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INFLUENCE OF CRYSTAL STRUCTURE
ON FRICTION CHARACTERISTICS OF
RARE-EARTH AND RELATED METALS IN
VACUUM TO 10^{-10} MILLIMETER OF MERCURY

by Donald H. Buckley and Robert L. Johnson

Lewis Research Center

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SUMMARY

The friction, wear, and metal-transfer characteristics were determined for rare-earth and related metals in vacuum to 10^{-10} millimeter of mercury. The metals studied were lanthanum, neodymium, praseodymium, cerium, holmium, erbium, gadolinium, dysprosium, samarium, yttrium, and thallium. Friction and wear experiments were conducted with the rare-earth or related metals generally sliding against 440-C stainless steel at sliding velocities to 2000 feet per minute and loads to 3000 grams. The rare-earth or related metals were the rider specimens (3/16-in.-rad. hemisphere) sliding on flat $2\frac{1}{2}$ -inch-diameter disk specimens of 440-C stainless steel. Factors studied were the effects of crystal structure and crystalline phase changes on the friction, wear, and metal-transfer characteristics of these metals in vacuum.

The results of the investigation indicate that crystal structure markedly influences friction, wear, and metal-transfer characteristics of the rare-earth and related metals in vacuum. Close-packed hexagonal crystal forms of the rare earths and of thallium had much lower friction, wear, and metal-transfer characteristics than face-centered or body-centered cubic structures. The lowest friction coefficients were obtained with those rare-earth metals that have the largest c-axis (crystal height), that is, those metals with the lanthanum- and samarium-type crystal structures. With neodymium a crystal transformation was observed at a temperature below that reported in the literature.

INTRODUCTION

Lubrication of mechanical components for space devices requires the selection of lubricants and other materials having extreme stability in a space environment. The rare-earth metals, atomic numbers 57 to 71 (lanthanum, . . . ,

lutetium), merit special consideration for research studies directed toward future space devices. The rare-earth metals will combine with a number of gases (e.g., oxygen, nitrogen, hydrogen, etc.) to form extremely stable compounds. The oxides of the rare earths are even more stable than such oxides as aluminum oxide. Many of these compounds, because of their stability, have potential for use in solid lubricant formulations; further, they can be used as phases of alloys for self-lubricated components of systems intended for space applications.

The rare-earth metals possess some interesting physical (e.g., they are relatively soft, table I) as well as chemical properties (refs. 1 and 2).

TABLE I. - PHYSICAL PROPERTIES OF RARE-EARTH AND RELATED METALS

| Metal | Approximate hardness, kg/sq mm | Melting point, °F | Temperature for vapor pressure of 1 mm Hg, °F | Ultimate tensile strength, psi | Young's modulus of elasticity, psi | Shear modulus, psi | Poisson's ratio | Density at 68° F, g/cc |
|--------------|--------------------------------|-------------------|---|--------------------------------|------------------------------------|---------------------|-----------------|------------------------|
| Lanthanum | 40 (DPH) ^a | 1688 | 4228 | 19×10 ³ | 5.6×10 ⁶ | 2.2×10 ⁶ | 0.29 | 6.17 |
| Cerium | 25 (DPH) ^a | 1463 | 3178 | 15 | 4.4 | 1.7 | .25 | 8.23 |
| Praseodymium | 40 (DPH) ^a | 1715 | 3362 | 16 | 5.1 | 2.0 | .31 | 6.78 |
| Neodymium | 35 (DPH) ^a | 1875 | 3212 | 25 | 5.5 | 2.1 | .31 | 7.00 |
| Samarium | 45 (DPH) ^a | 1962 | ---- | 18 | 5.0 | 1.8 | .35 | 7.53 |
| Europium | 20 (DPH) ^a | 1519 | ---- | -- | --- | --- | --- | 5.26 |
| Gadolinium | 55 (DPH) ^a | 2394 | ---- | 28 | 8.2 | 3.2 | .26 | 7.89 |
| Terbium | 60 (DPH) ^a | 2473 | ---- | -- | 8.3 | 3.3 | .26 | 8.27 |
| Dysprosium | 55 (DPH) ^a | 2565 | 2665 | 36 | 9.2 | 3.7 | .24 | 8.53 |
| Holmium | 70 (DPH) ^a | 2662 | ---- | 38 | 9.7 | 3.9 | .26 | 8.80 |
| Erbium | 60 (DPH) ^a | 2732 | ---- | 42.4 | 10.6 | 4.3 | .24 | 9.05 |
| Thulium | 65 (DPH) ^a | 2813 | ---- | -- | ---- | --- | --- | 9.33 |
| Ytterbium | 25 (DPH) ^a | 1515 | ---- | 10 | 2.6 | 1.0 | .28 | 6.98 |
| Lutetium | 85 (DPH) ^a | 3006 | ---- | -- | --- | --- | --- | 9.84 |
| Yttrium | 60 (DPH) ^a | 2748 | ---- | 15.20 | 9 - 10 | 3.8 | .27 | 4.48 |
| Thallium | 2(Brinell) | 577 | 1517 | 1.3 | ----- | --- | --- | 11.85 |

^aDiamond pyramid hardness.

With the exception of europium, ytterbium, and cerium, the metals in the group have a close-packed hexagonal crystal structure at room temperature. Many of the metals undergo crystal transformations from one phase to another. On the basis of the Hume-Rothery Rules (ref. 3) for solid solubility (size and electronegative valence effect), the rare earths should have limited or no solubility in many ferrous alloys. Such properties prompted a study of the adhesion characteristics of the rare earths with themselves and with iron in reference 4. The results of the study indicated that the rare earths have coefficients of adhesion with iron that are more than one order of magnitude less than those of other soft metals (e.g., lead, tin, or indium) with iron.

The crystal transformations for some of the rare earths occur at relatively moderate temperatures (refs. 5 to 7). Such transformations could be

useful in determining the effect of crystal structure on the friction properties of metals. By examining the friction behavior of a single material during various crystalline phases, the problem of differences in other physical properties encountered with dissimilar metals with the same crystal structure is avoided. Although attempts have been made to correlate crystal structures with friction properties in metals, these studies were restricted because of the presence of oxides and adsorbants on metal surfaces. Experiments in vacuum (10^{-9} to 10^{-10} mm Hg) greatly reduce the availability of these surface contaminants.

The objectives of this investigation were to determine (1) the effect of crystal structure in the rare-earth metals and in related metals on friction, wear, and metal-transfer characteristics and (2) the effect of crystalline phase changes in the rare-earth metals on these same properties.

