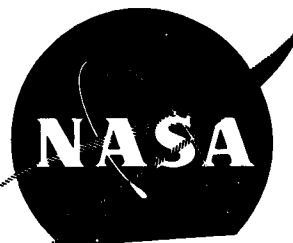


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by Donald H. Buckley and Robert L. Johnson

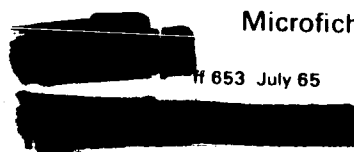
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FRICITION AND WEAR OF HEXAGONAL METALS AND ALLOYS AS RELATED
TO CRYSTAL STRUCTURE AND LATTICE PARAMETERS IN VACUUM
TO 10^{-10} MILLIMETER OF MERCURY

by Donald H. Buckley and Robert L. Johnson

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

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The friction and wear characteristics were determined for fourteen hexagonal metals in vacuum at temperatures to 850 F and sliding speeds to 2000 feet per minute. The metal examined included cobalt, titanium, zirconium, hafnium, beryllium, the rare earth metals, and binary alloys of some of these with other elements. Single crystals of cobalt were also examined to determine the influence of specifically oriented planes on friction. Differences in friction properties of these metals (e.g. cobalt and titanium) were found to be related to crystal slip systems and associated shear. Friction coefficients are further related to lattice parameters for fourteen hexagonal metals. For those hexagonal metals undergoing crystal transformation to a cubic form at elevated temperatures, marked changes were observed in friction and wear with the crystal transformation. While relatively moderate friction and wear is observed for the hexagonal form, high friction and complete welding is observed for the cubic structures. Selective alloying of other elements with these hexagonal metals was found to expand the crystal lattice and to delay crystal transformation, thereby improving friction and wear characteristics.

Authors

INTRODUCTION

The friction and adhesion characteristics of metals are markedly influenced by changes in physical and mechanical properties of these materials. In reference 1, for example, a correlation was shown for the adhesion of metals with hardness, Young's modulus, surface energy, crystal structure, and other factors. Much of the other data in literature on the effects of bulk properties of slider materials on friction and wear is misleading because surface reaction films such as oxides have a predominant role in research studies performed. In reference 2 with the rare earth metals, examination of individual metals that underwent a crystal transformation revealed a correlation between friction behavior in vacuum and crystal structure. When metals were in a hexagonal crystal form, relatively low friction was observed. If, however, the temperature was changed to beyond that for transformation to either body or face centered cubic a marked increase in friction and complete welding of materials was noted.

The marked change in friction properties of these metals was believed to be due to difference in crystallographic slip behavior. While with nearly ideal hexagonal metals a single slip plane and only three slip systems may operate, in the face-centered cubic there are twelve slip systems and in the body-centered cubic forty eight. With the greater number of slip systems, a higher number of slip plane and dislocation interactions can occur producing blocking of slip planes and dislocation motion. These factors produce changes in deformation characteristics and mechanical properties of metals.

There are a number of hexagonal metals in the transition series of elements. Many of these metals may be useful for lubrication systems. Since

in vacuum the hexagonal form of the rare earth metals exhibit superior friction characteristics to the cubic form, it would be useful to know more about the friction behavior of the transition hexagonal metals. For example, cobalt is known to undergo a crystal transformation from close packed hexagonal to a face-centered-cubic structure.

The objectives of this investigation were to determine in vacuum; (1) the influence of crystal transformation on the friction characteristics of a transition element, (2) the effect of alloying elements on the transformation and friction, (3) the effect of slip systems on the friction of a number of hexagonal transition metals, and (4) the influence of lattice parameter for a number of hexagonal metals on friction. Friction experiments were conducted in a vacuum (10^{-9} to 10^{-10} mm Hg) with a hemispherically tipped rider specimen sliding on the flat surface of a rotating disk. The metals examined included cobalt (single and polycrystalline), titanium, zirconium, hafnium, beryllium, and the rare earth metals. Alloys of cobalt with molybdenum, titanium with oxygen, and titanium with tin were also studied.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens (a $2\frac{1}{2}$ -in.-diam. flat disk and a $3/16$ -in.-rad. rider) mounted in a vacuum chamber. The disk specimen was driven through 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 that was outside the vacuum system was coupled to a hydraulic motor. 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 400-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 present in the vacuum system. A 20-foot-long stainless-steel coil of 5/16-inch-diameter tubing was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

In experiments where external heating of the specimens was required, a wire-wound tantalum heater was placed adjacent to the circumferential edge of the disk specimen (fig. 1). A thermocouple was inserted in the rider and the bulk specimen temperature recorded. No attempt was made to record interface temperatures.

Specimen Preparation

The polycrystalline cobalt used in this investigation was prepared from electrolytic cobalt. Electrolytic cobalt chips were packed into a zirconium oxide crucible and placed into an induction vacuum furnace, which was then evacuated. The furnace was then back filled with dry argon, and the cobalt was raised to a temperature of 2800 F. The cobalt was then poured into a copper mold and cooled to room temperature. The chemical analysis of the resulting

casting is presented in table I. The nickel and the iron specimens used in this investigation were prepared in a similar manner. After they were machined to required dimensions and surface finishing, the cobalt specimens were heat treated for 4 hours at 750 F and checked by X-ray diffraction to minimize the concentration of face-centered form. This particular heat treatment was employed because, as stated in reference 3, the amount of face-centered-cubic structure that may be present at room temperature can vary from 5 to 30 volume percent depending upon the thermal history of the material.

TABLE I. - COMPOSITION OF COBALT USED
IN FRICTION AND WEAR STUDIES

Element	Weight percent
Oxygen	0.026
Zirconium	.02
Nickel	.02
Iron	.01
Copper	.03
Carbon	.0094

The metals, beryllium, zirconium, hafnium, and titanium used in this study were 99.99 percent pure and were used as received. A commercially pure titanium was also examined in vacuum sliding friction experiments (99.2 percent). The rare earth metals were 99.9 percent pure.

Alloy Preparation

The titanium alloys used in this investigation, titanium-tin, titanium-oxygen, and titanium-zirconium, were all arc-cast under reduced argon pressure. Small pieces of the metal to be cast were placed in a water-cooled copper mold and arc-melted with a tungsten electrode. The specimen was then turned over in

the mold and remelted. This process was repeated a number of times to ensure homogeneity in the casting. After the alloys cooled, they were removed and metallographic as well as chemical analyses were made. Friction and wear specimens were then prepared. In order to ensure a maximum hexagonal form, all samples were sealed in evacuated quartz tubes and heat treated at 1400 F (650 C) for 72 hours.

Specimen Finish and Cleaning Procedure

The disk and the rider specimens used in friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and the rider were given the same preparatory treatment:

- (1) A thorough rinsing with acetone to remove oil and grease
- (2) A polishing with moist levigated alumina on a soft polishing cloth
- (3) A thorough rinsing with tap water followed by distilled water

For each experiment, a new set of specimens was used.

RESULTS AND DISCUSSION

Cobalt Sliding on Cobalt

Some friction experiments were conducted in vacuum with cobalt sliding on cobalt. Experiments were conducted to determine friction characteristics both as a function of sliding velocity and of ambient temperature. The results obtained in these experiments are presented in figures 2 and 3. In figure 2 an increase in sliding velocity resulted in an increase in friction coefficient at 1500 feet per minute. The increase in coefficient of friction at this sliding velocity is due to the transformation of cobalt from the hexagonal crystal form to the face-centered-cubic structure. The transformation, however reflects a transformation of only the rider specimen from the hexagonal to the

cubic form. In these friction studies the rider specimen is in continuous sliding contact and represents only one-twentieth of the mass of the disk specimen; consequently, it experiences much higher bulk temperatures than the disk specimen, which is in intermittent contact. At sliding velocities below 1200 feet per minute, a predominantly hexagonal crystal form is sliding on a predominantly hexagonal crystal form. At sliding velocities in excess of 1500 feet per minute, a predominantly face-centered-cubic structure is sliding on a predominantly hexagonal crystal form. Bulk rider-specimen temperatures measured during the experiment were 670 F at 1250 feet per minute and 770 F at 1500 feet per minute (fig. 2). At the higher sliding velocity, the temperature of the rider was in the region associated with the crystal transformation (refs. 4 to 6) from hexagonal to face-centered-cubic cobalt.

