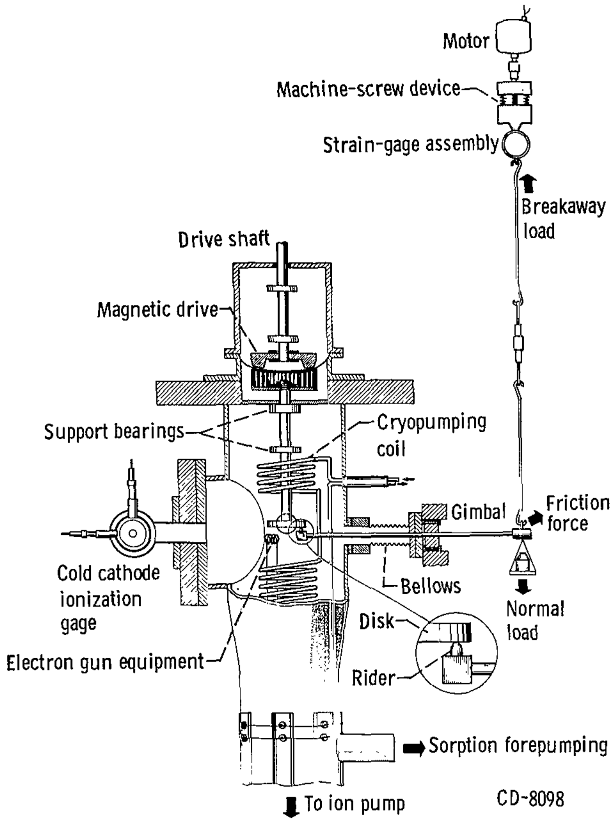

Figure 1. - Vacuum friction apparatus.

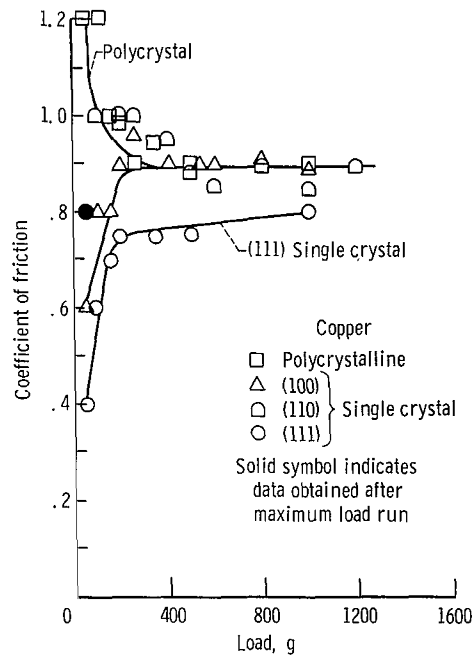

Figure 2. - Effect of load on friction for single and polycrystalline copper sliding on aluminum oxide in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2). Sliding velocity, 0.001 centimeter per second; no external specimen heating.

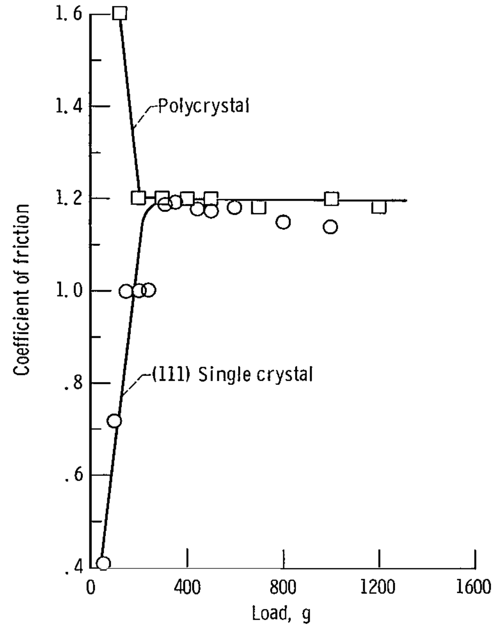

Figure 3. - Effect of load on friction for nickel sliding on polycrystalline aluminum oxide in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2). Sliding velocity, 0.001 centimeter per second; no external specimen heating.