Friction and wear experiments were conducted in a vacuum environment (10^{-9} to 10^{-10} mm Hg) with a hemispherically tipped rider specimen sliding on a flat rotating disk surface. The disk specimen was rotated to produce sliding velocities of 55 to 2000 feet per minute and the rider was loaded against the disk surface with loads to 3000 grams. Experiments were conducted at ambient temperatures from -100° to 500° F.

APPARATUS

The apparatus used in this investigation is described in detail in reference 8 and is shown in figure 1. Basically the apparatus consisted of the experimental specimens (a $2\frac{1}{2}$ -in.-diam.

flat disk and a $3/16$ -in.-rad. rider), which was 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, outside the vacuum system, was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing (see fig. 1) and was mounted on one end of the shaft within the chamber. The end of the shaft that was opposite the magnet carried the disk specimen.

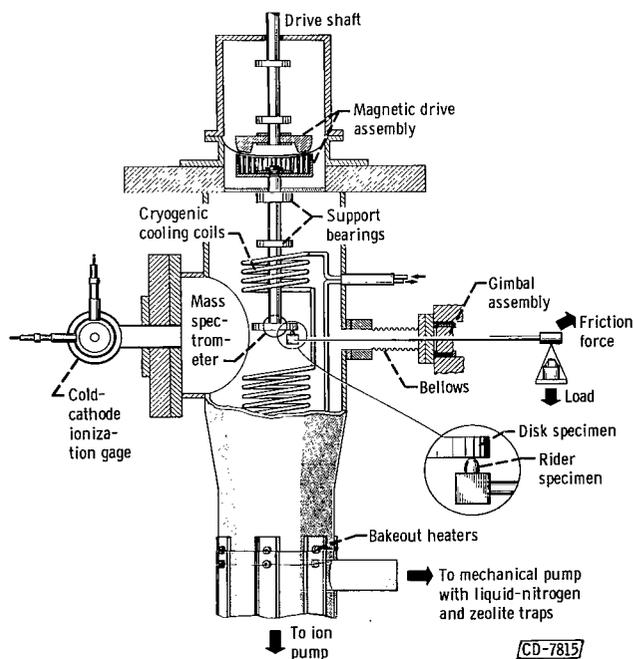


Figure 1. - Vacuum friction and wear apparatus.

The rider specimen was supported in the specimen chamber by an arm that was mounted by external gimbals and sealed by a flexible bellows to the chamber. A linkage at the other

end of the retaining arm from the rider specimen was connected to a strain-gage assembly, which was used to measure frictional force. Load was applied through a deadweight loading system. In order to heat the specimens, a small tantalum-wire-wound heater was placed around the disk and the rider specimens, and the specimens were radiantly heated. The bulk rider specimen temperatures were measured with a thermocouple positioned in the body of the rider.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a mechanical forepump with liquid-nitrogen and zeolite traps. The pressure in the chamber was measured adjacent to the specimen with an inverted magnetron cold-cathode gage (Kreisman). 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 coil of 5/16-inch-diameter stainless-steel tubing 20 feet long was used for either liquid-nitrogen or liquid-helium cryopumping of the vacuum system.

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) thorough rinsing with acetone to remove oil and grease, (2) polishing with moist levi-gated alumina on a soft polishing cloth, and (3) thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

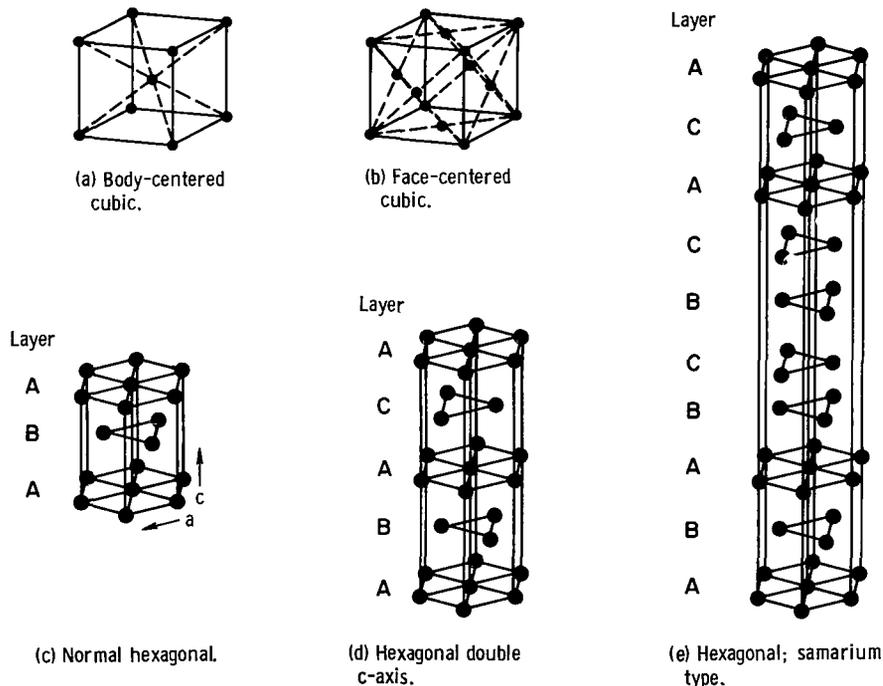


Figure 2. - Crystal structures.

RESULTS AND DISCUSSION

Polymorphism in Rare-Earth Metals

An interesting property of the rare-earth metals is their crystal structure. Many of these metals have a close-packed hexagonal crystal structure at room temperature. The hexagonal forms in which the rare earths may exist are of three types. These types are compared with body-centered and face-centered cubic structures in figure 2. The first or normal hexagonal form (fig. 2(c)) with the ABA stacking sequence of the A and the B layers is that represented by metals such as magnesium and in the rare-earth series by such metals as holmium, erbium, and gadolinium. This particular form of hexagonal structure has the shortest c-axis (crystal height) lattice constant. The second type of hexagonal crystalline form is the hexagonal double c-axis or the lanthanum-type crystal structure (fig. 2(d)) with ABACA stacking sequence of the A, B, and C layers. This crystalline form characterizes lanthanum, neodymium, and praseodymium. The third form is the samarium type (fig. 2(e)) with the stacking sequence ABABCBCACA. The c-axis lattice constant of this particular form is four and a half times that of the normal hexagonal structure. Some research investigators have termed this structure "rhombohedral" (refs. 8 and 9).