Friction data obtained for cobalt sliding on cobalt at various ambient temperatures are presented in figure 3. The coefficient of friction for cobalt sliding on cobalt was approximately 0.3 at ambient temperatures to 550 F in vacuum. Above 550 F, the friction coefficient began to increase very rapidly. At an ambient temperature of 850 F (above the temperature for crystal transformation), a friction coefficient of 1.5 was recorded; subsequently, complete welding of the disk and the rider specimen occurred. At temperatures below 550 F, the hexagonal crystal form of cobalt is sliding on the hexagonal crystal form of cobalt. Above 550 F, the influence of the transformation is observed, above 850 F, face-centered-cubic cobalt is sliding on face-centered-cubic cobalt. The effect of the transformation is observed at 550 F bulk temperature (250 F below transformation) because of a difference in thermocouple temperatures and the interface temperature. From the observed value it appears to be about 250 F.

It is of interest to note that in sliding velocity experiments where only one of the specimens (the rider) transformed from the hexagonal to the face-centered-cubic structure, the maximum friction coefficient obtained was 0.7. In the increasing temperature experiments, however, where the temperature of both specimens reached the transformation temperature, the friction coefficient was 1.5 with complete welding occurring. With cobalt sliding on cobalt, the results of these experiments indicate that the lowest coefficient of friction is obtained with the hexagonal crystal form sliding on the hexagonal crystal form.

The crystal transformation for cobalt is reversible as indicated in references 3, 4, 7 and 8. This reversible nature of the transformation is reflected in the friction data point shown in figure 3 at 75 F after the specimens were cooled slowly in vacuum from 850 F.

Separate wear experiments were conducted at two ambient temperatures (500 and 700 F) with cobalt sliding on cobalt in order to determine the influence of the transformation on wear. The rider wear values obtained at these two temperatures are also presented in figure 3. The rider wear rate at 500 F (hexagonal cobalt) was about one percent of that at 700 F. Wear was measured at 700 F rather than at 850 F because of the complete welding obtained at 850 F (cubic cobalt).

Oriented Cobalt Single Crystals

It has been demonstrated in the literature (refs. 9 and 10) that various crystal surfaces of copper exhibit differences in friction characteristics. If such differences exist for a cubic metal like copper, they must also exist for hexagonal metals such as cobalt. For hexagonal metals in which there are

strong tendencies for orientation, knowledge of the friction characteristics of various planes would be helpful.

Since crystal structure influences the friction characteristics of cobalt, the influence of orientation effects on a single crystal of cobalt was investigated. It is known that close-packed hexagonal metals with lattice dimensions giving lattice ratios c/a of 1.633 slip in compression along the 0001 basal plane (fig. 4). If the crystal dimensions are such that the c/a ratio is less than 1.633, slip can occur along planes other than the basal plane (0001). Friction data were obtained for two single crystals of cobalt sliding on polycrystalline cobalt. One rider specimen was oriented with the 0001 basal plane parallel to the direction of sliding and the other with the 1100 plane parallel to the direction of sliding. The deviation was $\pm 2^\circ$ as indicated by the single-crystal supplier. The single crystals were examined at a low speed (4.5 ft/min) and at a light load (250 g) to inhibit conversion to the polycrystalline state (fig. 5). When the basal plane (0001) was parallel to the direction of sliding, the final friction coefficient was lower than that obtained with the 1100 plane parallel to the direction of sliding. The initially high friction (>0.6) for the 0001 plane oriented crystal and the initially low friction for the (1100) oriented crystal may be due to orientation deviations.

In hexagonal close-packed metals having c/a ratios of less than 1.633, the lattice is compressed along the c -axis, which tends to make the basal planes less favorable for slip inasmuch as the compression reduces the interplanar spacing. It has been experimentally demonstrated for titanium (a metal with a c/a ratio of less than 1.633) that slip occurs in the $[11\bar{2}0]$ close-packed direction when the $10\bar{1}0$ plane is highly stressed (refs. 11 and

12). It is stated in reference 11 that the slip plane for titanium are $(10\bar{1}0)$ and $(10\bar{1}1)$ and that no matter how complex the deformation in no case was slip on the basal plane (0001) .

Metals like magnesium and cobalt are, however, borderline cases with reference to modes of slip. Both metals have c/a ratios of 1.62 or very close to the normal 1.633 required for basal slip. These metals may, therefore, have one or two modes of slip. Reference 13 indicates that for magnesium basal slip occurs almost exclusively at room temperature, while at elevated temperatures both pyramidal and basal slip occur. A similar mechanism may prevail for cobalt with basal slip at room temperature (ref. 14). The friction data of figure 5 would seem to substantiate this mechanism, since friction was lower for slip along the (0001) or basal plane in cobalt. The load of 250 grams used in figure 5 was deliberately kept light to avoid recrystallization.

Molybdenum-Cobalt Alloys

The crystal transformation temperature of cobalt can be influenced by the presence of alloying elements as indicated in references 5 and 15 to 18. In reference 15, it is indicated that the presence of 1 to 2 percent molybdenum in cobalt can shift the crystal transformation temperature of cobalt from 760 to 464 F and the presence of 25 percent molybdenum will inhibit the hexagonal to cubic transformation. Two molybdenum-cobalt alloys that contained nominally 2 and 25 percent molybdenum were therefore prepared. These alloys were cast. Chemical analysis of the compositions revealed that the 25 percent alloy actually contained 24.4 percent molybdenum and the 2 percent alloy, 2.1 percent molybdenum. These alloys are simple solid solutions.

The two molybdenum-cobalt alloys were examined in vacuum friction experiments at various sliding velocities. The results of these experiments are presented in figure 6. With the 25 percent molybdenum-cobalt alloy (fig. 6(a)), the coefficient of friction remained low (approximately 0.3) at sliding velocities to 2100 feet per minute, well beyond the region where crystal transformation resulted in a marked increase in friction with cobalt sliding on itself. The data would seem to indicate that the desirable friction properties of the hexagonal form of cobalt can be retained by selective alloying.

The friction data obtained with the 2 percent molybdenum-cobalt alloy are also presented in figure 6. With this alloy, the change in friction was observed at the same sliding velocity as was noted with cobalt sliding on cobalt (fig. 2). It was anticipated that with a 300 F shift in crystal transformation temperature the change in friction would have occurred at a lower sliding velocity. Figure 6(b) suggests that a transformation did take place at a slightly lower temperature for the 2 percent molybdenum-cobalt alloy than for the unalloyed cobalt.

