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Cleveland, Ohio

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SUMMARY

An investigation was conducted in vacuum to determine the friction characteristics of rhenium in its single-crystal and polycrystalline forms. Experiments were conducted with a hemispherical rider sliding on a flat disk at 0.001 to 700 centimeters per second at ambient pressures to 10^{-11} torr. Polycrystalline rhenium was examined sliding on itself at temperatures to 680° C and loads to 2500 grams. Single-crystal experiments were conducted at 20° C for loads to 1000 grams with the basal (001) plane sliding in the $[11\bar{2}0]$ and $[10\bar{1}0]$ directions and the prismatic plane $(10\bar{1}0)$ sliding in the $[11\bar{2}0]$ and [0001] directions on polycrystalline rhenium.

The results of this investigation indicate that the friction characteristics of rhenium are highly dependent on its anisotropic nature. Comparative friction experiments with tantalum indicate that cubic tantalum exhibits high friction coefficients and welding in vacuum. With rhenium, no evidence of cold welding was observed. Friction data for rhenium correlate with the relation established for lattice parameters and the friction coefficients of hexagonal metals. The marked work-hardening characteristics of rhenium influenced both single-crystal and polycrystalline friction.

INTRODUCTION

Rhenium metal has some extremely interesting physical and mechanical properties (refs. 1 to 4 and table I). Only tungsten and graphite have higher melting points. The vapor pressure of rhenium is in the same range as those of tungsten and tantalum, and its density is the fourth highest among the elements. Rhenium has a hexagonal crystal structure and no allomorphic transformation. Among its mechanical properties, its modulus of elasticity is higher than that of any element with the exception of osmium and iridium. Its tensile strength at room temperature is comparable to that of tungsten. In con-

TABLE I. - PHYSICAL AND MECHANICAL PROPERTIES OF POLYCRYSTALLINE RHENIUM[a]

Physical properties	
Melting point, ^{o}C	3180
Boiling point, ^{o}C	5900
Crystal structure	Hexagonal close packed
Lattice constants:	
a, Å	2.760
c, Å	4.458
Ratio c/a	1.615
Atomic number	75
Atomic weight	186.31
Density, g/cm^3	21.02
Vapor pressure at 2000^{o} C, mm	3×10^{-8}
Thermal conductivity at 0^{o} to 100^{o} C, $cal/(cm^2)(cm)(sec)(^{o}C)$	0.17
Electrical resistivity at 20^{o} C, ohm/cm	19.3×10^{-6}
Recrystallization temperature, ^{o}C	[b]1400
Mechanical properties[c]	
Tensile strength (ultimate, annealed), psi	164 000
Yield strength (0.2) offset, psi	135 000
Elongation, percent	28
Modulus of elasticity, psi:	
At 20^{o} C	67×10^{6}
At 900^{o} C	54×10^{6}
Hardness:	
Vicker's annealed	250
30 Percent cold rolled	575
Poisson's ratio	0.49

[a]Ref. 3.

[b]Varies with degree of cold work.

[c]At room temperature unless otherwise specified.

trast to tungsten, however, rhenium is ductile at room temperature. Rhenium is readily oxidized in air, much like tungsten. Rhenium oxides are relatively unstable and decompose at modest temperatures.

The properties of a high modulus of elasticity and hexagonal close-packed crystal structure with a near ideal c/a lattice ratio (1.615 as compared to the ideal value of 1.633) indicate that rhenium might have relatively low adhesion and friction characteristics. The relation between adhesion and these properties is shown in reference 5 and that between friction and crystal structure in reference 6. Rhenium has been evaluated for use in electric contacts (refs. 2 and 7 to 9), and it might be extremely useful for this application in vacuum provided it possesses low friction, adhesion, and wear characteristics in vacuum.

A unique property of rhenium, and one that is not normally associated with hexagonal metals, is its high rate of work hardening (refs. 10 to 12). Rhenium work hardens with deformation at a much greater rate than nickel, which is usually considered to have a high work-hardening rate. The influence of work hardening on metallic junctions formed at sliding interfaces is not clearly understood. Friction experiments with rhenium could therefore assist in gaining a further understanding into the behavior of metals in sliding contact.