Many of the rare-earth metals undergo crystal transformation. Lanthanum, for example, will transform from a hexagonal crystal structure to a face-centered cubic structure at about 500° F as shown in figure 3 and transform from the face-centered cubic to a body-centered cubic structure at 1594° F. Transformations from hexagonal to body-centered cubic structure occur with neodymium at 1584° F and with praseodymium at 1472° F. Cerium, as indicated in figure 3, undergoes three crystal transformations. Cerium transforms from the

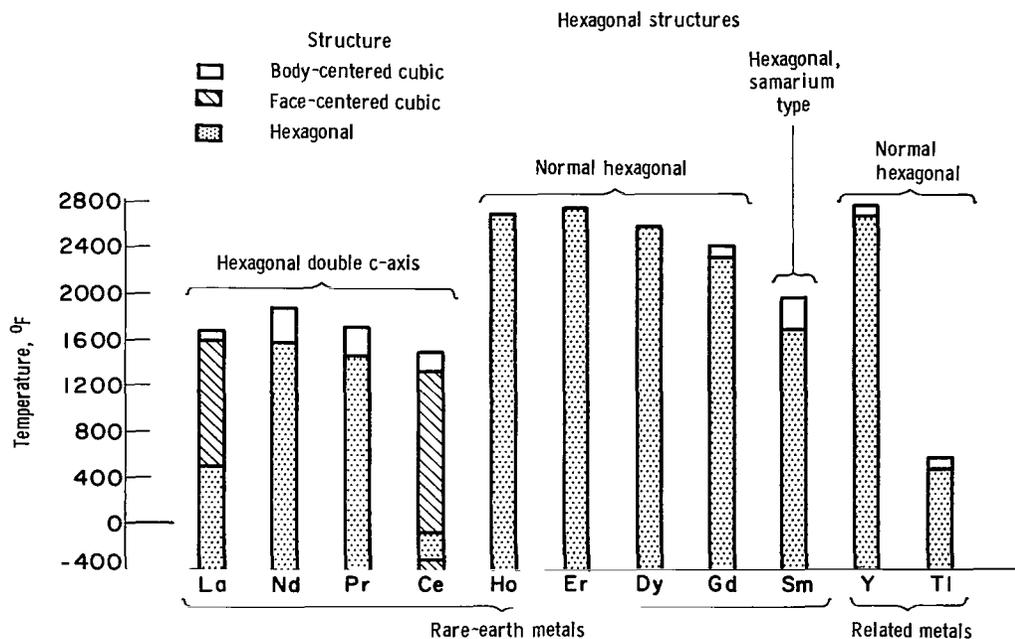


Figure 3. - Crystal transformations indicated in the literature for rare-earth and related metals (ref. 1).

face-centered cubic to the close-packed hexagonal structure at -321°F and retains this structure to -99°F . At -99°F it transforms to the face-centered cubic structure, which it retains to 1337°F , when it transforms to the body-centered cubic structure. Thallium metal, which is not a rare earth, transforms from the close-packed hexagonal to the body-centered cubic structure at 446°F (refs. 2 and 10).

Lanthanum

Most friction experiments were conducted in vacuum with 99.9-percent-pure lanthanum metal sliding on 440-C stainless steel. Some check data were obtained with lanthanum of only 99-percent purity. Experiments with the rare-earth metals dictate the use of a vacuum or inert environment because of the extremely reactive nature of the rare earths with oxygen, water, and various other gases.

In order to determine the influence of the crystal transformation in

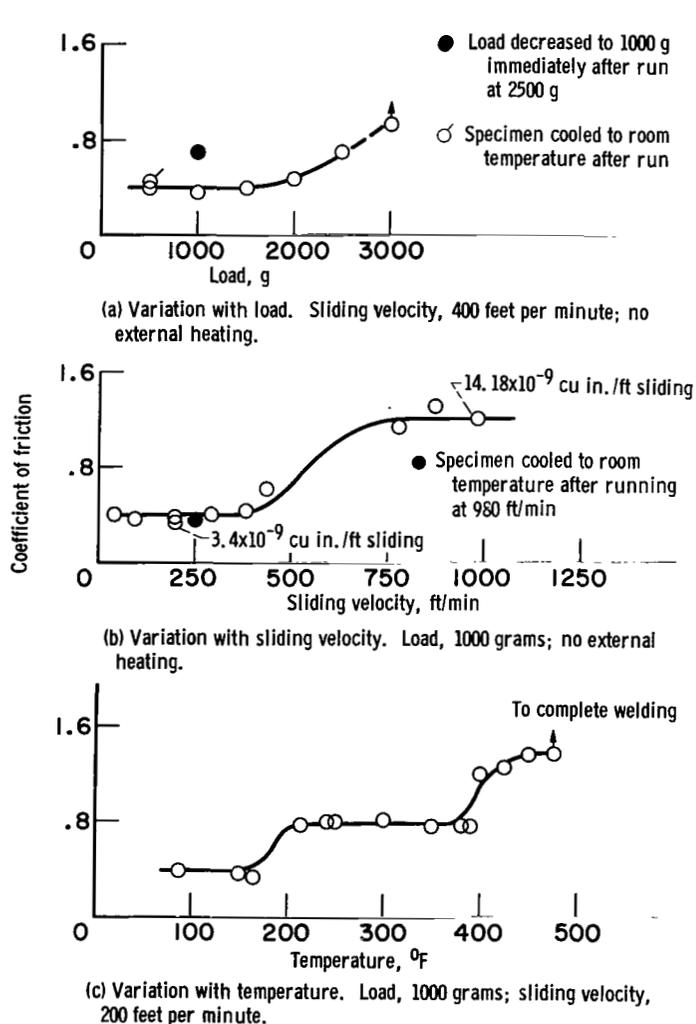


Figure 4. - Coefficient of friction of lanthanum sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg).

lanthanum on its friction behavior, a friction experiment was conducted as a function of ambient temperature. The results obtained in the friction experiment are presented in figure 4. With a 1000-gram load and a sliding velocity of 200 feet per minute in vacuum of 10^{-9} millimeter of mercury, the friction coefficient was less than 0.4 at 85° , 150° and 165°F (fig. 4(c)). At temperatures above 165°F the friction coefficient began to increase. Between 200° and 400°F the friction coefficient was constant at slightly less than 0.8. Above 400°F the friction coefficient further increased and reached a maximum of 1.35 at a temperature possibly associated with crystal transformation. The portion of the curve below 165°F is believed to represent the close-packed hexagonal crystalline form of lanthanum sliding on 440-C stainless steel. The plateau between 200° and 400°F is very similar to that observed in cooling curves. It may be that with lanthanum the plateau represents incomplete transformation to the face-centered cubic structure. This effect seems to