TITANIUM

The friction characteristics were determined for titanium metal in a vacuum environment (fig. 7). The friction coefficient decreased slightly with increase in sliding velocity; a value of about 0.6 was obtained at sliding velocities in excess of 750 feet per minute. Examination of table II

TABLE II. - CRYSTALLINE PROPERTIES OF VARIOUS HEXAGONAL METALS

Metal	Atomic radius, Å	Interatomic distance		Lattice ratio, c/a	Slip plane	Slip direction	Critical resolved shear stress, kg/sq cm	Reference
		a, Å	c, Å					
Cobalt	1.162	2.502	4.061	1.624	(0001)	[21 $\bar{1}$ 0]	0.675	7
Hafnium	1.442	3.200	5.077	1.587	(10 $\bar{1}$ 0)	-----	-----	24
Beryllium	.889	2.281	3.577	1.568	{ ^a (0001) (10 $\bar{1}$ 0)}	{[11 $\bar{2}$ 0] [11 $\bar{2}$ 0]}	{1.40 6.69}	25
Zirconium	1.454	3.223	5.123	1.592	{ ^a (10 $\bar{1}$ 0) (0001)}	{[11 $\bar{2}$ 0] [11 $\bar{2}$ 0]}	{---- ----}	24
Titanium	1.324	2.953	4.729	1.587	{ ^a (10 $\bar{1}$ 0) (0001)}	{[11 $\bar{2}$ 0] [11 $\bar{2}$ 0]}	{5.0 11.0}	11,12,20

^a Predominant slip plane at room temperature.

indicates much higher shear stress associated with titanium in the 10 $\bar{1}$ 0 planes than with other hexagonal metals along the basal plane. In the hexagonal metals having basal glide or slip, only one plane is involved, while with titanium there are a number of prismatic planes. With an increased number of possible slip systems, an increase in blocking of dislocations and strain hardening might be anticipated. Reference 19 indicates that this in fact is the case, that is, a high degree of strain hardening is observed for cubic metals (e.g., nickel and copper), while very little is observed for the hexagonal metals, magnesium, zinc, and cadmium.

The friction coefficient for titanium is higher than that obtained with the hexagonal metal cobalt. Cobalt has crystal lattice parameters which

result in its slipping primarily on the basal plane (0001). A relatively low critical resolved shear stress (0.675 kg/sq mm) is therefore required to initiate slip (table II). In contrast, however, slip in hexagonal titanium occurs primarily in the $10\bar{1}0$ planes (refs. 11, 12 and 20). The critical resolved stress to shear on these planes is 5.0 kilograms per square millimeter in compression, and, consequently, higher friction coefficients might be expected for titanium than for cobalt. This high stress value may be compared with values for other hexagonal metals in table II.

TITANIUM ALLOYS

Tin-Titanium

With the increase in the lattice ratio of titanium, a decrease in resolved critical shear stress may be anticipated and, consequently, a reduction in friction coefficients. Increasing the lattice ratio in titanium may be achieved by means other than high temperatures. For example, retaining a solid solution by adding selected alloying agents, which are stabilizers of the hexagonal form, may enable expansion of the crystal lattice of titanium without increasing temperature. Examination of crystallographic parameters given in references 21 and 22 for titanium binary alloys indicates that a number of elements (e.g., oxygen, nitrogen, carbon, tin, etc.) could be added to titanium to expand the crystal lattice. Tin and oxygen appear attractive because of the expansion characteristics gained with moderate additions of the alloying elements. These simple binary alloys are not necessarily bearing compositions; in fact, oxygen is highly embrittling.

Alloys of titanium-tin were prepared. These alloys contained up to 20.5 percent tin in titanium. The effect of the addition of tin on the lattice parameters of titanium were measured with X-ray diffraction, and the

resultant effect is shown in figure 8. With 20.5 percent tin, a solid solution was obtained; this percentage is very near the maximum solid solubility limit (at room temperature) of tin in titanium.

Friction data were obtained for the tin-titanium alloys in vacuum (fig. 9). The addition of as little as 2.5 percent tin resulted in a marked decrease in friction coefficient, friction continued to decrease with the addition of tin to a concentration of 15.0 percent tin.

Titanium-Oxygen

Consideration of the phase diagram indicated that the c/a lattice ratio continues to increase with the addition of oxygen to 14.5 weight percent. Alloys of oxygen in titanium were therefore prepared with 14.5 weight percent oxygen. Such alloys were very brittle, and consequently oxygen concentration was reduced to 10 weight percent and below. The lattice expansion of titanium with the addition of 10 weight percent oxygen is shown in figure 10. The lattice ratio (c/a) expanded to 1.616 with the addition of the 10 weight percent oxygen; the ideal stacking sequence gives a ratio of 1.633. Friction data for the titanium-oxygen alloy are also presented in figure 8 with the alloy sliding on 440-C stainless steel at various sliding velocities.

ZIRCONIUM

The friction data obtained for 99.99 percent titanium sliding on titanium and on 440-C stainless steel indicate that slip on the $10\bar{1}0$ planes results in higher friction than that found for the hexagonal transition metal cobalt when basal slip (0001) occurs. Two metals among the transition series that have properties very similar to those of titanium are zirconium and hafnium. Because of the extreme similarity in these two elements, the slip mechanisms can be expected to be the same. References 23 and 24 indicate that this is in fact

the case. The friction behavior of zirconium and hafnium might therefore be expected to be very similar to that of titanium. Table II indicates the slip systems for these metals.

The friction coefficients for 99.99 percent zirconium sliding on zirconium was measured in vacuum at various sliding velocities, and the results are presented in figure 11(a). The friction coefficient was in excess of 1.0 at 25 and at 500 feet per minute. At approximately 700 feet per minute, the friction coefficient was less than 0.4 and decreased to 0.2 at 2000 feet per minute. When the velocity was reduced after running at 2000 feet per minute, the friction coefficient at sliding velocities less than 500 feet per minute remained relatively low. The relatively low values obtained at these velocities may be associated with the fact that the sliding velocity was deliberately decreased while the specimens were still considerably above the temperatures that would be obtained in the initial portion of the experiment.

The friction characteristics for 99.99 percent zirconium sliding on 440-C stainless steel were determined at various sliding velocities in vacuum, and the results obtained are presented in figure 11(b). The friction decreased at a sliding velocity of approximately 1400 feet per minute.

An examination of the lattice ratios c/a for hexagonal zirconium indicates that this ratio increases with increasing temperature. Based on similar results obtained with titanium, a gradual decrease in friction with increasing sliding velocity (interface temperature) might be anticipated. Although a decrease in friction was observed for zirconium sliding on zirconium (fig. 11(a)), the decrease at a velocity of about 600 feet per minute was very abrupt.

The c/a lattice ratio does not indicate any such abrupt changes. If, however, the c/a lattice ratio is separated into its individual components, the reason for abrupt change in friction may be better explained.

The lattice ratio c/a indicates a marked change in the slope for the lattice parameter c at a temperature of approximately 600 F (ref. 24). This marked change in lattice spacing may account for the change in friction characteristics observed at a sliding velocity of about 700 feet per minute. In the experiment with the 440-C disk, the rider-specimen (zirconium) temperatures were measured (fig. 11(b)). Temperatures of 500 to 600 F were measured at those sliding velocities associated with the friction change.

Although the predominant mode of slip at room temperature for zirconium is on the $10\bar{1}0$ planes, it is not the only mode, as indicated in table II. Slip on the basal plane also occurs, but to a lesser degree. If, however, the axis continues to expand with increasing temperature, then the tendency to slip on the basal plane will continue to increase with increasing temperature (ref. 24). At high temperature, it may be the preferred mode of slip. With a continued increase in interplanar spacing (c lattice), a decrease in shear stress for basal shear might be anticipated.

HAFNIUM

The friction characteristics were measured for 99.99 percent hafnium sliding on 99.99 percent hafnium and on 440-C stainless steel. The results obtained in these studies are presented in figure 12. The friction coefficient for hafnium sliding on hafnium in vacuum was relatively high but decreased with increasing sliding velocity (fig. 12(a)). This result was also noted with hafnium sliding on 440-C stainless steel. On 440-C at sliding velocities in excess of 1000 feet per minute the friction was less than 0.3. Data (other

than at room temperature) could not be found on the measured lattice parameters c and a for high purity hafnium. Based on friction data obtained in this investigation with hafnium, zirconium, and titanium, hafnium would be expected to show an increase in the c/a lattice ratio with temperature.