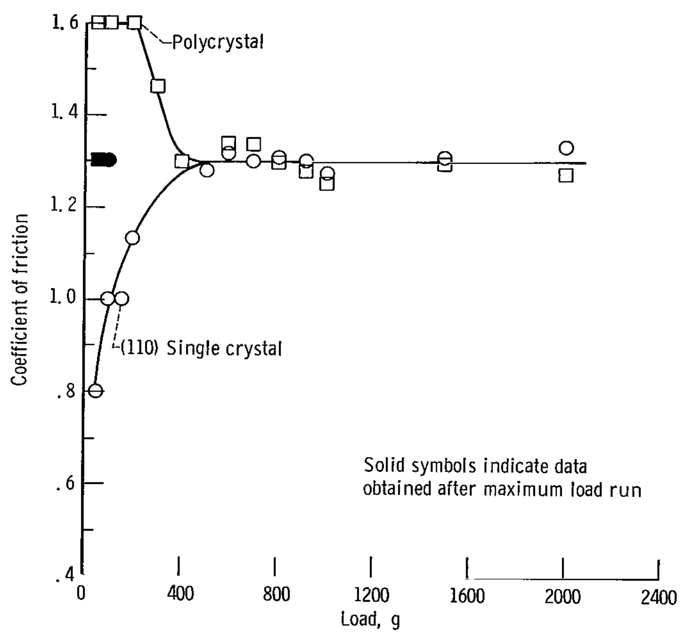

Figure 4. - Effect of load on friction for iron sliding on polycrystalline aluminum oxide in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2). Sliding velocity, 0.001 centimeter per second; no external specimen heating.