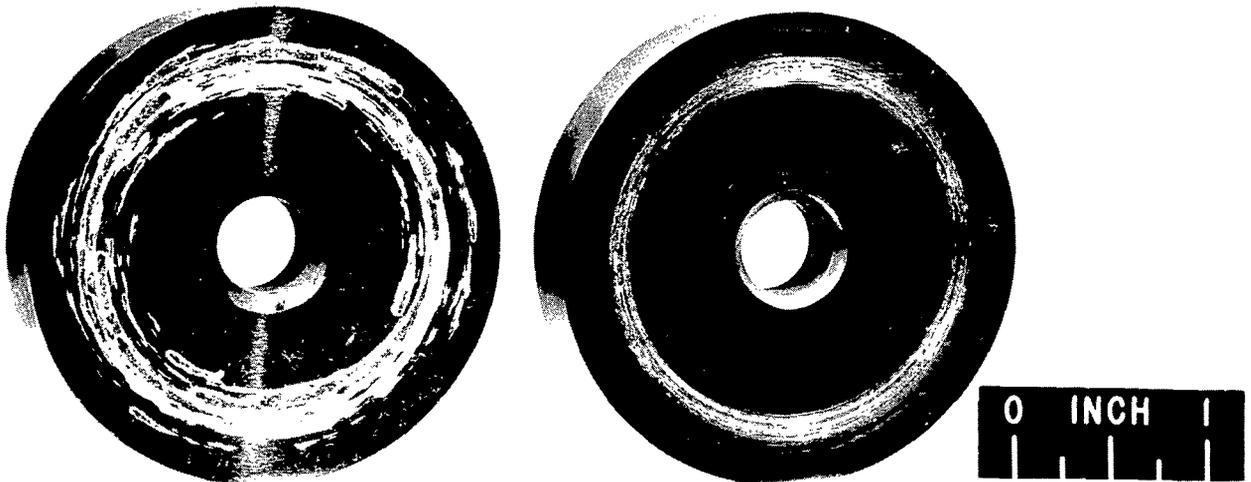
TABLE II. - X-RAY DIFFRACTION DATA FOR LANTHANUM AND NEODYMIUM

| Lanthanum | | | | | | Neodymium | | | | | | | | | |
|------------------------|-----------------------------|------------------------------------|-----------------------------|--------------------------------|-----------------------------|-------------------|-----------------------------|------------------------|-----------------------------|------------------------------------|-----------------------------|--------------------------------|-----------------------------|-------------------------------|-----------------------------|
| Hexagonal α -La | | | | Immediately on reaching 650° F | | β -La, ASTM | | Hexagonal α -Nd | | | | Immediately on reaching 850° F | | Temperature dropped to 350° F | |
| ASTM | | Experimentally determined at 75° F | | d value, A | Intensity, I/I ₀ | d value, A | Intensity, I/I ₀ | ASTM | | Experimentally determined at 75° F | | d value, A | Intensity, I/I ₀ | d value, A | Intensity, I/I ₀ |
| d value, A | Intensity, I/I ₀ | d value, A | Intensity, I/I ₀ | | | | | d value, A | Intensity, I/I ₀ | d value, A | Intensity, I/I ₀ | | | | |
| ---- | -- | ---- | -- | 3.45 | 60 | ---- | -- | ---- | -- | ---- | -- | 3.48 | 100 | ---- | -- |
| 3.29 | 60 | 3.29 | 60 | 3.32 | 100 | ---- | -- | ---- | -- | 3.40 | 40 | 3.42 | 100 | 3.40 | 70 |
| 3.04 | 100 | 3.07 | 100 | 3.09 | 80 | 3.06 | 100 | ---- | -- | ---- | -- | 3.30 | 20 | ---- | -- |
| 2.86 | 80 | 2.89 | 70 | 3.02 | 40 | ---- | -- | 3.14 | 40 | ---- | -- | 3.10 | 30 | ---- | -- |
| ---- | -- | 2.87 | 20 | 2.87 | 20 | ---- | -- | 3.03 | 70 | ---- | -- | 3.04 | 80 | 3.03 | 100 |
| ---- | -- | ---- | -- | 2.67 | 70 | 2.65 | 70 | 2.92 | 70 | 2.99 | 70 | 2.99 | 30 | 2.98 | 50 |
| ---- | -- | 2.04 | 10 | 2.06 | 30 | ---- | -- | 2.77 | 100 | 2.81 | 100 | 2.86 | 20 | ---- | -- |
| 1.88 | 80 | ---- | -- | 1.98 | 30 | ---- | -- | 2.45 | 50 | 2.49 | 60 | 2.53 | 10 | 2.51 | 50 |
| ---- | -- | ---- | -- | 1.88 | 60 | 1.87 | 90 | 2.14 | 20 | ---- | -- | 2.29 | 10 | 2.26 | 40 |
| 1.71 | 80 | ---- | -- | 1.72 | 20 | ---- | -- | ---- | -- | ---- | -- | 1.95 | 5 | 1.94 | 20 |
| ---- | -- | ---- | -- | 1.66 | 20 | ---- | -- | 1.88 | 40 | ---- | -- | 1.92 | 5 | ---- | -- |
| ---- | -- | ---- | -- | 1.64 | 30 | ---- | -- | 1.82 | 50 | ---- | -- | 1.86 | 10 | 1.84 | 10 |
| 1.60 | 100 | ---- | -- | 1.60 | 20 | 1.60 | 100 | ---- | -- | ---- | -- | 1.74 | 5 | ---- | -- |
| 1.52 | 80 | ---- | -- | 1.53 | 20 | 1.53 | 50 | ---- | -- | ---- | -- | 1.72 | 10 | ---- | -- |
| 1.41 | 10 | 1.39 | 10 | 1.40 | 10 | ---- | -- | 1.66 | 70 | 1.67 | 60 | 1.71 | 10 | 1.69 | 10 |
| 1.27 | 20 | 1.17 | 30 | ---- | -- | 1.33 | 20 | 1.56 | 20 | ---- | -- | ---- | -- | ---- | -- |
| 1.21 | 40 | ---- | -- | ---- | -- | 1.21 | 70 | 1.55 | 80 | ---- | -- | ---- | -- | ---- | -- |
| 1.09 | 40 | ---- | -- | ---- | -- | 1.18 | 70 | 1.53 | 50 | ---- | -- | ---- | -- | ---- | -- |
| 1.05 | 40 | ---- | -- | ---- | -- | 1.08 | 50 | 1.48 | 40 | 1.49 | 50 | 1.59 | 10 | 1.67 | 10 |
| 1.00 | 20 | ---- | -- | ---- | -- | 1.02 | 60 | 1.47 | 50 | 1.41 | 20 | 1.41 | 20 | 1.39 | 10 |
| .95 | 40 | ---- | -- | ---- | -- | .94 | 20 | ---- | -- | ---- | -- | ---- | -- | ---- | -- |
| ---- | -- | ---- | -- | ---- | -- | .90 | 60 | ---- | -- | ---- | -- | ---- | -- | ---- | -- |
| ---- | -- | ---- | -- | ---- | -- | .88 | 50 | ---- | -- | ---- | -- | ---- | -- | ---- | -- |

be substantiated by the X-ray data of table II for lanthanum. When X-ray data were obtained at a temperature above the transformation temperature (500° F), the pattern contained lines for some retained hexagonal form. If the sample were held at temperature (above transformation) for a long period of time, complete conversion would occur. The friction data obtained above 400° F represent the cubic structure of lanthanum.