BERYLLIUM

Although beryllium has a c/a lattice ratio very near that of titanium, zirconium, and hafnium, its primary mode of slip is on the basal plane (0001) (refs. 25 to 27). Based solely on the c/a lattice ratio, beryllium might be expected to have a slip system similar to that of hafnium. If, however, size factor and interatomic bonding forces are considered, the reason for slip on the basal plane in beryllium can be more easily seen. A consideration of bond forces may be made using the following simple equation from reference 28:

$$k^{-1/2} = a(D - b)$$

Where k is the bond force in megadynes per centimeter, a and b are constants for a particular metal, and D is the internuclear distance in angstroms.

For interatomic bonding in the c -axis, a force of 20×10^{-3} megadyne per centimeter was calculated for beryllium, a force of 33.7×10^{-3} megadyne per centimeter for zirconium, and 31.4×10^{-3} megadyne per centimeter for titanium. Because of interatomic interaction within a plane, these values can be considered only approximations, but they do give an indication of differences in bond forces. Based on the slip mechanism of beryllium, friction coefficients comparable with that obtained with cobalt might be anticipated.

Friction experiments were conducted in vacuum with beryllium metal sliding on beryllium metal at various sliding velocities, and the results

are presented in figure 13(a). At relatively low sliding velocities the friction coefficient was similar to that for cobalt. As the sliding velocity increased, however, the friction coefficient began to increase. This increase in friction is the opposite of the trend observed for titanium, zirconium, and hafnium.

Examination of the c/a lattice ratio for beryllium as a function of ambient temperature shows the reverse trend of that observed for titanium, zirconium, and hafnium, that is, the c/a lattice ratio decreases with increasing temperature (fig. 13(b)). Just as the c/a lattice ratio decreases, the critical resolved shear stress for beryllium increases (fig. 13(b)), and as a consequence, an increase in friction with increasing sliding velocity (interface temperature) is observed. The critical resolved shear stress of figure 13(b) is for single-crystal beryllium. These values were selected because they avoid the variation in shear stress associated with grain boundaries and differences in grain size. An approximate shear stress may be obtained for polycrystalline beryllium by multiplying the values in figure 13(b) by two (ref. 25).

CUBIC AND HEXAGONAL METALS

Since the slip system for titanium, zirconium, and hafnium is not the ideal basal slip characterizing other hexagonal metals, and the friction are not as low as might be encountered with ideal hexagonal metals, the friction and wear characteristics were compared for two cubic and three hexagonal metals. The object of the comparison was to determine whether the hexagonal metals that did not exhibit basal slip were superior to cubic metals in friction characteristics in vacuum. The results obtained in friction experiments with

the cubic metals, copper and nickel, and the hexagonal metals, zirconium, titanium, and beryllium, are presented in figure 14. With the two cubic metals, copper and nickel, a load of 500 grams instead of the normal 1000 grams had to be used because complete welding of the specimens occurred with a 1000-gram load. The friction coefficients for these two metals as indicated in the figure were more than twice the values obtained for zirconium and titanium ($\{10\bar{1}0\}$ slip) and five to six times the value for beryllium ($\{0001\}$ slip). Further, even with the 500-gram load, intermittent welding of the cubic metals occurred. The hexagonal metals were run under a load of 1000 grams.

FRICITION AS FUNCTION OF INTERBASAL PLANAR SPACING FOR SOME HEXAGONAL METALS

The c-axis dimension for hexagonal metals normally refers to the distance in angstroms of the unit cell, that is, the distance between outermost basal planes. Many metals have, however, more than two basal planes within the cell. Lanthanum, neodymium, and praseodymium, for example, each have three basal planes and consequently two units within the cell. Samarium, of the same series, has four basal planes. In friction studies it is not the cell dimension but the distance between adjacent basal planes that is important, since slip is initiated between these planes. In this discussion of hexagonal metals, it is therefore not the c/a lattice ratio that will be considered but rather the ratio of spacing between adjacent basal planes of the unit cell to the lattice parameter.

The effect of interplanar spacing of basal planes of hexagonal metals on their friction characteristics is shown in figure 15(a), in which the

coefficients of friction for various hexagonal metals are presented as a function of interbasal planar spacing. The results of figure 15(a), summarizes the data of references 2 and 29 to 31 from which the data for this paper were taken and indicates a direct correlation between interbasal planar spacing and friction for hexagonal metals. The two noted exceptions are titanium and beryllium. The metal beryllium does not fall on the curve because of its basal slip mechanism, despite the lattice parameters. The atomic size of beryllium and the resulting interbasal bonding forces are less than for the metals zirconium, hafnium, and titanium with similar c/a lattice ratios. Titanium could have approached the curve had friction values been obtained at a higher sliding velocity. The particular sliding velocity for the data shown in figure 15(a) was 400 feet per minute. This sliding velocity was selected because a number of the metals included undergo crystal transformations at slightly higher sliding velocities. The results of figure 15(a) indicate direct correlation of friction properties and interbasal planar spacing for hexagonal metals. A decrease in friction was observed with an increase in the ratio of interbasal planar spacing to the lattice parameter a .

In order to determine whether the relation of lattice parameters to friction characteristics could be related to hexagonal metals sliding on themselves, coefficient of friction was plotted in figure 15(b) as a function of lattice parameter as in figure 15(a). Although a limited number of points were available, the relation appears to hold for metals sliding on themselves. A better correlation of friction with lattice parameter for titanium exists with the metal sliding on itself than was observed with it sliding on 440-C.

In hexagonal closely packed metals there is a single slip plane when the lattice ratio c/a is near ideal (1.633) for closest packing of atoms. There are in turn three possible slip directions for the hexagonal crystal to slip. There are therefore three slip systems for the hexagonal closely packed metal. With the face-centered-cubic metal, there are four slip planes each with three slip directions on twelve slip systems.

In a polycrystalline aggregate each crystal may be somewhat independent with respect to the orientation of the crystals about it. Crystallographic anisotropy can and does occur, however, with preferred crystal orientation of the grains resulting from severe deformation such as that which occurs during sliding contact. Since the strength of a single crystal is highly anisotropic, a severe plastic deformation such as encountered at the interface of contacting metal under load, will produce a strong preferred orientation in a polycrystalline aggregate that will approach the anisotropy of single crystals, for example, preferred orientation of beryllium sheet on rolling. This would then account for the dependence of the polycrystal materials of this investigation upon crystal slip systems.

The differences in slip behavior in the hexagonal metals and the face-centered-cubic metals rests with the larger number of slip systems in the face-centered-cubic structure. Interaction of slip planes (four sets intersecting each other at an angle of $70^{\circ} 32'$) in the face-centered-cubic structure under deformation gives rise to Lomer-Cottrell dislocations (ref. 32). It is the behavior of these dislocations together with the stacking faults which are generated as a result of these dislocations that account for the principal difference in deformation behavior of closely packed hexagonal and face-

centered-cubic metals. When two planes 111 and $1\bar{1}\bar{1}$ intersect with extended dislocations on each, the dislocations attract one another and run toward the place where the planes meet or cross. Here they form a new dislocation of lower energy. Their position, however, is not now in a common slip plane and consequently may be difficult to move. This may be followed by another step that tends to fix the dislocation. This dislocation now inhibits the motion of slip dislocations. The pinned dislocation may separate with two partial dislocations moving back on the slip planes. Between the two partial dislocations in each of the slip planes is a layer across which the atoms are misfit to some degree. This region between partial dislocations is referred to as a stacking fault because it disturbs the normal atom stacking sequence. The energy with which the two partial dislocations repel one another is referred to as the stacking fault energy. The difference in stacking and behavior of the face-centered cubic and close-packed hexagonal structures lies in this energy. This energy may be essentially considered as the difference in free energy of the two crystal structures.

With closely packed hexagonal metals slipping on a single plane, the Lomer-Cottrell dislocations are not present. It is difficult to say if such dislocations would form in hexagonal metals exhibiting prismatic slip (Ti, Zr, and Hf).

