NACA RM E58B11

RM E58B11

NACA

RESEARCH MEMORANDUM

EFFECT OF SLIDING VELOCITY ON FRICTION PROPERTIES AND ENDURANCE LIFE OF BONDED LEAD MONOXIDE COATINGS AT TEMPERATURES UP TO 1250° F

By Harold E. Sliney

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

May 16, 1958
Declassified July 17, 1958

NACA RM E58B11

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF SLIDING VELOCITY ON FRICTION PROPERTIES AND ENDURANCE LIFE OF BONDED LEAD MONOXIDE COATINGS AT TEMPERATURES UP TO 1250° F

By Harold E. Sliney

4817

CO-1

SUMMARY

Studies were made to determine the effect of sliding velocity and ambient temperature on the friction properties and endurance life of thin lead monoxide (PbO) coatings bonded to type 440-C martensitic stainless steel. Friction coefficients were determined at ambient temperatures from 75° to 1250° F with sliding velocities ranging from 6 to 10,000 feet per minute. Endurance life was determined over the same temperature range at sliding velocities of 350 and 2400 feet per minute. For reference, bonded molybdenum sulfide (MoS_2) coatings were run as a standard at a sliding velocity of 350 feet per minute and temperatures of 75° and 500° F.

In general, the friction coefficient of PbO decreased with increasing ambient temperature and sliding velocity. Endurance life increased with increasing temperatures to 1000° F but decreased slightly at 1250° F. Since the coating material begins to melt at about 1320° F, the ambient temperature in this investigation was limited to 1250° F.

INTRODUCTION

A serious lubrication problem has resulted from the ever-increasing temperatures at which many aircraft and missile components are required to operate. This problem has stimulated research with solid lubricants capable of reducing the friction and wear of metal surfaces in sliding contact at high ambient temperatures.

Previous NACA Lewis research on bonded lead monoxide coatings for use as high-temperature dry-film lubricants is described in reference 1. The coatings were applied by fusing mixed lead monoxide (PbO) and silica (SiO_2) powders to steel surfaces in a manner similar to that employed in applying ceramic enamels. The effects of coating composition, coating thickness, and ambient temperature were studied. Coatings were found that, at a sliding velocity of 430 feet per minute, provided good lubricating properties and endurance lives from 500° to 1250° F.

Reference 1 indicates that good lubrication is related to the formation of glazed wear tracks when high surface temperatures are generated in the zone of sliding. Two variables that have a direct effect on the average surface temperature are ambient temperature and sliding velocity. Accordingly, in the present study, composition and thickness were held constant, and the controlled variables were sliding velocity and ambient temperature.

4817

This investigation was conducted to determine the combined effects of ambient temperature and sliding velocity on the lubricating properties of one of the more promising coating compositions of reference 1. The coefficient of friction was determined from 75° to 1250° F over a range of sliding velocities from 6 to 10,000 feet per minute. Endurance life was determined over the same temperature range at sliding velocities of 350 and 2400 feet per minute.

APPARATUS AND MATERIALS

Apparatus

The apparatus used for low sliding velocities (6 ft/min) is described in reference 2. The apparatus used for high sliding velocities (2400 to 10,000 ft/min) is described in reference 3. The apparatus used for all endurance tests and for friction tests at medium sliding velocities (300 to 2400 ft/min) has not been described in previous reports and is shown in figure 1. The disk specimen was fastened to the end of a rotating shaft driven by an electric motor through a pulley and belt drive. Sliding velocities were varied by changing pulley ratios and wear-track diameters. The rider specimen was mounted in the base of a stainless-steel pot, around which two 750-watt half-shell heaters were mounted to serve as a furnace. The furnace assembly was mounted on a rolling-contact thrust bearing supported through a vertical loading shaft. Loading was accomplished by first lowering the disk until it contacted the rider and then applying a normal upward force to the loading shaft by means of a lever system. Friction between the rotating disk and the rider tended to rotate the entire furnace assembly on the thrust bearing; this rotation was restrained through a linkage by a dynamometer ring. Friction force was measured with four strain gages attached to the dynamometer ring.

Materials

The rider specimens were cast Inconel with initial room-temperature hardnesses of Rockwell B-75 to 80. Each rider was cylindrical (3/8-in. diam. and 3/4-in. length) with a hemispherical tip (3/16-in. rad.) ground on one end. The disk specimens to which the coatings were bonded were type 440-C martensitic stainless steel. For sliding velocities up to 2400 feet per minute, the disks had 2.5-inch diameters and were 0.5-inch thick; for higher sliding velocities, the disks had 13-inch diameters and were also 0.5-inch thick. Before the coatings were applied, the plane surfaces of each disk were ground flat and parallel within 0.0005 inch.