A crystal transformation is introduced by increasing the temperature of the material. Increasing sliding velocity can produce increases in specimen temperatures without increasing the ambient temperature. Friction data were therefore obtained with lanthanum sliding on 440-C stainless steel in vacuum at various sliding velocities. The results obtained are presented in figure 4(b)). At sliding velocities to 375 feet per minute, the friction coefficient was less than 0.4 or very nearly the same as obtained at ambient temperatures to 165° F. At sliding velocities above 375 feet per minute, the friction coefficient increased and reached a maximum of 1.2 at about 750 feet per minute. This marked change in friction is believed to reflect the crystal transformation of lanthanum from close-packed hexagonal (friction coefficient of less than 0.4) to face-centered cubic (friction coefficient of 1.2). If after running at 980 feet per minute the specimens were stopped and allowed to cool to room temperature overnight, the friction data obtained at 250 feet per minute corresponded to those obtained with the hexagonal crystal form, which indicated that the transformation was reversible on slow cooling.

The portion of the friction experiments conducted with the face-centered cubic form of lanthanum were not only characterized by high friction values but by very marked surface distress as indicated by unstable sliding of the rider



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(a) Sliding velocity, 980 feet per minute.

(b) Sliding velocity, 196 feet per minute.

Figure 5. - 440-C stainless steel disk specimens. Rider specimen, lanthanum; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; ambient temperature, 75°F; duration of run, 1 hour.

TABLE III. - WEAR FOR VARIOUS RIDER MATERIALS

[Sliding against hardened 440-C stainless steel; load, 1000 g; ambient pressure, 10^{-9} mm Hg; duration of experiment, 1 hr.]

| Material | Hardness (DPH) ^a | Sliding velocity, ft/min | Rider wear, cu in./ft sliding |
|-----------------------|-----------------------------|--------------------------|--------------------------------|
| Lanthanum | 40 | 200 980 | 3.40×10^{-9} 14.18 |
| Samarium | 45 | 390 | 1.31×10^{-9} |
| 440-C stainless steel | 600 | 390 | 10.47×10^{-9} |

^aDiamond pyramid hardness.

specimen against the disk. This behavior pattern is analogous to that observed with other cubic structures (e.g., iron and nickel) in vacuum. The result of this behavior can be seen in the photographs of the 440-C disk specimen of figure 5. At a sliding velocity of 980 feet per minute (cubic structure), mass metal transfer of lanthanum to the 440-C disk specimen occurred. The globules of metal transferred in some instances stood $3/32$ inch above the 440-C surface. With the same material combination at 196 feet per minute (hexagonal structure), the run was very smooth and a very thin transfer film of lanthanum to 440-C was observed. The wear values to lanthanum obtained at the two sliding velocities are presented in figure 4(b) (p. 6) and in table III.

Reference 1 indicates that the crystal transformation of lanthanum is pressure sensitive. Increasing the load upon the lanthanum rider specimen should induce the crystal transformation. Examination of the friction coefficient as a function of load in figure 4 indicates that increasing the load can bring about the crystal transformation. This transformation, however, could be due to increasing temperature resulting from increasing load. At loads above 1500 grams the coefficient of friction begins to increase. If

after running at 2500 grams the load is reduced to 1000 grams the friction coefficient remains high. The specimens were allowed to stand overnight unloaded. At 500 grams the friction returned to near the original value, which indicated again the reversibility of the crystal transformation of lanthanum.

Although in those experiments with the lanthanum sliding on 440-C a transfer film of lanthanum to 440-C resulted in lanthanum sliding on lanthanum, it was decided to determine the friction characteristics of lanthanum sliding on itself. The friction results obtained at various sliding velocities with lanthanum sliding on lanthanum are presented in figure 6. At sliding velocities below 350 feet per minute the friction coefficient was less than 0.4. When the sliding velocity was increased above 375 feet per minute, the friction coefficient increased and reached a value of about 1.4. The increase occurred at approximately the same sliding velocity encountered with lanthanum sliding on 440-C stainless steel. When the specimens were allowed to cool, the friction coefficient returned to the original value (less than 0.4), which again attested to the reversibility of the crystal transformation.

Although the concept of the influence of solid solubility on friction, wear, and welding tendencies is frequently referred to in this literature, the data obtained with lanthanum sliding on lanthanum would seem to indicate that crystal structure may be of appreciable importance.

Neodymium

Neodymium, praseodymium, and lanthanum have, among the rare-earth metals, the greatest similarities in both chemical and physical properties. The literature (refs. 1 and 2), however, does not indicate a crystalline transformation

for neodymium from the hexagonal form below 1584° F. Friction experiments were therefore conducted as a function of sliding velocity and temperature for neodymium (99 percent, with praseodymium as the principal impurity) sliding on 440-C stainless steel. The results obtained in these experiments are presented in figure 7. Based on the high temperature associated with the transformation from the hexagonal to the body-centered form, the friction coefficient was anticipated to remain relatively low in the range of sliding veloc-

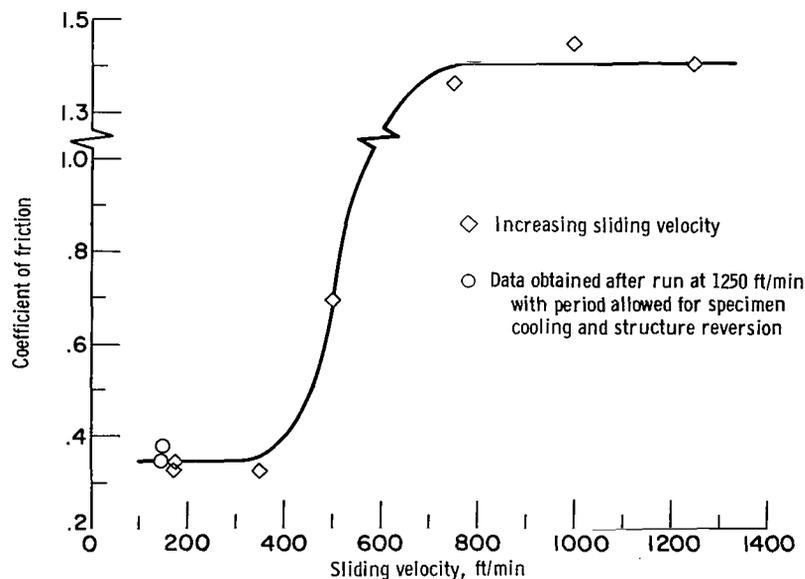


Figure 6. - Coefficient of friction for lanthanum sliding on lanthanum at various sliding velocities in vacuum (10^{-9} mm Hg). Load, 500 grams; ambient temperature, 75° F.