This investigation was conducted to determine, in vacuum friction experiments, the coefficient of friction for polycrystalline rhenium sliding on itself, and, with the aid of single crystals, to gain some insight into the deformation and work-hardening behavior of rhenium and their influence on friction.

Experiments were conducted with single-crystal and polycrystalline rhenium sliding on polycrystalline rhenium in vacuum (to 10^{-11} torr). Friction measurements were made at sliding velocities of 0.001 to 700 centimeters per second with loads of 100 to 2500 grams. Data were obtained at specimen temperatures to 680° C.

MATERIALS

The rhenium single-crystal riders used in this investigation were all triple-zone refined with a minimum purity of 99.99 percent. The spectrographic analysis of the polycrystalline rhenium is as follows: iron, 30 parts per million; molybdenum, 25 parts per million; and aluminum, nickel, silicon, calcium, chromium, copper, and magnesium, less than 1 part per million each. The rider specimens were cut from rods. The disks were obtained from rhenium polycrystalline sheet which was recrystallized to minimize preferred orientation effects.

APPARATUS

The basic elements of the apparatus used in this investigation (fig. 1) were the specimens (a 2-in. -diam flat disk of rhenium and a 3/8-in. -diam rider with a hemisphere of 3/16-in. radius on one end) mounted in a vacuum chamber. The disk specimen rotated by means of 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 driver magnet, outside the vacuum system, was coupled to an electric motor. The driver magnet was completely covered with a nickel-alloy housing (cutaway in fig. 1) and was mounted on one end of the shaft within the chamber. The end of the shaft opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm opposite the rider specimen was connected to a strain-gage assembly. The assembly 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 vac-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. 1) for determination of gases present in the vacuum system. A 20-foot, 3/16-inch-diameter stainless-steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

PROCEDURE

The fully annealed rhenium specimens were cut, finish-ground, and lapped prior to electropolishing. The specimen was then electropolished in a proportional solution of phosphoric acid and glycerol to remove the worked layer. After polishing, the single-crystal specimens were mounted in a fixture and Laue patterns of the various orientations were obtained. The orientations indicated in the figures are within $\pm 2^{\circ}$ of those stated. Sliding was always parallel to the plane indicated and in the direction cited.

After the specimens were mounted in the vacuum chamber, the system was evacuated, and the rhenium specimens were electron bombarded for 3 hours to remove adsorbed gases and surface oxides. The disk temperature at this time was approximately 400° C. The specimens were cooled to room temperature before friction experiments. While the specimens cooled to room temperature, liquid-helium cryopumping of the chamber was initiated. With liquid-helium cryopumping the only gas which could be detected by the mass spectrometer was hydrogen.

RESULTS AND DISCUSSION

Friction experiments were conducted with fully annealed polycrystalline rhenium sliding on itself in vacuum at various temperatures. The results obtained in these experiments are presented in figure 2. At specimen temperatures to 680° C, the coefficient of friction exhibited little change. A friction coefficient of approximately 0.4 was obtained over the entire temperature range. There was no evidence or tendency for the rhenium to cold weld. This was expected since rhenium is a hexagonal metal with no known allomorphic transformations. Previous experiments have shown that crystal transformation influences observed friction. For example, with cobalt, transformation from hexagonal to cubic structure resulted in a marked increase in friction and welding of the cobalt in the cubic form (ref. 13). For comparison a friction experiment was conducted with the polycrystalline form of the body-centered cubic metal tantalum sliding on itself. The friction coefficient obtained was 4.0 with subsequent welding of the tantalum specimens occurring, as indicated in figure 2. Tantalum was selected for comparison because of its relative proximity to rhenium in the periodic table. The range of ambient pressure (10^{-8} to 10^{-10} torr) indicated in figure 2 resulted from the heating of rhenium specimens and apparatus components.