The coatings evaluated in these experiments were prepared from mixed PbO and SiO_2 powders. Both oxides were certified reagent grades with particle sizes of less than 200 mesh.

PROCEDURE

Coating

The details of the coating procedure are reported in reference 1. In general, a thin layer of dry mixed powder consisting of 95 percent PbO and 5 percent SiO_2 (by weight) was dusted onto the flat surfaces of type 440-C stainless-steel disks, which were then placed in a furnace at 1650° F until the powder melted and formed a uniform molten film. The disks were removed from the furnace, placed on a water-cooled steel block, and cooled in room air. The coatings were finish ground to the desired thickness on a surface grinder with abrasive wheels of alumina with a vitrified bond, about a 46 grit and a K or J hardness. Peripheral wheel speed was about 4500 feet per minute; 0.0005 to 0.0002 inch of coating material was removed per cut. The surfaces were flooded with a coolant during grinding.

The phase diagram for the PbO-SiO_2 system indicates that a melt containing 5 percent by weight SiO_2 and a balance of PbO would, upon cooling to room temperature, result in a two-phase structure with an equilibrium composition of 75 percent by weight tetralead silicate and a balance of free PbO (ref. 4). The actual coatings probably approximated this composition but were complicated by nonequilibrium cooling and by the presence of about 5 percent iron oxide (Fe_3O_4), which was formed by oxidation of the base metal during firing of the specimen at 1650° F.

Cleaning

Prior to each test, both rider and disk specimens were cleaned according to the following procedure:

(1) Wash with acetone

(2) Scrub riders with levigated alumina (this step was omitted in cleaning coated disks to avoid embedding alumina particles) 4817

(3) Wash in tap water

(4) Wash in distilled water

(5) Wash in 95-percent ethyl alcohol

(6) Dry in room air

Experimental Testing

The friction properties of the coatings at various temperatures and sliding velocities were determined as follows: Temperature and load were held constant during each run. Friction was measured at each sliding velocity for a period of time sufficient to obtain representative values (usually 5 to 15 min). The sliding velocity was then increased, and the friction was again determined. This procedure was repeated until the maximum sliding velocities were obtained. The test was then repeated with new specimens by starting at the highest sliding velocities and incrementally decreasing the speed. Speed was varied in both directions and with separate sets of specimens to determine whether the prior sliding history of the specimens would have an effect on the friction properties in this type of test. No appreciable differences were noted under the conditions studied.

All tests, other than endurance, were run with the specimens under a normal load of 1 kilogram. A 2-kilogram load was used in the endurance experiments to reduce the time required for failure of the coatings. In some endurance tests, the full 2-kilogram load was applied at the beginning of the run. In others, the specimens were run in at incrementally increased loads according to the following loading sequence: 2 minutes each at 200, 400, 600, 1000, and 1600 grams, and, finally, the balance of the test at 2000 grams. The two methods of loading were used in order to study the effect of run-in on the endurance properties of the coatings.

RESULTS

Effect of Sliding Velocity and Temperature on Friction

In general, friction decreased when either sliding velocity or ambient temperature was increased. Figure 2(a) gives the friction coefficients of bonded PbO at three temperatures for sliding velocities in the medium-to-high speed range. Figure 2(b) gives the friction coefficients of bonded PbO at various temperatures in the low-to-medium speed range. In order to facilitate discussion, the data in these figures are summarized in figure 3, where friction is plotted against temperature for a number of different sliding velocities. The family of constant velocity curves was obtained as a series of cross plots through the faired-in isothermal curves of figure 2. Figure 3 illustrates that, at a very low sliding velocity (6 ft/min), friction decreased almost linearly with increased ambient temperature. At any given sliding velocity from 300 to 1200 feet per minute, a considerable decrease in friction was obtained as the ambient temperature was increased from 75° to about 500° F; friction was essentially constant from 500° to 1000° F, and a slight increase in friction occurred from 1000° to 1250° F. Similarly, at any given temperature from 75° to 1250° F, a considerable decrease in friction was obtained as the sliding velocity increased from 6 to 2400 feet per minute. At sliding velocities from 2400 to 10,000 feet per minute, the friction coefficient was very low (0.05 to 0.08) and was practically insensitive to changes in either sliding velocity or ambient temperature.

Effect of Sliding Velocity and Temperature on Endurance Life

In many applications, the endurance life of bonded solid lubricants is of more practical importance than the coefficient of friction. Therefore, the endurance characteristics of the PbO coatings were determined.