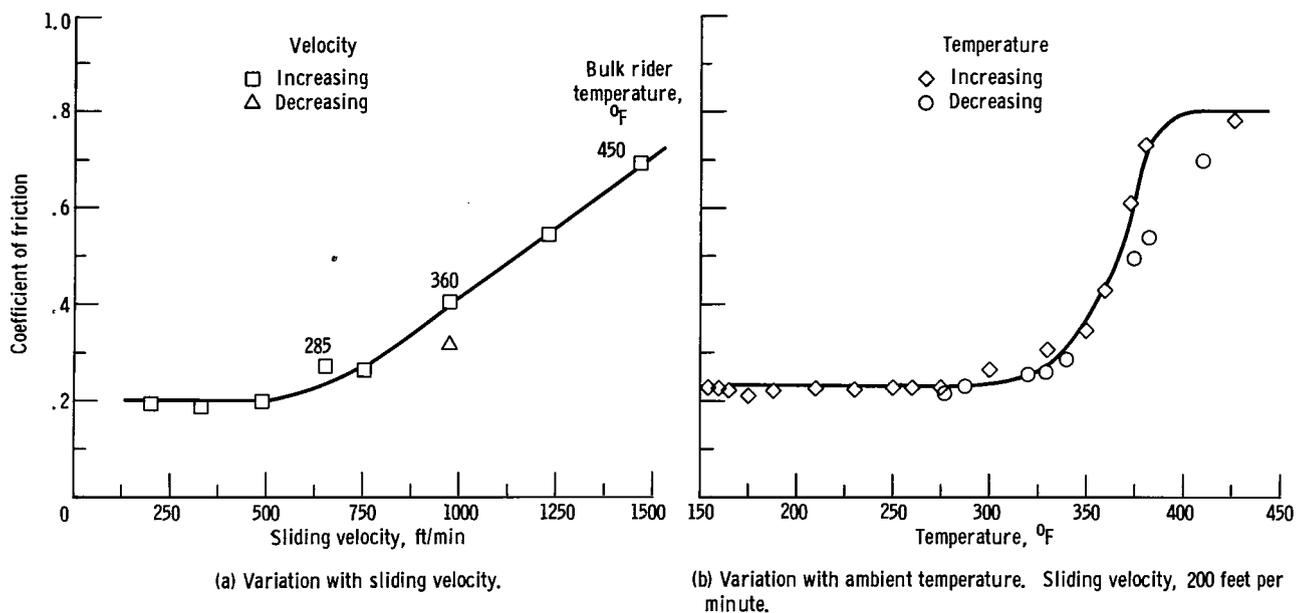


Figure 7. - Coefficient of friction for neodymium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams.

ities and temperatures investigated. The experimental evidence, however, as indicated in figure 7, did not bear out the anticipated results.

Examination of the coefficient of friction as a function of ambient temperature for neodymium sliding on 440-C stainless steel indicated that the friction coefficient was less than 0.25 at ambient temperatures to 300° F. Above 300° F, as indicated by figure 7, the coefficient of friction began to increase markedly.

Friction data obtained in figure 7 for neodymium sliding on 440-C stainless steel as a function of sliding velocity indicated an increase in friction coefficient at sliding velocities above 500 feet per minute. The rider specimen (neodymium) bulk temperature was measured during the sliding velocity experiments, and some of the values obtained are presented in figure 7. With the first friction data point obtained above 0.2 an indicated temperature of 285° F was recorded. This value is about 15° F below that obtained in the ambient-temperature experiments.

The sliding-velocity and ambient-temperature experiments with the neodymium sample examined (99 percent) indicated that a crystal transformation for neodymium must occur below 1584° F, the temperature indicated in the literature. The rider specimens used in this study were therefore placed in an argon atmosphere and heated in an X-ray furnace to 850° F. X-ray patterns obtained at 850° F did not correspond to those obtained at room temperature. The interplanar spacing d values obtained are presented in table II (p. 7) and indicate a crystal transformation. Further, as indicated in reference 1, small amounts of alloying elements (impurities) can influence crystal transformation temperatures. This effect is reflected in the transformation temperatures reported in references 1 to 3. With 99.0 percent lanthanum refer-

ence 3 reports a crystal transformation temperature of lanthanum from the hexagonal to the cubic structure of 1112° to 1202° F, while with higher purity lanthanum (99.9 percent) references 1 and 2 report 500° F as the transformation temperature. The addition of small percentages of alloying materials may be a method for retaining the desirable friction properties of the hexagonal form.

Praseodymium

Since, as mentioned earlier, the properties of lanthanum, neodymium, and praseodymium are extremely similar and they all have the same form of the hexagonal crystal structures, it was decided to examine the friction properties of praseodymium (99 percent and 99.9 percent). Some experiments were conducted with praseodymium sliding on 440-C stainless steel and the friction coefficient was determined both as a function of sliding velocity and ambient temperature. The results obtained in these experiments are presented in figure 8. In general, at low sliding velocities and ambient temperatures the

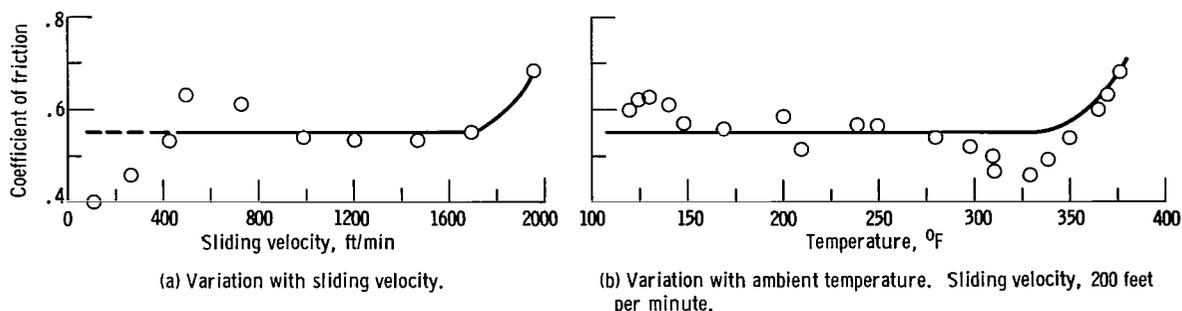


Figure 8. - Coefficient of friction for praseodymium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams.

friction coefficient was higher than those observed with lanthanum and neodymium. At ambient temperatures above 350° F or at a sliding velocity of 1950 feet per minute an increase in friction was observed. This increase may reflect a transformation similar to that observed for neodymium and lanthanum. Insufficient evidence, however, is available to substantiate a transformation.