Rhenium metal work hardens very rapidly. It might be anticipated that, for clean metals in sliding contact, this tendency to work harden will markedly increase the shear strength of junctions at the sliding interface. The sliding velocity in figure 2 was 0.001 centimeter per second and the load was 250 grams. Increased sliding velocity and/or increased loading increases the strain at the sliding interface. For metals which work harden rapidly, an increase in strain results in an increase in shear stress. Thus, the force to shear junctions at the interface increases. A change in friction coefficient might therefore be expected at some point with changes in these mechanical parameters.

The friction coefficients for polycrystalline rhenium sliding on itself at various loads and speeds are presented in figure 3. At a sliding velocity of 0.001 centimeter per second, a load of 2500 grams was reached before an effect on friction was noted. A one-hundred-fold increase in sliding velocity (0.1 cm/sec) resulted in friction increases at significantly lighter loads than 2500 grams. If, after loading to 2500 grams at a sliding velocity of 0.1 centimeter per second, the load was decreased to 250 grams, the friction coefficient remained high (0.7) indicating that the change at the interface was permanent. This change was believed to be a work hardening of the rhenium causing an increase in the shear strength of the interfacial junctions. Further increases in sliding velocity resulted in further increases in friction coefficient. Figure 3 indicates that an increase of one-hundred-thousand times in sliding velocity was necessary to increase the coefficient of friction from 0.4 to 1.0. In a vacuum environment, the initial friction force is determined by contact area and shear strength of metallic junctions. With clean metal surfaces, the effect of work hardening the metal may not be desirable because shear must occur at junctions with higher shear strengths or in the junction subsurface to the point of contact where a larger area must be sheared. Thus, a hardened surface may be desirable in air or other environments where contaminating surface films are present and where shear takes place in the film because the hard surface serves to support the load and minimize true contact area; however, this is not true for clean metal surfaces. Further, any mechanical action, such as increases in load or speed, increases strain rate and shear stress for work-hardenable metals. This may explain in part, why a tenfold increase in load only increased friction from 0.4 to 0.6.

A relation between the lattice parameters of hexagonal metals and their friction coefficients is shown in reference 6; the curve showing that relation is presented in figure 4 along with the data obtained for rhenium at a load of 1000 grams. The data point falls near the curve indicating that, prior to marked work hardening, rhenium behaves in sliding much like other hexagonal metals (e.g., colbalt). The friction coefficient of rhenium can be related to its lattice parameters.

The anisotropic behavior of hexagonal metals makes single-crystal studies extremely useful in gaining a better understanding of such metals. Single-crystal studies (refs. 10 and 11) indicate that, in mechanical deformation, marked difference in shear and work-hardening characteristics exist for the prismatic and basal orientations of rhenium (see section MATERIALS). Friction experiments were therefore conducted in vacuum with the basal plane and a prismatic plane of rhenium parallel to the sliding interface. In these experiments, single crystals of rhenium slid on polycrystalline rhenium disks.

The results obtained in these experiments are presented in figure 5. Data were obtained on each of the planes in two separate crystallographic directions. The four resulting curves indicate that friction coefficients for all four orientations are relatively unaffected by load changes up to 1000 grams. Any interfacial change such as surface recrystallization could be expected to result in a change in friction coefficient. The friction data of figure 5 indicate that the coefficient of friction for single-crystal rhenium is a definite function of the anisotropy and properties of this metal (for example, the critical resolved shear stress).

Just as with many other hexagonal metals (ref. 6), rhenium exhibits a lower coefficient of friction on the basal plane. It is of further interest that the differences in friction in the two crystallographic directions are markedly greater for the prismatic than for the basal orientations. A difference in friction with direction on a plane might be anticipated since atomic density on a plane differs with changes in direction. The basal and prismatic slip systems are the two found to operate in rhenium in references 10 and 11. Interstitial impurities, however, raise the shear stress in these two crystallographic systems (ref. 11). This is believed to result from the prevention of dislocation dissociation and pegging effects of impurity atoms. Under such conditions, a third

TABLE II. - SHEAR STRESS AND WORK-HARDENING RATE FOR RHENIUM SINGLE CRYSTAL[a]

Orientation	Critical resolved shear stress, kg/mm^2	Rate of work hardening, [b]ds/da, kg/mm^2
Basal (0001)	1.48	27.5
Prismatic	2.18	52.2

[a]Ref. 10.
[b]s, critical resolved shear stress; a, plastic shear strain.

system, the (1011) system, may operate. It was for this reason that the single crystals used in this study were high purity (99.99 percent) zone-refined materials.