SUMMARY OF RESULTS

Based on the friction and wear data obtained with various hexagonal metals in vacuum, the following summary remarks can be made:

1. A correlation between friction characteristics and lattice ratio for hexagonal metals was demonstrated, with lower coefficients of friction being obtained for those metals with the greatest interbasal planar spacing.

2. The crystal structure of cobalt markedly influenced its friction, wear, and metal transfer characteristics in vacuum. Relatively low friction and wear values were obtained for cobalt in the hexagonal form. With crystal transformation to the face-centered cubic form, an increase in wear and complete welding of cobalt was observed. These effects are believed to be related to the differences in crystallographic slip behavior of the hexagonal and cubic metals.

3. The friction and wear characteristics for the hexagonal metals titanium, zirconium, and hafnium are higher than was observed for metals like cobalt. This difference is believed to be due to a difference in slip behavior. Cobalt has lattice parameters close to that for ideal hexagonal packing and consequently exhibits basal slip while titanium, zirconium, and hafnium in lattice ratio (c/a) sufficiently to exhibit prismatic rather than basal slip.

4. The relatively low friction characteristics for beryllium, despite its deviation from ideal close packing, can be related to atomic size, shear strength, and slip behavior. Beryllium slips (at low temperatures) like cobalt under deformation on primarily basal planes.

5. The friction characteristics of titanium can be markedly changed by selective alloying with elements that will expand the hexagonal lattice of titanium in the c -axis.

6. The crystal transformation of cobalt and its friction characteristics can be markedly influenced by alloying.

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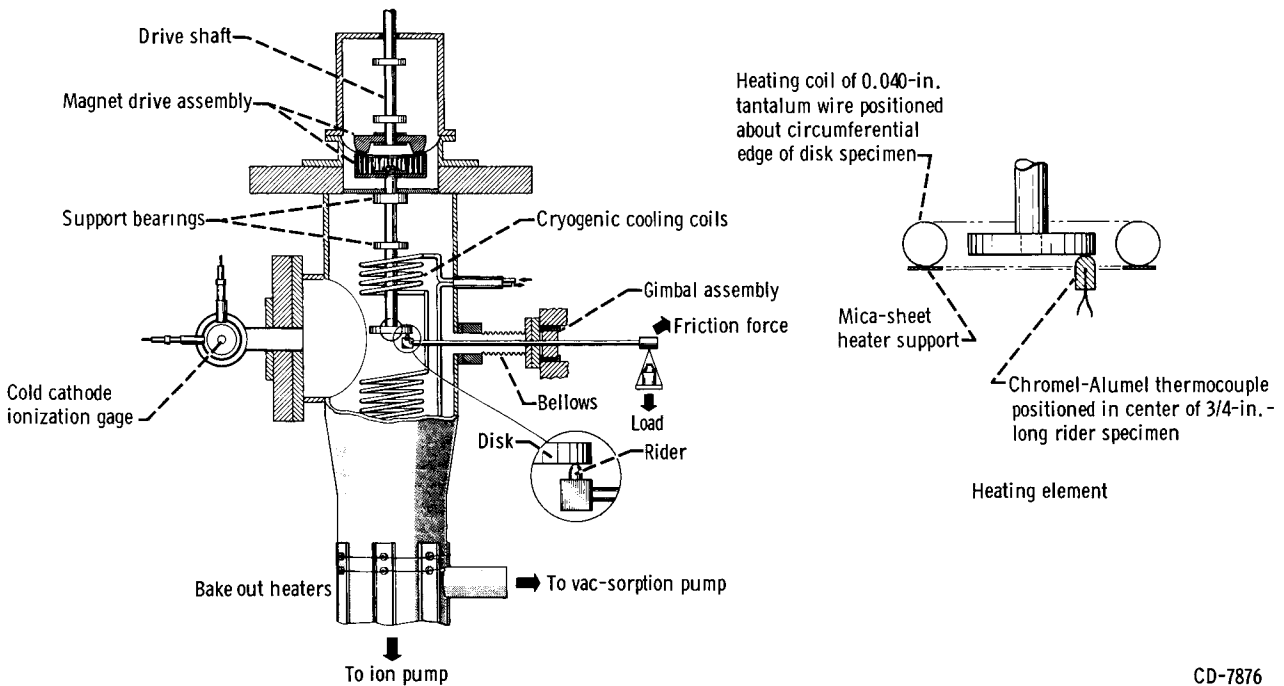


Figure 1. - High-vacuum friction and wear apparatus.

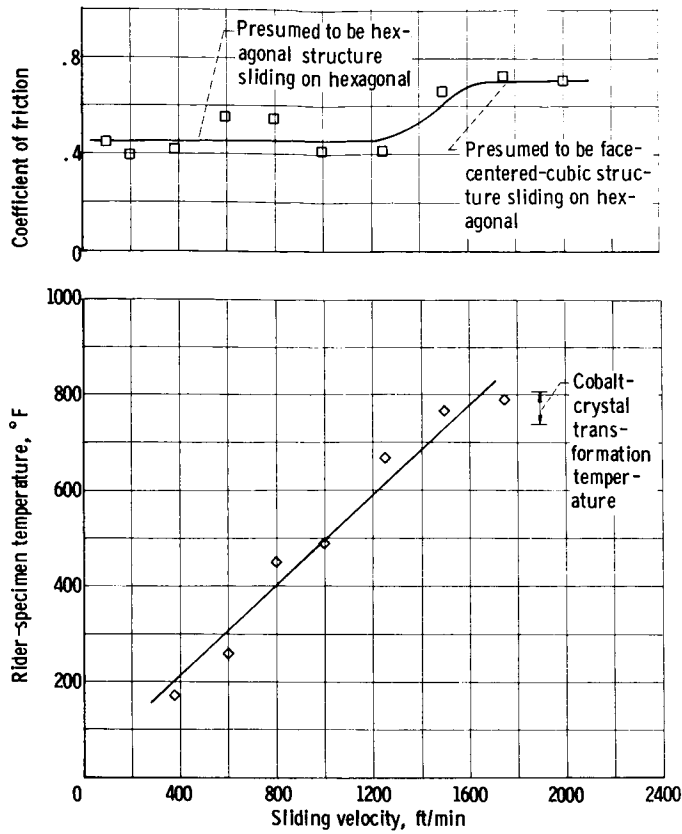


Figure 2. - Coefficient of friction and rider specimen temperatures at various sliding velocities for cobalt sliding on cobalt in vacuum (10^{-9} mm Hg). Load, 1000 grams.

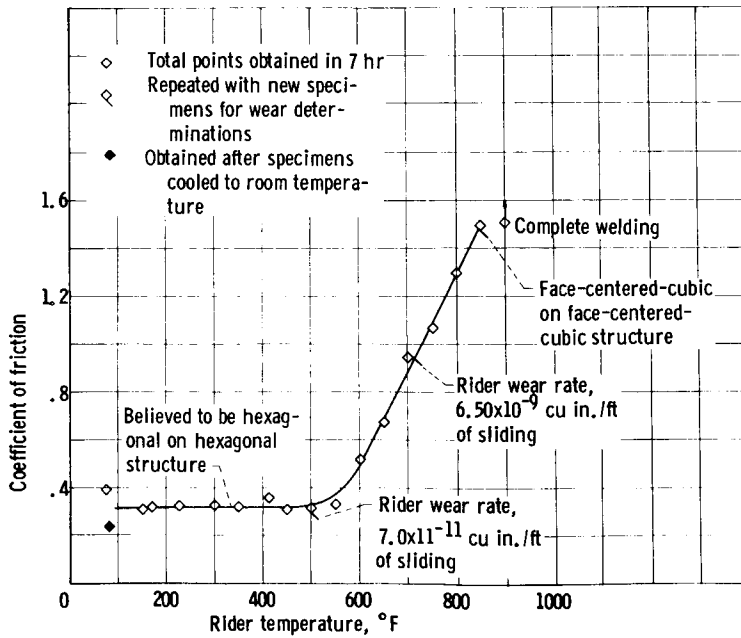


Figure 3. - Coefficient of friction at various ambient temperatures for cobalt sliding on cobalt in vacuum (10^{-8} to 10^{-7} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams.