Holmium, Erbium, Gadolinium, Dysprosium, and Yttrium

The rare-earth metals, holmium, erbium, gadolinium, and dysprosium, as well as yttrium, have the magnesium-type, AB packing sequence or the simplest type of stacking in the hexagonal crystal form. Since this form differs from that of lanthanum, neodymium, and praseodymium, some friction experiments were conducted as a function of sliding velocity for these metals sliding on 440-C. The results obtained in these experiments are presented in figure 9. With holmium, dysprosium, and erbium the coefficient of friction increased with increasing sliding velocity. This effect was not observed with gadolinium, where the friction remained relatively constant. Yttrium metal, however, did not exhibit the same trend of increase in sliding velocity. Yttrium, although similar to the rare earths in many respects, has properties that differ from those of the rare earths. It is interesting to note that the coefficients of

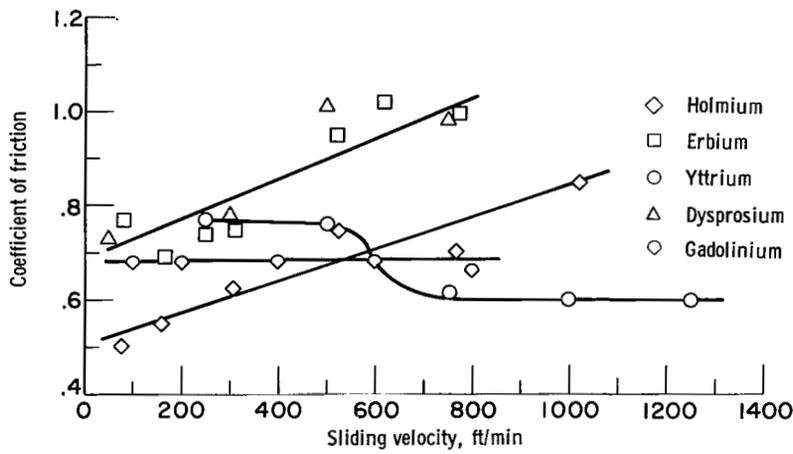


Figure 9. - Coefficient of friction of various rare-earth metals sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; ambient temperature, 75° F.

friction with the magnesium-type structure of erbium, holmium, gadolinium, dysprosium, and yttrium are higher than those obtained with those metals possessing the lanthanum-type hexagonal form.

Samarium

The most complex hexagonal crystal form is that of the metal samarium (refs. 9 and 10; see fig. 2, p. 4). The friction coefficients for

samarium sliding on 440-C at various sliding velocities in vacuum were determined and the results obtained are presented in figure 10. The coefficient of friction for samarium showed a slight increase with increasing sliding velocity. The friction values were, however, lower than those obtained with the materials possessing the simple magnesium-type hexagonal crystal form. The mean values obtained with samarium sliding on 440-C were very much lower than those obtained with 440-C sliding on 440-C despite a wide margin of difference in hardness (see table III, p. 8).

Effect of Hexagonal Crystal Form on Friction

If the three hexagonal crystal forms of the rare-earth metals are considered, the lowest friction coefficients are obtained with the lanthanum- and samarium-type structures. The rare earths and yttrium with the simple hexagonal, magnesium-type structure exhibit higher friction coefficients. Examination of lattice constants for the crystalline forms indicate variations in the c-axis. The friction coefficients for the rare earths, plotted as a function

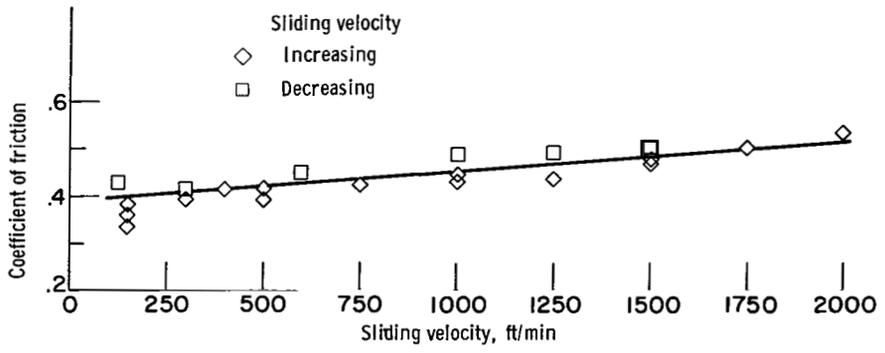


Figure 10. - Coefficient of friction of samarium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; ambient temperature, 75° F.

of c-axis length in angstroms, are presented in figure 11. The metals with the smallest c-axes exhibit the highest coefficients of friction.

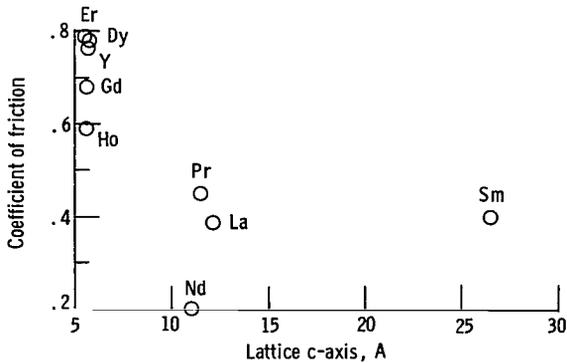


Figure 11. - Coefficient of friction as function of axis length in hexagonal crystal system of rare-earth metals. Ambient pressure, 10^{-9} millimeter of mercury; load, 1000 grams; sliding velocity, 250 feet per minute; ambient temperature, 75° F.

Thallium

In addition to the rare-earth metals there are other metals that exhibit polymorphism. Iron, cobalt, tin, zirconium, rhodium, hafnium, thorium, titanium, and thallium are some of these (ref. 11). Thallium metal has a close-packed hexagonal crystal form below 446° F. Above this temperature, it is transformed to the body-centered cubic structure. In order to determine the effect of crystal transformation on a metal outside the rare-earth series, some friction experiments were conducted with thallium metal sliding on

440-C in vacuum. Thallium metal was selected because it has a relatively low transformation temperature and has the normal hexagonal structure at room temperature. In addition it can be obtained with high purity. The material used in this study was 99.999 percent pure. The results obtained in the friction experiments are presented in figure 12.