Friction experiments were conducted at various sliding velocities in order to gain some insight into the influences of the marked differences in work-hardening rate (table II) on friction coefficients for basal and prismatic orientations of rhenium. The results of these experiments are presented in figure 6. Data for polycrystalline rhenium sliding on itself are also included in figure 6 for reference purposes.

The data of figure 6 indicate a rapid increase in the friction coefficient for the prismatic and polycrystalline rhenium. This rapid rise is believed to be caused by work hardening of the rhenium during sliding. The friction coefficient reaches some maximum value when the material is fully work hardened and further increase in sliding velocity does not result in any notable changes in friction.

The rate of work hardening for the basal orientation of rhenium is about half that of the prismatic orientation (table II). The friction coefficient measured for the basal orientation of rhenium in figure 6 reflects this difference. An increase in friction coefficient was observed with an increase in sliding velocity; however, this change was very gradual. The effect of work-hardening rate on friction coefficient can be seen from comparison of the slope of the three curves presented for sliding velocities to 50 centimeters per second.

In the polycrystalline experiment, after sliding at 700 centimeters per second, the sliding velocity was reduced to 0.001 centimeter per second to determine what effect sliding at high speeds had on the interface. The data point at 0.7 in figure 6 indicates that the friction coefficient was intermediate between the value obtained at 700 centimeters per second and the original friction coefficient obtained at 0.001 centimeter per second. The fact that the friction did not return to its original value indicates that a permanent interfacial change did take place. This change is believed to be caused by work hardening. Why the friction coefficient did not remain 1.0 is not known.

It might normally be anticipated that the work-hardening rate would be higher for polycrystals than for any single-crystal orientation. The work of reference 11 indicates that the high rate of work hardening in rhenium is associated with the intersection of prismatic slip systems. The low stacking fault energy postulated for rhenium would indicate wide faulted regions between dislocation partials. These regions would make movement of prismatic slip plane dislocations more difficult and lead to high work-hardening rates. With the polycrystalline material, random distributions of crystallite orientations can be expected, and any preferred orientation effects would be toward a basal texturing. This would tend to reduce friction from values observed for random orientation of crystallites.

The mechanical action of sliding at an interface can produce a number of changes in nature of the metal surface. Severe deformation, work hardening, texturing, and ultimately recrystallization may occur, depending on the amount of energy involved. With body-centered cubic and close-packed hexagonal metals, mechanical deformation can produce twinning in crystals. Twinning in hexagonal metals occurs along with defined systems, just as does slip.

Rhenium metal is known to twin on the $\{11\bar{2}1\}$, $\{11\bar{2}2\}$, and $\{10\bar{1}2\}$ planes with the $\{11\bar{2}1\}$ planes predominating (refs. 14 and 15). The development of twins adjacent to the wear area on a rhenium single-crystal rider after sliding at high speeds is shown in figure 7. A large number of twins developed as a result of sliding. This twinning was not observed at slow speeds.

SUMMARY OF RESULTS

Based on the friction results obtained in this investigation with single-crystal and polycrystalline rhenium sliding on polycrystalline rhenium in vacuum, the following remarks are made:

1. Friction coefficients for polycrystalline rhenium are comparable to those obtained for other hexagonal metals with similar c/a lattice ratios (e.g., cobalt).

2. The measured friction coefficients for rhenium indicated anisotropic properties. Lowest friction was obtained on the preferred slip system (0001) plane $[11\bar{2}0]$ direction with sliding of rhenium single crystals on polycrystalline rhenium.