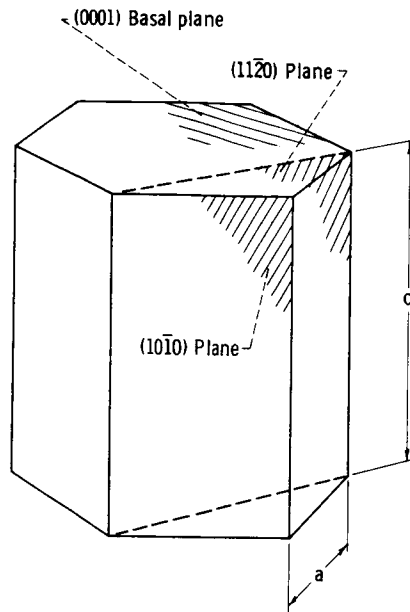


Figure 4. - Hexagonal crystal.

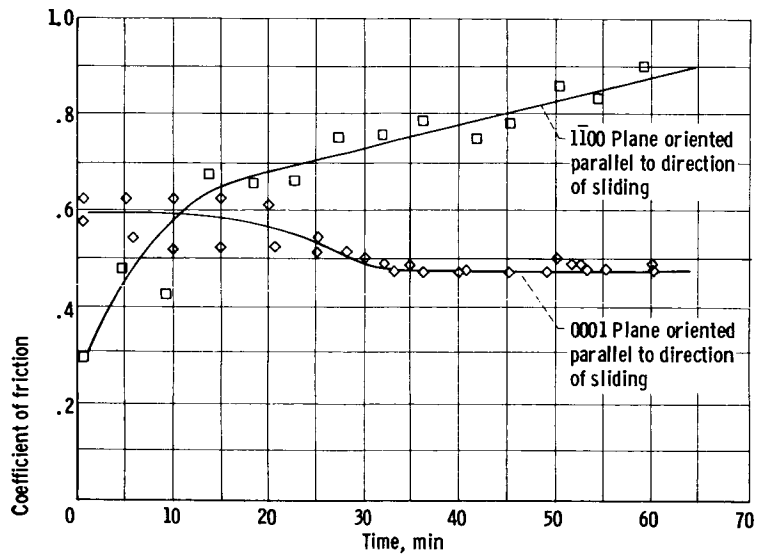


Figure 5. - Coefficient of friction for single-crystal cobalt sliding on polycrystalline cobalt in vacuum (10^{-9} mm Hg). Sliding velocity, 4.5 feet per minute; load, 250 grams; ambient temperature, 75° F.

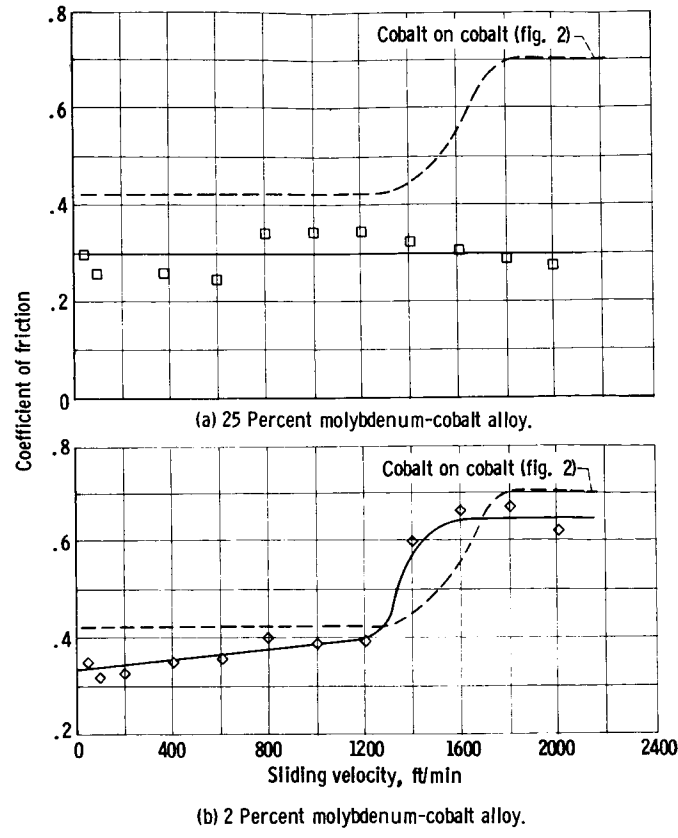


Figure 6. - Coefficient of friction for two molybdenum-cobalt alloys sliding on disks of the same materials in vacuum (10^{-9} mm Hg). Load, 1000 grams; ambient temperature, 75° F.

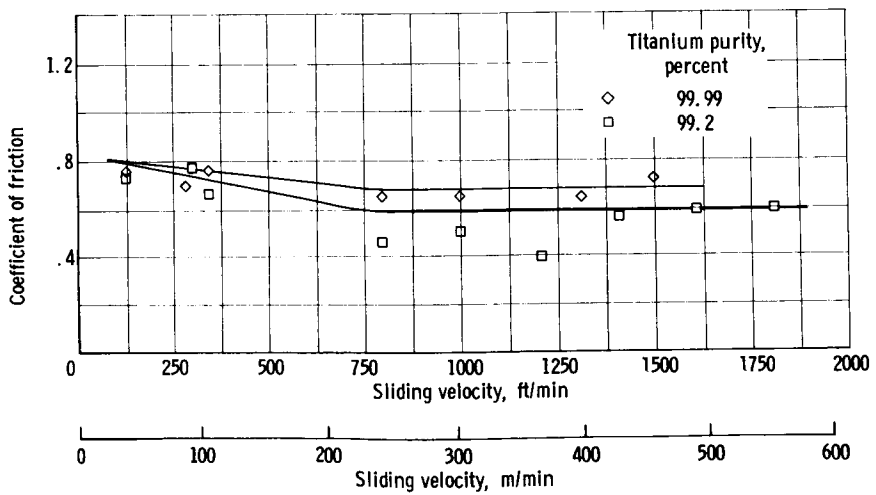


Figure 7. - Coefficient of friction for titanium sliding on titanium in vacuum (10^{-9} mm Hg) at various sliding velocities. Load, 1000 grams; no external specimen heating.

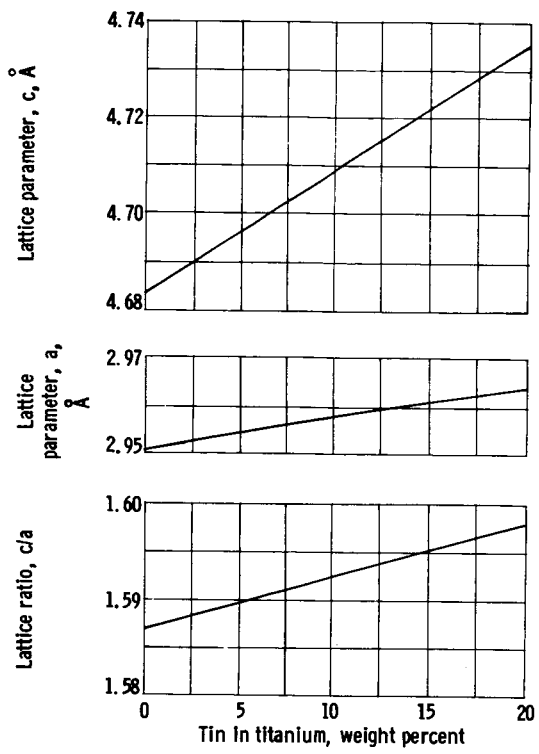


Figure 8. - Lattice parameters of binary tin-titanium alloys.

