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INFLUENCE OF NUMBER OF OPERABLE SLIP SYSTEMS ON FRICTION CHARACTERISTICS OF SINGLE-CRYSTAL AND POLYCRYSTALLINE MAGNESIUM

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SUMMARY

An investigation was conducted to determine the influences of a change in the number of operable slip systems in magnesium on its friction behavior. Friction experiments were conducted with a hemisphere sliding on a flat disk surface. The load was 50 grams and the sliding velocity was 0.001 centimeter per second. Single crystals of basal and prismatic orientations and polycrystalline magnesium were examined over the temperature range of -195° to 90° C.

The results of this investigation indicate that the friction properties of magnesium, like other hexagonal metals, are anisotropic. Friction is lower on the basal than on the prismatic plane by a factor of 2. Multiple slip introduces greater ductility in polycrystalline magnesium and increases the friction. Friction is the lowest for polycrystalline magnesium at those temperatures where basal slip is the primary deformation slip mechanism.

INTRODUCTION

The friction characteristics of metals are markedly dependent on crystal structure and hexagonal metals, in general, exhibit lower friction and wear than do cubic metals (refs. 1 and 2). Furthermore, for hexagonal metals, a relation between slip behavior and friction properties has been established. Those metals exhibiting primarily basal slip (e.g., cobalt, beryllium, rhenium, etc.) at room temperature have lower friction coefficients than metals such as titanium, which slip primarily on prismatic and pyramidal planes. This difference in friction can be explained on the basis of the number of operable slip systems in the metal. The metals that exhibit basal slip have a total of three slip systems, while metals such as titanium have a total of nine slip systems. The greater the number of slip systems, the more likely it is that one will be favorably oriented under an applied stress to permit deformation. The hexagonal metals with only three systems are therefore less ductile than those with nine, such as titanium (refs. 3 and 4).

Magnesium is an interesting hexagonal metal with respect to slip behavior. At room temperature and below, magnesium slips primarily on the basal plane (three slip systems), but above room temperature, it slips on prismatic and pyramidal planes as well (refs. 3 to 5). Thus, a study of magnesium makes it possible, through an examination of its friction properties over a range of temperatures, to determine the effect of the number of operable slip systems on friction. Until now, this effect has been shown by comparing friction results for the hexagonal metal, titanium, and by alloying (refs. 1 and 2).

The present investigation was conducted to determine (1) the influence of the number of slip systems operating in magnesium on friction and (2) the effect of orientation of crystals on friction behavior. Experiments were conducted with both single-crystal and polycrystalline materials in a vacuum environment of 10^{-10} to 10^{-11} torr (1.33×10^{-8} to 1.33×10^{-9} N/m^2) and at specimen temperatures ranging from -195° to 90° C. The specimen configuration was a hemisphere that slid on a flat disk surface. The load was 50 grams and the sliding velocity was 0.001 centimeter per second.

MATERIALS

The single-crystal and polycrystalline magnesium used in this investigation was 99.99 percent pure. The materials were finished to the desired geometry and annealed in evacuated quartz tubes. All surfaces were electropolished, and the single-crystal orientations were determined by Laue back reflection X-ray technique. The orientations indicated are within $\pm2^{\circ}$.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens, which included a 1.27-centimeter-diameter flat disk mounted in a 6.35-centimeter-diameter disk holder and a 0.50-centimeter-radius rider, mounted in a vacuum chamber. The disk specimen was driven by a magnetic-drive coupling, consisting of two 20-pole magnets 0.381 centimeter apart with a 0.076-centimeter diaphragm between magnet faces. The extended driver magnet was coupled to an electric motor. The driven magnet was shrouded completely with a nickel-alloy