3. Rhenium metal did not cold weld in vacuum when sliding on itself. The body-centered cubic metal tantalum, however, which is closely related to rhenium in many of its properties, except crystal structure, did weld.

4. The work-hardening characteristics of rhenium as affected by sliding velocity influenced friction results.

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

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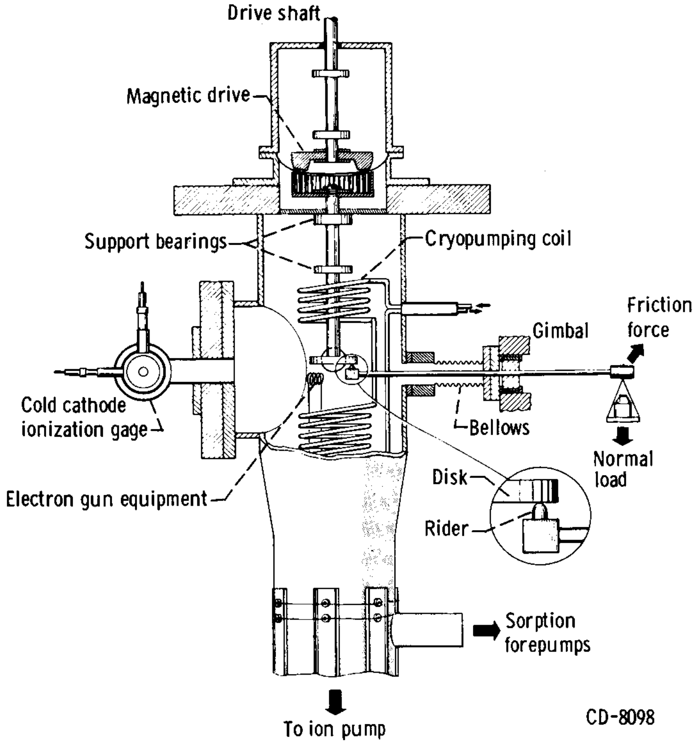

Figure 1. - Vacuum friction apparatus.

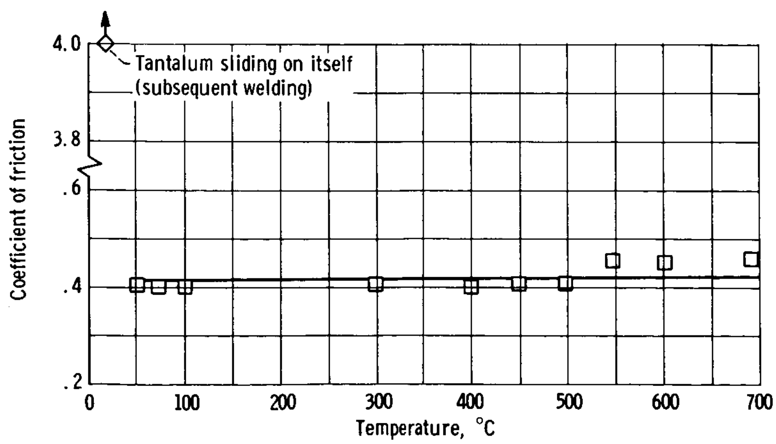

Figure 2. - Coefficient of friction as function of temperature for polycrystalline rhenium sliding on itself in vacuum (10^{-8} to 10^{-10} torr). Data for body-centered cubic tantalum are included for comparison. Sliding velocity, 0.001 centimeter per second; load, 250 grams.