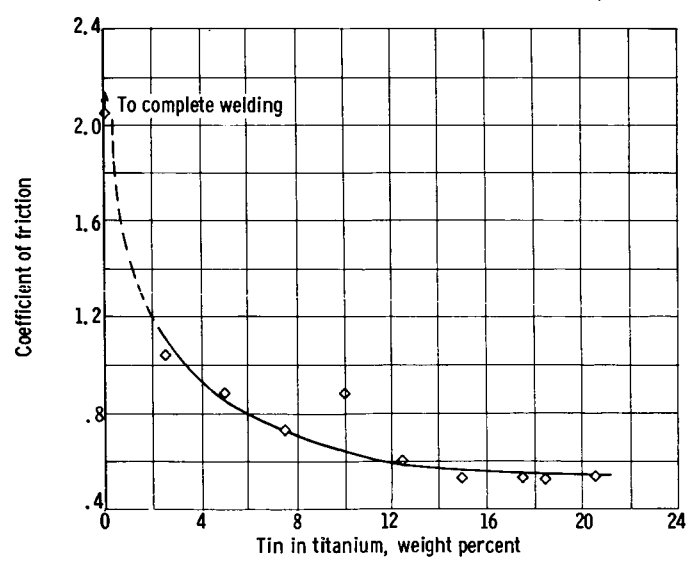
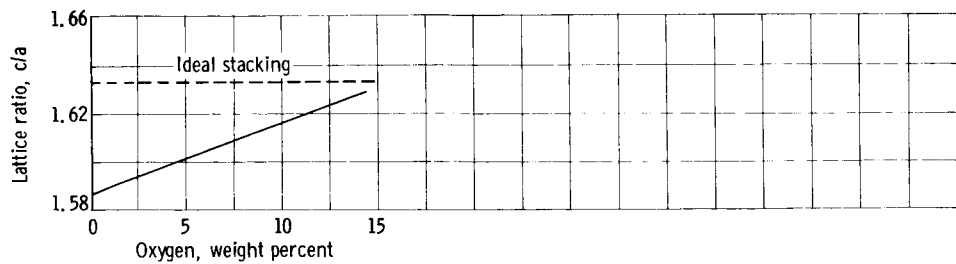
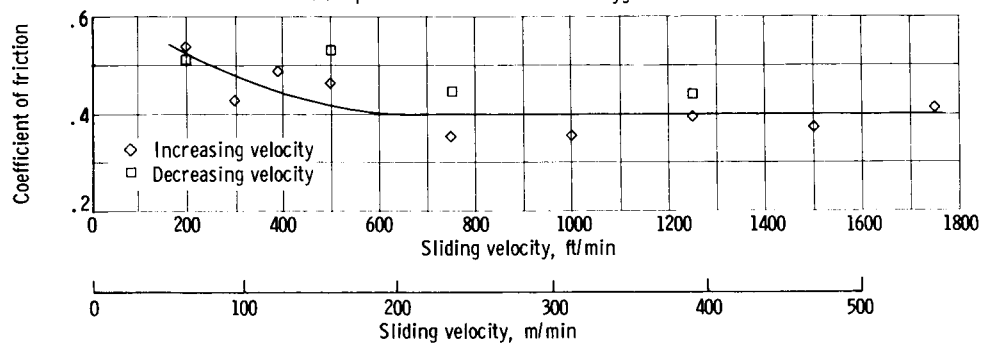


Figure 9. - Coefficient of friction and rider wear rate for titanium-tin alloys sliding on 440-C stainless steel in vacuum. Sliding velocity, 390 feet per minute; load, 1000 grams; no external specimen heating.



(a) Expansion of lattice ratio with oxygen content.



(b) Change in coefficient of friction with sliding velocity.

Figure 10. - Lattice ratio c/a as a function of weight percent oxygen and coefficient of friction for 10 percent oxygen-titanium alloy sliding on 440-C stainless steel in vacuum. Load, 1000 grams; no external specimen heating.

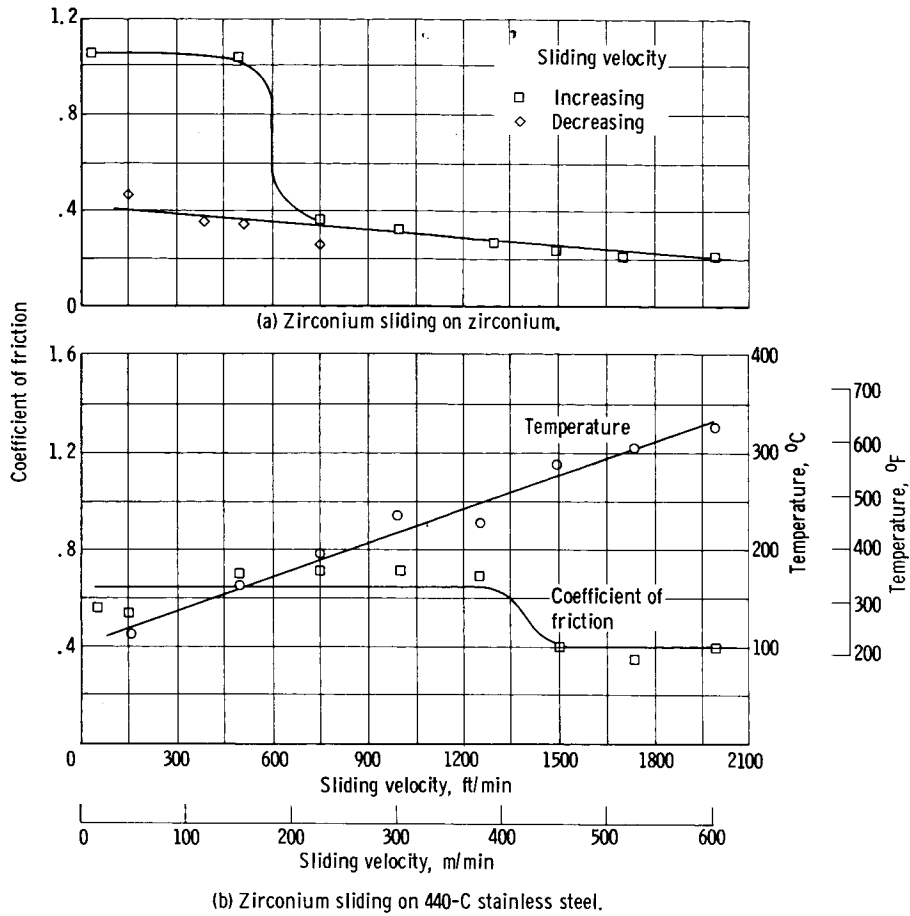


Figure 11. - Coefficient of friction for 99.99 percent zirconium sliding on 99.99 percent zirconium and on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external heating.