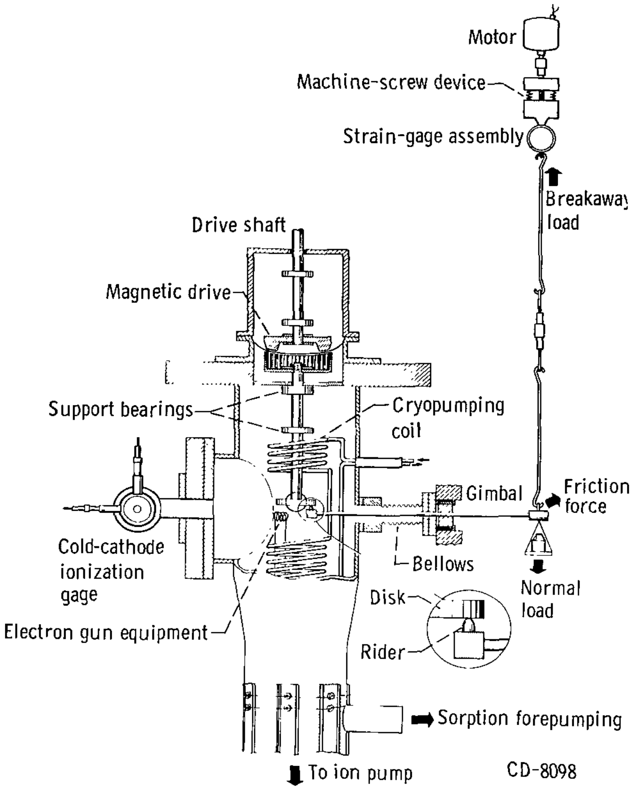


Figure 1. - Vacuum friction apparatus.

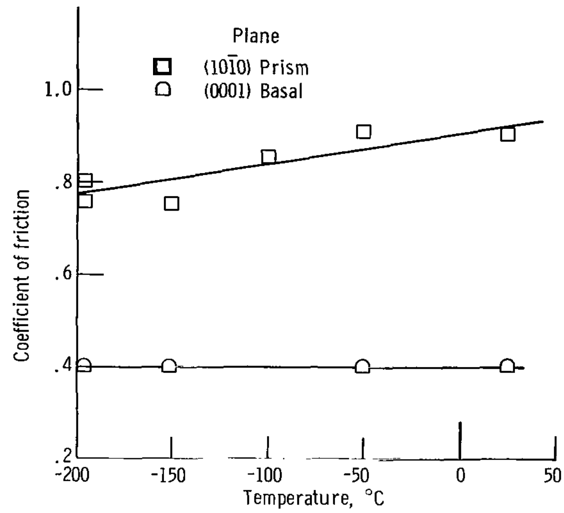


Figure 2. - Effect of temperature on coefficient of friction for single-crystal magnesium sliding on polycrystalline magnesium. Load, 20 grams; sliding velocity, 0.001 centimeter per second; ambient pressure, 10^{-10} torr (1.33×10^{-8} N/m^2).

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. The load was applied through a deadweight loading system.

Attached to the lower end of the specimen chamber was an 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 the determination of gases present in the vacuum system. A 7.0-meter, 0.762-centimeter-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 were obtained to determine their 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 (1.33×10^{-1} N/m^2) 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 and were then cooled to the desired temperature immediately prior to the start of the experiments.

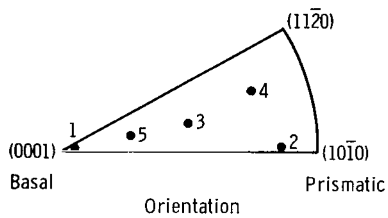
The contact time under load for simple adhesion experiments was 10 seconds. In sliding, the total distance slid was held at a constant 0.735 centimeter, and the velocity was 0.001 centimeter per second. The breakaway force after sliding was measured immediately after sliding had ceased. When the specimens broke more than once, a 10-second contact time interval was used.

RESULTS AND DISCUSSION

Single-Crystal Magnesium

Magnesium has a lattice ratio c/a of 1.624, which is near the ideal stacking ratio of hexagonal metals of 1.633. Therefore, magnesium slips primarily on basal planes (refs. 3 to 6) at room temperature and below (refs. 5 and 7 to 9), as indicated by experimental evidence. It might also be anticipated, in light of other experimental friction results, that friction could be lower on basal than on other planes in magnesium when it is sliding in the preferred slip direction (ref. 10).