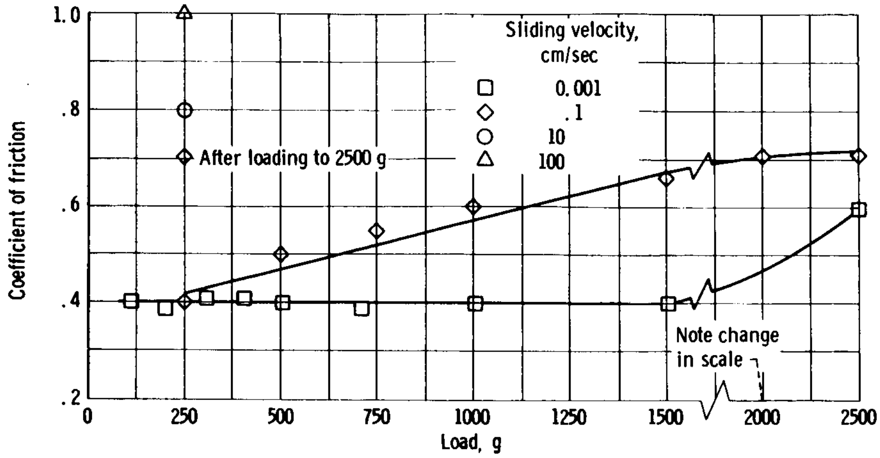

Figure 3. - Coefficient of friction as function of load and speed for polycrystalline rhenium sliding on itself. Ambient pressure, 10^{-11} torr. No external specimen heating.

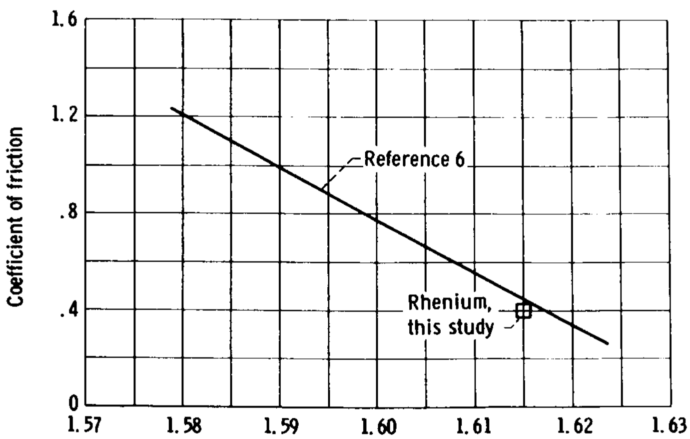

Figure 4. - Influence of lattice parameters on friction coefficients of hexagonal metals sliding on themselves in vacuum (10^{-11} torr).

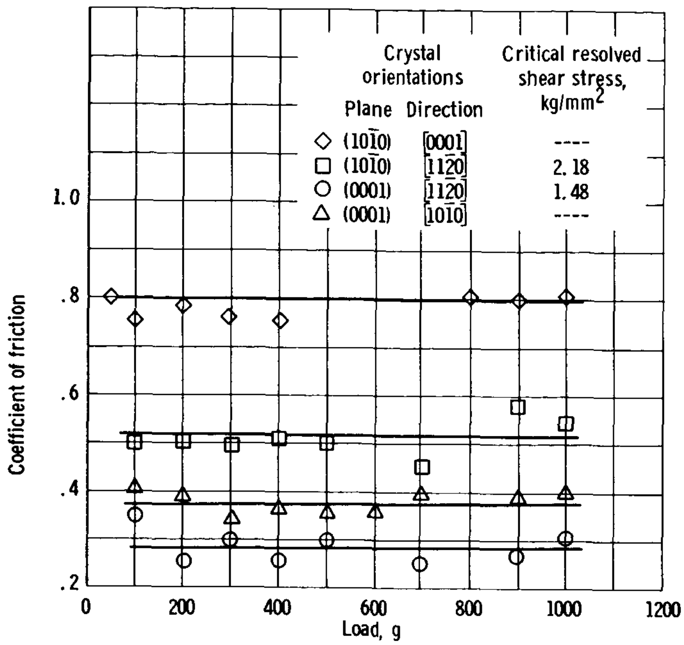

Figure 5. - Coefficient of friction for various orientations of single crystals of rhenium (99.99 percent purity) sliding on polycrystalline rhenium in vacuum (10^{-11} torr). Sliding velocity, 0.001 centimeter per second. No external heating of specimens during experiments.