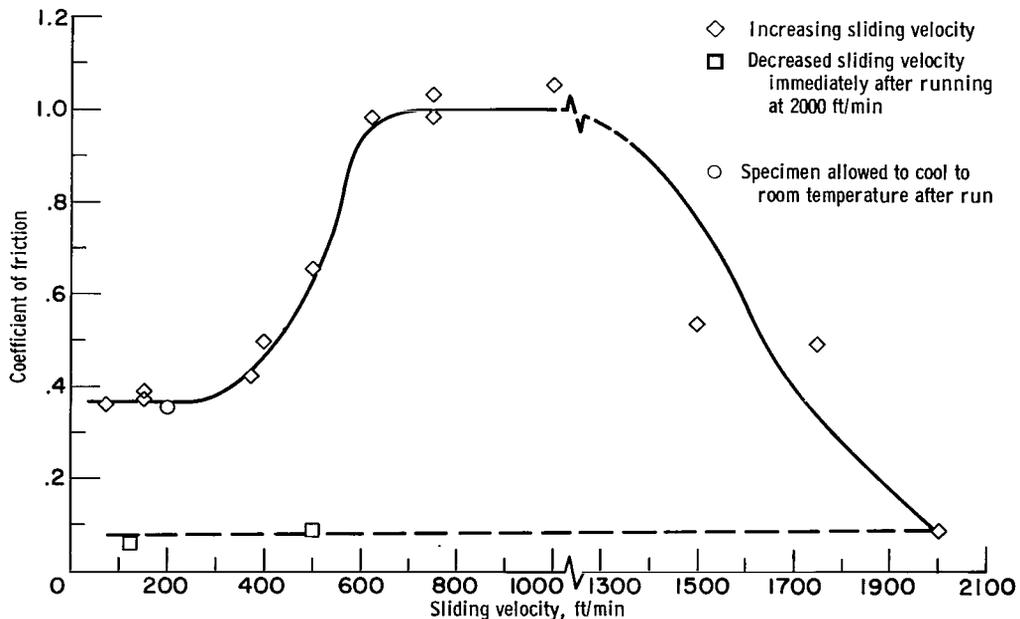


Figure 12. - Coefficient of friction for thallium sliding on 440-C stainless steel in vacuum (10^{-10} mm Hg). Load, 1000 grams; ambient temperature, 75° F.

At sliding velocities of less than 200 feet per minute the coefficient of friction was less than 0.4. The friction coefficient increased markedly at

sliding velocities in excess of 200 feet per minute and reached values in excess of 1.0. This marked change in friction is believed to be due to the crystal transformation from a close-packed hexagonal to a body-centered cubic structure. If the sliding velocity is further increased to 1000 feet per minute, the friction coefficient decreases. The melting point of thallium is 577° F. The decrease was believed to be due to melting of the thallium at the sliding interface. The friction coefficient at 2000 feet per minute was less than 0.1. In order to check that melting had occurred, the sliding velocity was decreased first to 500 and then to 125 feet per minute and the friction coefficient remained less than 0.1, which indicated that melting had, in fact, occurred. Normally an increase in friction is observed at the point of melting and is followed by a marked decrease. This may be assumed to have occurred at some point between 1000 and 2000 feet per minute, where friction data were not obtained.

The specimens were allowed to cool to room temperature and the friction coefficient returned to that obtained initially, which indicated that the crystal transformation was reversible.

Although the friction data for thallium were obtained with a 99.999-percent-pure metal and the experiments were conducted in a vacuum of 10^{-10} millimeter of mercury, two sets of results were obtained at a sliding velocity of 175 feet per minute. Five different friction experiments were conducted with thallium at this sliding velocity. These experiments gave three friction values of less than 0.4 and two values of near 1.0. Checking the ASTM X-ray Diffraction Card File shows that five different patterns exist for thallium. Since thallium exhibits only one crystal transformation, only two patterns should exist. It is possible, however, to quench in the high-temperature crystalline form. Thallium was heated and rapidly quenched in liquid nitrogen with some evidence of retaining the high-temperature form as identified by X-ray diffraction analysis. If the specimens were allowed to cool slowly in vacuum, the transformation was reversible (see fig. 12). If, however, rapid quenching during machining of the specimens occurred, then the high-temperature form could possibly be obtained. The existence of the two forms is believed to be responsible for the differences in friction observed.

Cerium

Some friction experiments were conducted with cerium metal in an argon atmosphere at -100° F and at room temperature. Cerium has a normal hexagonal lanthanum-type structure at -100° F and a face-centered cubic structure at room temperature. A friction coefficient of 0.22 was obtained at -100° F and of 1.2 at room temperature. These results again indicate the effect of crystal structure on friction.

Cobalt

Cobalt also undergoes a crystal transformation from the normal hexagonal to the face-centered cubic structure at about 750° F. It is indicated in the

literature that the transformation is very sluggish and that cobalt tends to exist as a mixture of two allotropes over a wide range of temperatures with the normal hexagonal structure predominating below 750° F and the face-centered cubic structure above that temperature. Friction data obtained in vacuum with cobalt sliding on itself indicated no real conclusive changes that might be attributed to a transformation. It may be that with proper heat treatment and quench, the two distinct forms could be obtained.

CONCLUSIONS

From an investigation of the crystal structure on friction characteristics of rare-earth and related metals in vacuum to 10^{-10} millimeter of mercury, the following observations and conclusions are made:

1. The crystal structure of some of the rare-earth metals and thallium markedly influence their friction, wear, and metal-transfer characteristics in vacuum. The hexagonal crystalline phase of the rare-earth metals and thallium exhibit much lower friction, wear, and metal-transfer characteristics than do the face-centered or the body-centered phases of these metals.
2. Crystal transformation for some of these metals (e.g., lanthanum) could be induced by varying sliding velocity and load as well as by varying ambient temperatures.
3. Of the three hexagonal-type crystal structures, the most favorable friction characteristics are obtained with those with the largest c-axis, that is, those metals with the lanthanum- and samarium-type crystal structures.
4. Although data in the literature do not indicate a crystalline transformation for neodymium below 1584° F, friction data of this investigation indicated that one can occur at a considerably lower temperature. X-ray diffraction data obtained in an argon furnace confirmed a transformation at a temperature below 850° F.
5. Friction data obtained with lanthanum sliding on either lanthanum or on 440-C stainless steel indicated a crystal transformation of lanthanum.

Lewis Research Center
National Aeronautics and Space Administration
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