Friction experiments were conducted with single-crystal magnesium sliding on polycrystalline magnesium in a vacuum of 10^{-10} to 10^{-11} torr (1.33×10^{-8} to 1.33×10^{-9} N/m^2) over a range of temperatures from -195° to 25° C. The two single-crystal orientations examined were the basal plane (0001) and the prismatic plane $(10\bar{1}0)$ sliding parallel to the interface in the preferred slip direction $\langle 11\bar{2}0\rangle$. The friction results obtained are presented in figure 2 (p. 3), an examination of which indicates a twofold difference in the friction for the two orientations of magnesium. The friction for the basal orientation is constant over the range of temperatures examined. These data are in agreement with shear data presented in reference 3, which indicates that initial resolved shear stress is constant over the same temperature range -195° to 25° C for the basal orientation. The prismatic orientation, however, shows an increase in friction with an increase in temperature (fig. 2). With an increase in temperature from -195° C, the shear stress increases as room temperature is approached. It might normally be expected that friction should also decrease. This decrease would occur if only prismatic slip were involved, but as



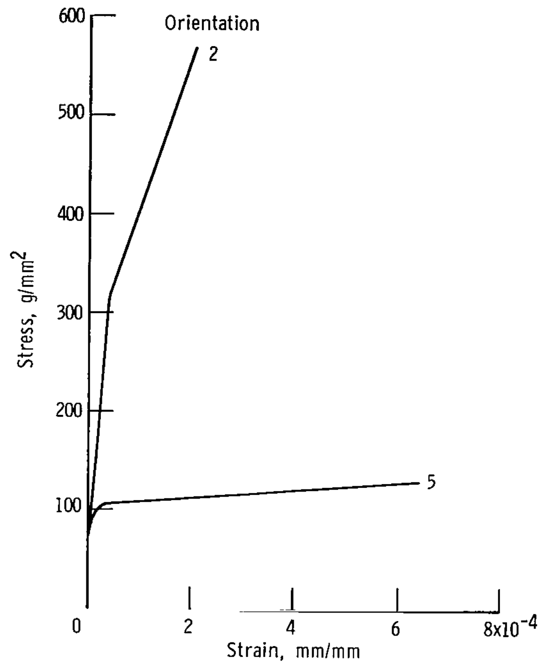


Figure 3. - Effect of orientation of single-crystal magnesium on yield stress, shear stress, and strain hardening. (Data taken from ref. 7.)

TABLE I. - INFLUENCE OF ORIENTATION ON YIELD AND CRITICAL RESOLVED SHEAR STRESS

Crystal orientation *see fig. 3	Yield stress, g/mm^2	Critical resolved shear stress, g/mm^2
1	348	42.5
2	307	47.5
3	106	49.7
4	193	46.0
5	110	48.5

the temperature is increased, pyramidal slip also becomes operative. Thus, with deformation, increases in temperature bring a greater number of slip systems into operation.

The influence of orientation and slip systems on friction is best illustrated in figure 3 (data from ref. 5). An examination of the unit triangle of figure 3 indicates that, for the basal orientation (crystal orientation 1) with the basal plane near normal to the crystal axis (basal orientation of fig. 2), the yield stress is the highest and the shear stress the lowest of those orientations examined in the unit triangle of figure 3 (see data in table I). Since friction force is determined by the area in contact and the shear, it might be expected that, of all the orientations indicated in the unit triangle and in the table of figure 3, the basal orientation should have the lowest friction coefficient under a constant load.

If friction force is calculated with the use of the yield and shear strengths from table I, the difference in friction for the basal (crystal orientation 1) and prismatic orientation (orientation 2) would not be so great as that indicated in figure 3. Thus, factors other than shear stress and contact area (as determined by yield stress) must influence friction. One factor which changes is shear stress with strain hardening for various orientations (more commonly termed work hardening). The stress-strain curves for two single-crystal orientations of magnesium (2 and 5 in the unit triangle) are presented in figure 3. Orientation 2, near the prismatic plane, exhibits a markedly greater increase in shear stress with small amounts of strain than does orientation 5, near the basal plane. The difference in the slopes of figure 3 could account for the difference in friction for the two orientations of figure 2 (p. 3). (See refs. 7 and 11 for a discussion of work hardening in magnesium.)