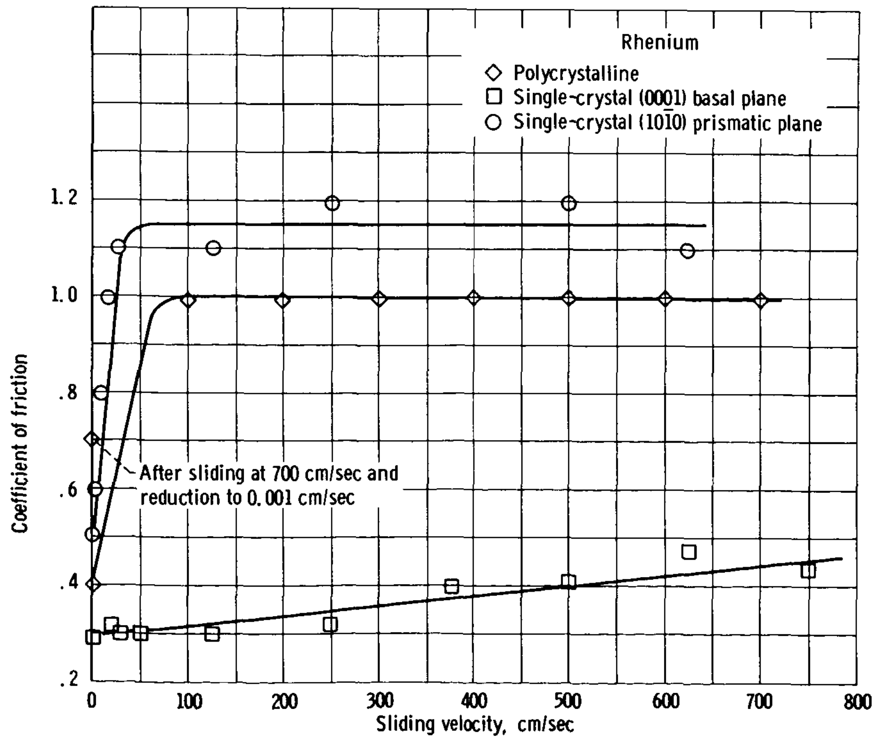

Figure 6. - Coefficient of friction for rhenium sliding on itself at various velocities in vacuum (10^{-10} to 10^{-11} torr). Rider specimens were single and polycrystalline; all disks were polycrystalline. Load, 250 grams; ambient temperature, 20° C.

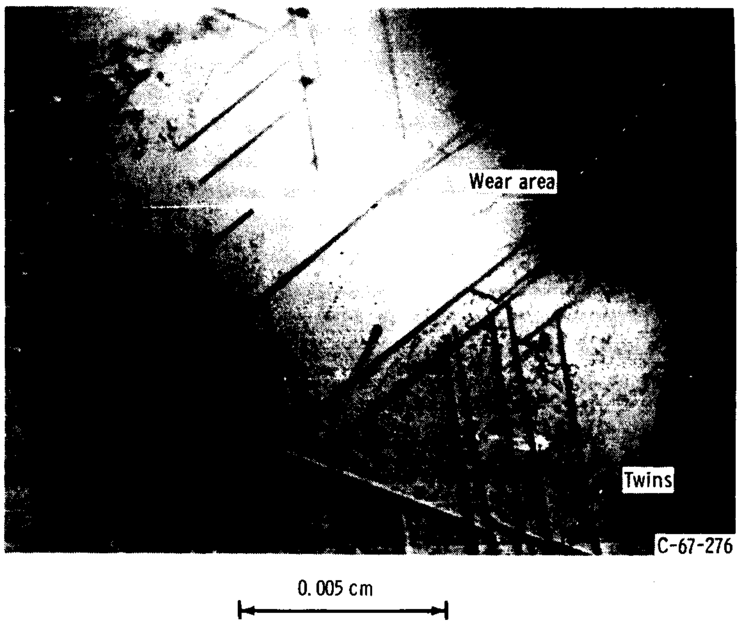

Figure 7. - Photomicrograph showing development of twins adjacent to wear scar of rhenium single crystal after loading to 1000 grams.

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