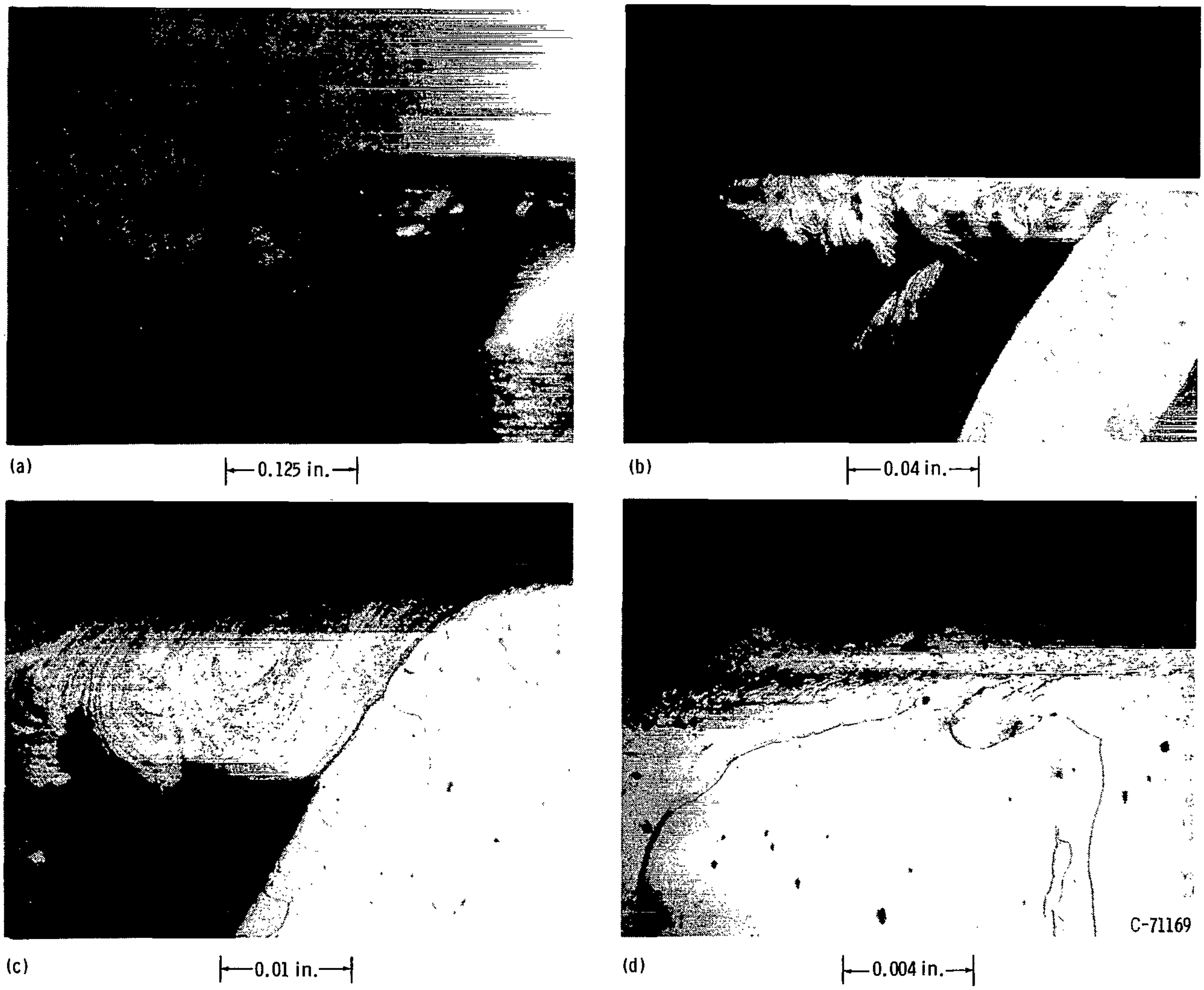

Figure 5. - Photomicrographs of high-purity iron rider specimen (ref. 4). Disk specimen polycrystalline Al_2O_3. Load, 1000 grams; sliding velocity, 198 centimeters per second; vacuum, 10^{-9} torr ($1.33 \times 10^{-7} N/m^2$); no external specimen heating.

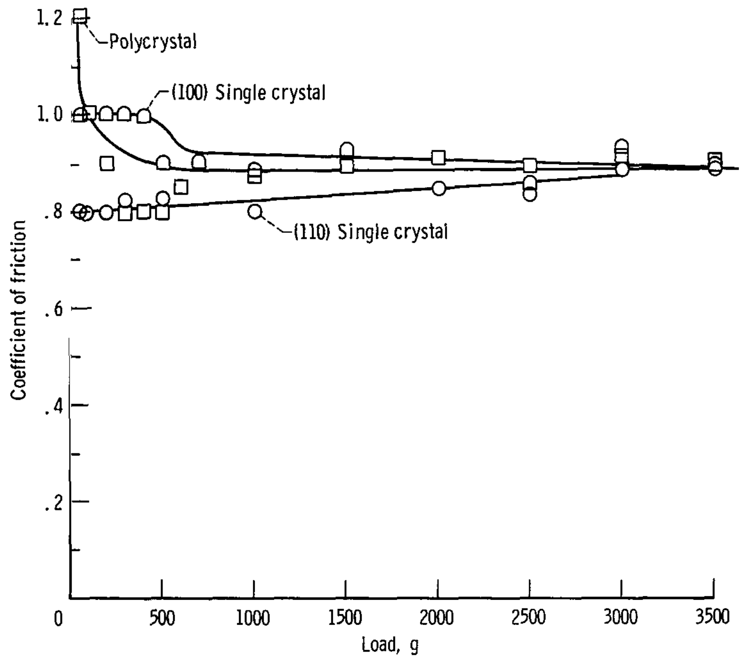

Figure 6. - Effect of load on friction for single-crystal and polycrystalline tungsten sliding on polycrystalline aluminum oxide in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2). Sliding velocity, 0.001 centimeter per second; no external heating.