The possibility of brittle behavior at cryogenic temperatures exists with metals (ref. 12). If metals in sliding friction behave in a brittle manner at the sliding interface, then concern should be given to cleavage rather than to slip behavior. Cleavage can be induced in hexagonal-close-packed metals which are extremely ductile if stress is applied perpendicular to the basal plane. This (0001) plane in magnesium at cryogenic temperatures is both the slip and the cleavage plane; however, at 20° C the $(10\bar{1}2)$ plane is the cleavage plane. When a tensile stress is applied normal to the plane, the component available for initiating slip is less than the critical stress for slip. Nothing then prevents the stress from increasing until the cohesive forces between basal planes are overcome. In the sliding friction process, the force on the basal plane is a resultant of two forces: (1) the applied compressive force (in the form of load) which is normal to the plane and (2) the friction force. Consequently, slip could be expected to occur more readily with sliding surfaces than it would in a tensile test. After the cryogenic experiments, the surface of the basally oriented single crystal was examined for cleavage cracks, but none were found in or about the contact area, which indicates plastic behavior without cleavage in sliding friction for magnesium at -195° C.

Polycrystalline Magnesium

With polycrystalline metals, the presence of grain boundaries can be expected to influence deformation and friction. Friction coefficients were measured for polycrystalline magnesium in sliding contact with itself over the range of temperatures from -195° to 90° C. The results obtained in these experiments are presented in figure 4. An examination of this figure indicates that at -195° C the friction for polycrystalline magnesium is higher than it is for basally oriented single-crystal magnesium (fig. 2, p. 3). The crystallites of the polycrystal are randomly oriented, with grain boundaries acting as barriers to slip and shear; hence, friction is higher for the polycrystal than for the basally oriented single crystal.

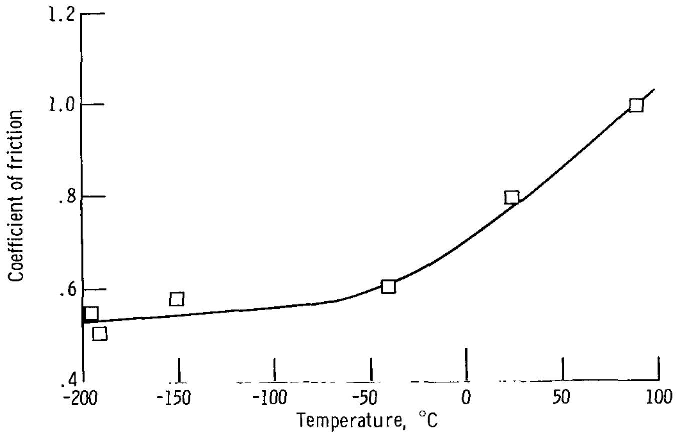


Figure 4. - Coefficient of friction for polycrystalline magnesium sliding on polycrystalline magnesium in vacuum at various temperatures. Load, 50 grams; sliding velocity, 0.001 centimeter per second; ambient pressure, 10^{-10} torr (1.33×10^{-8} N/m^2).

The friction coefficient of polycrystalline magnesium increases with an increase in temperature. The friction increases rapidly above -50° C; multiple slip is observed in normal tensile studies at about 20° C. The sharp increase in friction above -50° C is believed to be caused by multiple slip, which facilitates plastic deformation. The friction data at 20° C represent an appreciable increase in friction from the value obtained at -50° C. For some time it was believed that nonbasal slip did not occur with magnesium below 225° C; however, more recent studies indicate that it occurs at 20° C. These data and those of reference 13 for ductility indicate that nonbasal slip may occur at even lower temperatures.

Further evidence of the effect of multiple slip on the mechanical behavior of polycrystalline magnesium is gained from measurements of magnesium ductility as a function

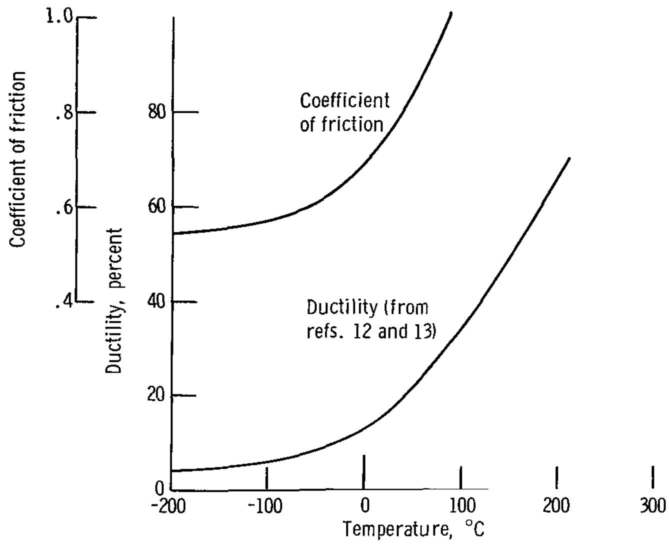


Figure 5. - Coefficient of friction and ductility for polycrystalline magnesium.