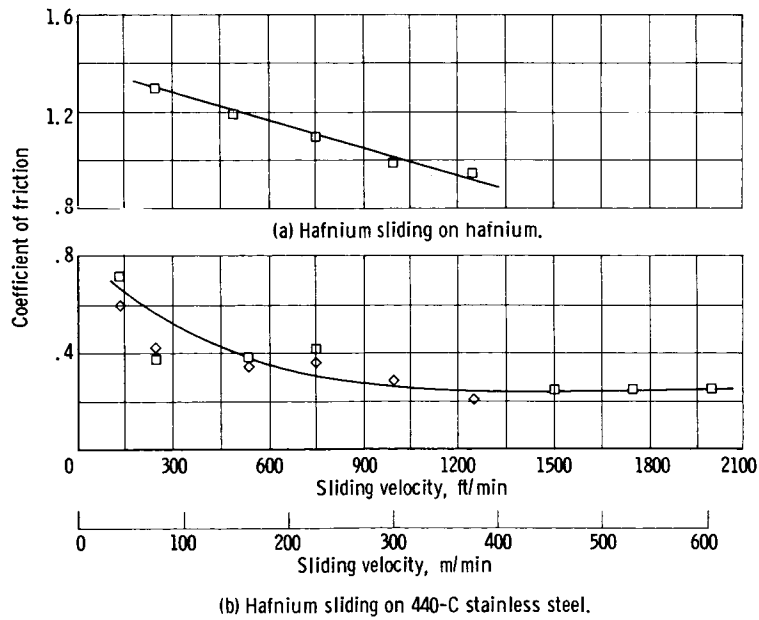
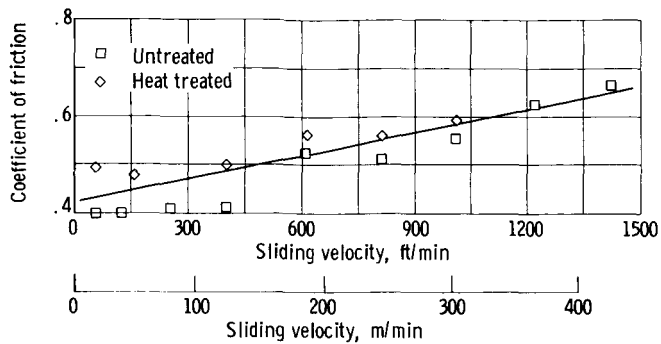
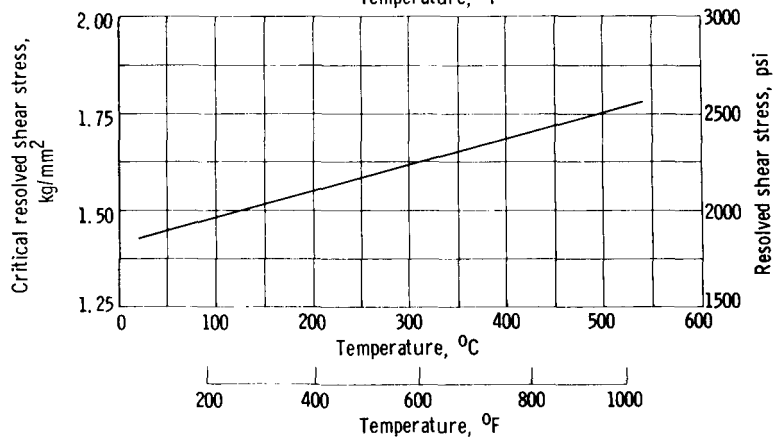
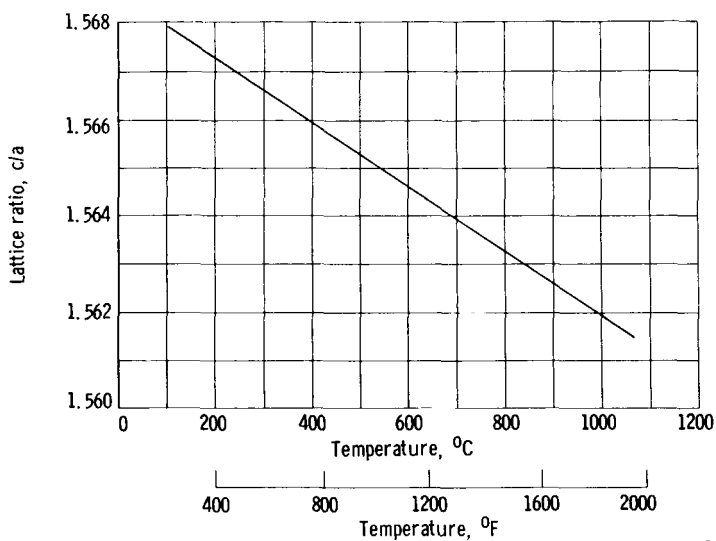


Figure 12. - Coefficient of friction for 99.99 percent hafnium sliding on 99.99 percent hafnium and on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external heating.



(a) Coefficient of friction for beryllium sliding on beryllium in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external specimen heating.



(b) Effect of temperature on c/a lattice ratio and critical resolved shear stress for beryllium metal (from ref. 8).

Figure 13. - Friction, lattice ratio, and critical resolved shear stress for beryllium.

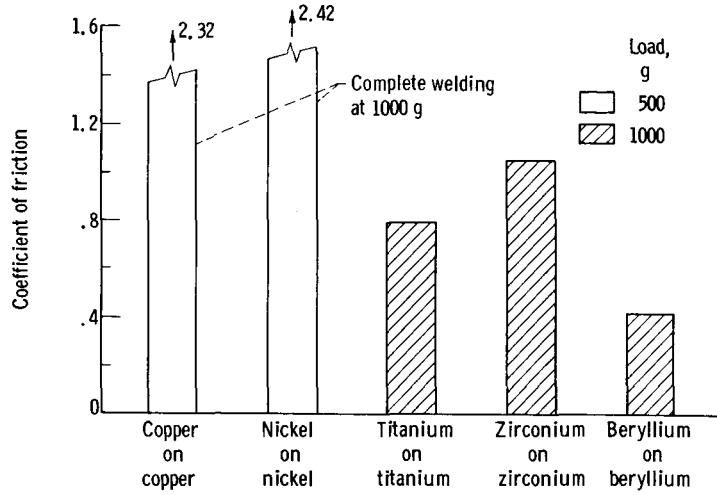


Figure 14. - Coefficient of friction and rider wear rate for various metals in vacuum (10^{-9} mm Hg). Sliding velocity, 4.5 feet per minute; no external heating of specimens; duration of test, 1 hour.

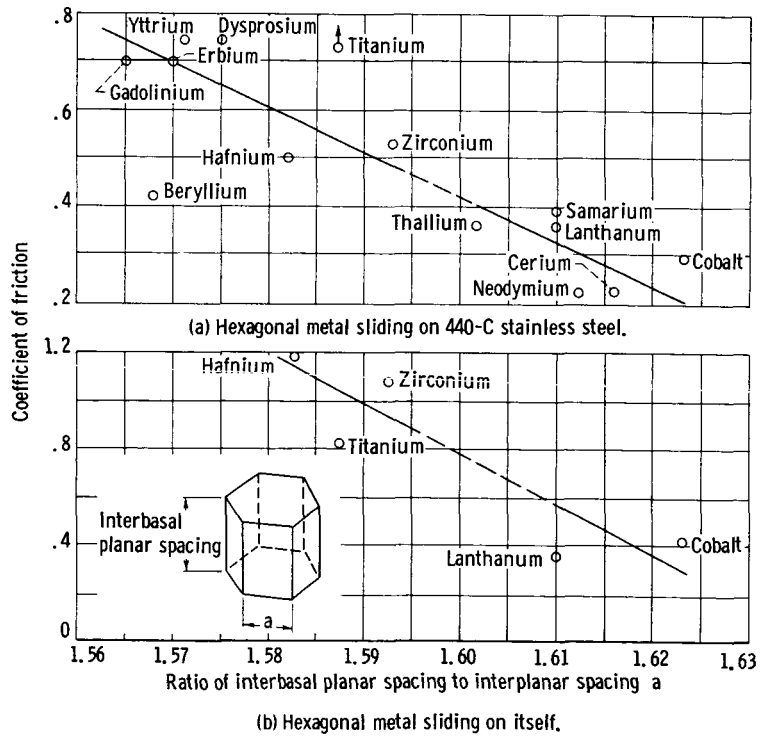


Figure 15. - Coefficient of friction for various metals as function of lattice ratio. Vacuum, 10^{-9} millimeter of mercury; sliding velocity, 400 feet per minute; load, 1000 grams; no external specimen heating.