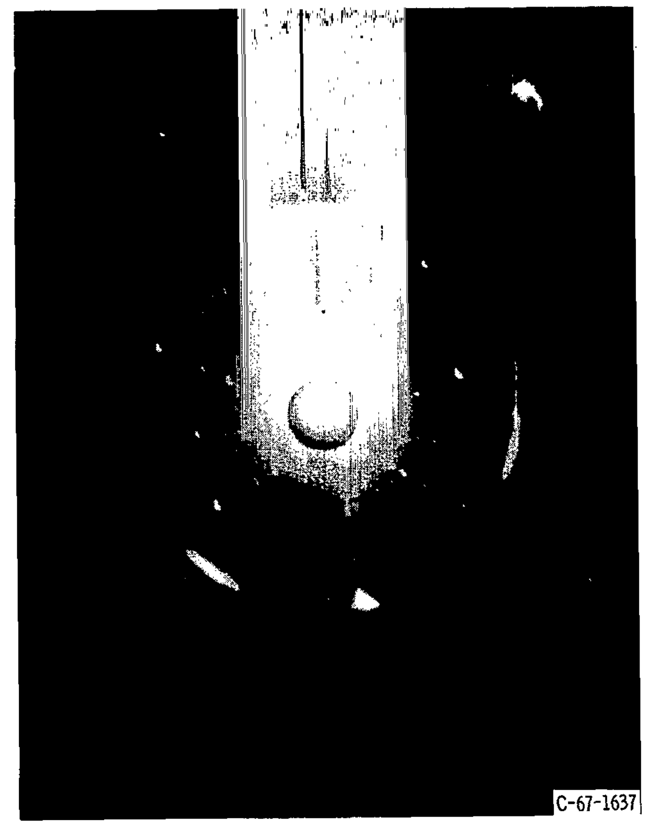

Figure 7. - Laue X-ray pattern for (110) plane of single-crystal tungsten after sliding friction experiment. Patterns show recrystallization and texturing on tungsten single-crystal surface. Sliding velocity, 0.001 centimeter per second; loads, 3500 grams; no external heating.

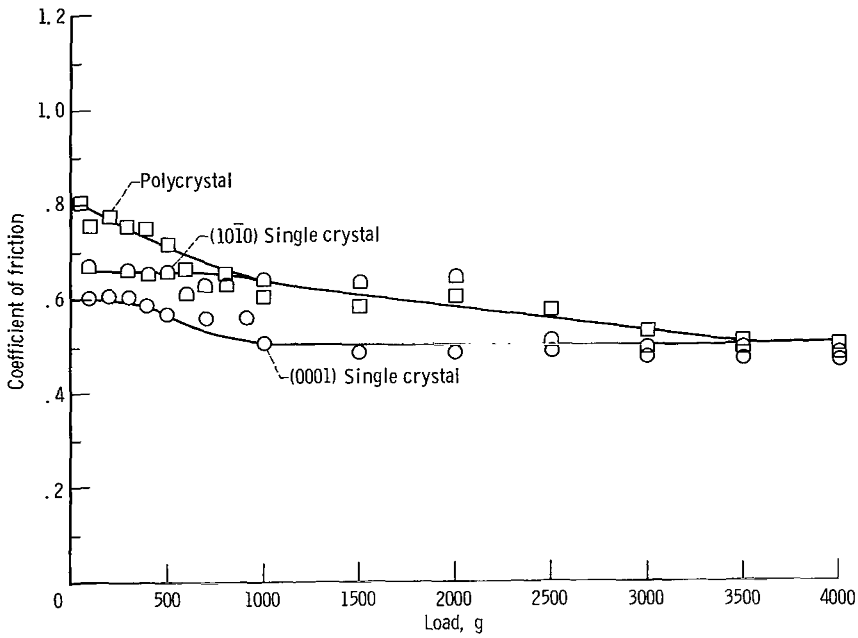

Figure 8. - Effect of load on friction for single-crystal and polycrystalline beryllium sliding on polycrystalline aluminum oxide in vacuum (10^{-11} torr; 1.33×10^{-9} N/m^2). Sliding velocity, 0.001 centimeter per second; no external heating.

NASA-Langley, 1967 —— 15 E-3872

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