of temperature (data from refs. 12 and 13). The ductility data of polycrystalline magnesium together with friction data are presented in figure 5. As multiple slip becomes effective, a noted increase in both ductility and friction occurs. The more ductile magnesium becomes, the greater is its friction. Thus, at -195° C magnesium is relatively brittle and is easier to shear.

It was mentioned earlier that no evidence of cracks due to brittle fracture were observed in magnesium on or near the sliding track over the temperature range -125° to 90° C. (See the photomicrograph of fig. 6.) The wear track appears to be formed by simple plastic deformation; however, it is somewhat different in nature from that formed at room temperature. At room temperature the entire width of the track shows evidence of deformation. In figure 6, the deformation appears to occur only at points of contact that are deformed markedly less at -195° C and have the raked appearance shown in the figure.

Also of interest in figure 6 is that the rider passed over a junction of the boundary of three grains. Wherever the rider passed over grain boundaries, the surface deformation was noticeably reduced, as shown in the figure. This reduction is believed to occur because deformation of the grain and movement of the rider across the grain cause dislocations to build up at the grain boundary. This buildup results in a hardening of the boundary area, which gives it greater resistance to deformation. Dislocation buildup at grain boundaries is discussed in detail in reference 12.

The influence of repeated passes over the same surface on the friction behavior of randomly oriented polycrystalline copper is discussed in references 1 and 10. General-

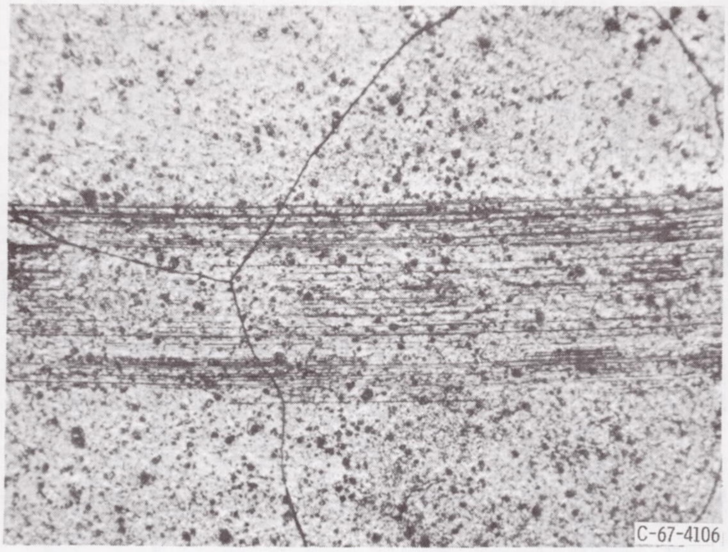


Figure 6. - Photomicrograph of polycrystalline magnesium wear scar. Load, 50 grams; sliding velocity, 0.001 centimeter per second; ambient pressure, 10^{-11} torr (1.33×10^{-9} N/m^2); ambient temperature, -195° C; rider, polycrystalline magnesium.

ly, at some load, speed, or surface temperature, the energy input to a surface is sufficient from combined mechanical and thermal effects to bring about localized surface recrystallization and texturing of polycrystalline metals. With this recrystallization (of randomly oriented polycrystalline materials) and texturing, marked changes in friction are observed. In reference 1, changes in interfacial energy were achieved by changing the load and holding other parameters constant. In the present experiments for magnesium, friction was measured as a function of surface passes over the same track at any one temperature. The results obtained are presented in figure 7.

The friction data of figure 7 were obtained with a load of 50 grams. This load was selected because recrystallization could be achieved at room temperature. Examination of the data of figure 7 indicates that the randomly oriented polycrystal exhibits a friction coefficient greater than 3.0 at 25° C. After four passes over the same track, the wear track is completely recrystallized and textured (as shown by the reduction in friction), and no further changes in friction are observed. Texturing of the surface was also identified by X-ray analysis after the eight passes. At 90° C, only two passes were required to complete surface recrystallization and texturing. This recrystallization and texturing is to be expected since increasing the temperature requires less deformation to achieve recrystallization. When the temperature is decreased to -195° C, the friction coefficient is unchanged because the interface does not deform and heat sufficiently to bring about surface recrystallization. The friction therefore remains unchanged through eight passes over the same surface.

The sixfold difference in friction coefficient for 90° and -195° C curves during the

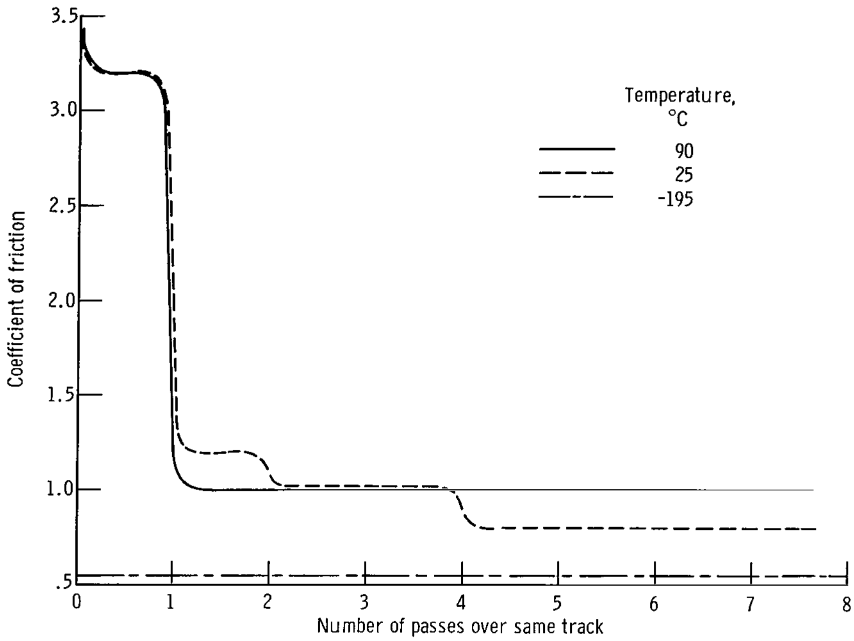


Figure 7. - Coefficient of friction for polycrystalline magnesium sliding on polycrystalline magnesium in vacuum at various temperatures. Load, 50 grams; sliding velocity, 0.001 centimeter per second; ambient pressure, 10^{-10} torr (1.33×10^{-8} N/m^2).

first pass of figure 7 may be attributed to the two interrelated factors: (1) multiple slip as opposed to single slip and (2) the associated marked difference in ductility of the magnesium at these two temperatures.

The friction data obtained for magnesium in its polycrystalline form at -195° C is comparable with those obtained for other polycrystalline hexagonal metals exhibiting basal slip when measurements for these metals are made at room temperature. The friction coefficients for the hexagonal metals, cobalt, rhenium, beryllium, ruthenium, and osmium, are all between 0. 35 and 0. 55 in vacuum at room temperature. At room temperature, magnesium with its multiple slip behaves more like titanium (also multiple slip) in its friction properties.

SUMMARY OF RESULTS

In an investigation of the influence of the number of operable slip systems on friction characteristics of single and polycrystalline magnesium, the following results were obtained:

1. For polycrystalline magnesium the number of operative slip systems markedly influences the friction coefficient. At -195° C where the basal slip mechanism is pre-

dominant, friction is comparable with other hexagonal metals exhibiting primarily basal slip. At room temperature and above, the increase in operable slip planes (prismatic and pyramidal) increases the ability of the material to deform, and increases in friction are observed.

2. For single-crystal magnesium, a twofold or greater difference in friction coefficient exists for the basal and prismatic orientations over the temperature range of -195° to 25° C; the basal orientation had the lower friction. These results are in agreement with other related mechanical properties and friction observations for other hexagonal single-crystal metals.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 24, 1967,
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