The bar graphs in figure 4 give the endurance lives at 75°, 500°, 1000°, and 1250° F with sliding velocities of 350 and 2400 feet per minute. In these tests, the surfaces were run in at gradually increased loads during the first 10 minutes of each experiment. At a given ambient temperature, the endurance life (expressed as cycles to failure) was somewhat longer at the lower sliding velocity. Figure 4 indicates, however, that ambient temperature generally had more effect than sliding velocity on the cyclic endurance life. The poorest endurance life was obtained at 75° F. As the ambient temperature was increased, the endurance life increased and approached a maximum at around 1000° F, and then decreased somewhat at 1250° F. The maximum ambient temperature at which the coatings should be used is 1250° F; this limit is necessary because the coating material begins to melt at about 1320° F.

Effect of Run-in on Endurance Life

Figure 5 illustrates the effect of run-in on the endurance life of bonded PbO coatings at 75° and 500° F with a sliding velocity of 350 feet per minute. For reference, the endurance-life values for bonded molybdenum disulfide (MoS_2) coatings, which were run under identical conditions as a standard, are also shown. Run-in at gradually increased loads did not improve the endurance life of the PbO coatings. Bonded MoS_2 coatings, on the other hand, appeared to be sensitive to the rate of initial loading. 4817 At 75° F, run-in of the MoS_2 coatings greatly improved endurance life but, at 500° F, the improvement was slight.

At room temperature, the endurance life of PbO coatings was approximately equal to that of MoS_2 coatings which had not been initially run in at light loads. At 500° F, the endurance of PbO coatings was superior, regardless of the loading rate. At 1000° and 1250° F, no comparisons were made because of the chemical instability of MoS_2 at these temperatures.

DISCUSSION OF RESULTS

Changes in sliding velocity generally had a more pronounced effect on the coefficient of friction than on the cyclic endurance life of the PbO coatings. Increasing the sliding velocities resulted in some decrease in endurance life but had a very beneficial effect in lowering the friction.

The low friction associated with high sliding velocity is probably attributable to the higher surface temperatures generated at high speeds. High surface temperatures favor the formation of glazes on the sliding surfaces. Glazes are essentially noncrystalline in structure; therefore, they become quite soft over a considerable temperature range below the melting point of the corresponding crystalline material. Within the temperature range for softening, a glaze under stress flows plastically or viscously. The higher the temperature within this range, the lower is the shear strength (viscosity) and, thus, the friction. Since the thermal conductivity of ceramics is very low, most of the frictional heat will be confined to the surface, while the bulk of the coating will be essentially at ambient temperature. Friction is dependent on surface phenomena influencing interfacial shear; therefore, it is not surprising that it should be affected by increases in surface temperature accompanying increased sliding velocity.

Because cyclic endurance life is more dependent on ambient temperature than on sliding velocity, endurance is apparently determined primarily by subsurface or bulk properties of the coating. With the

4817

particular specimen configurations used in these experiments (hemisphere against flat coated surfaces), each cycle was essentially a stress cycle over every particle of the coating in the sliding zone. This suggests that the characteristics of the coating that determine endurance life are properties such as the bond strength through the ceramic-metal transition layer.

Comparison of the effects of run-in on the PbO coatings and the reference MoS_2 coatings should be of interest. The observation that the life of bonded MoS_2 is improved by careful run-in agrees with reports in the literature (refs. 5 to 7) concerning orientation of MoS_2 crystals. Careful preliminary running at moderate loads allows time for the orientation of MoS_2 crystals prior to the application of high loads. A considerable number of cycles may be required to strongly orient MoS_2 held in a resinous matrix. Properly oriented crystals will have the low-shear-strength planes parallel to the direction of sliding, and the high-shear-strength planes will usually be parallel to the direction of loading. Such an orientation may impart good compressive strength and thereby improve endurance life. Since PbO coatings were practically unaffected by the loading rate, crystal orientation does not appear to be a factor in determining the film strength. This is to be expected because the actual lubricant is an amorphous glaze with completely isotropic properties.

A further contrast between MoS_2 and PbO coatings was observed. With MoS_2 lubrication, the coefficient of friction decreases with increasing load (refs. 8 and 9). The PbO coatings showed no significant variation in the coefficient of friction as the load was increased from 200 to 2000 grams during the run-in prior to endurance tests.

Lead monoxide coatings provided excellent lubrication from 500° to 1250° F at moderate-to-high sliding velocities (300 to 10,000 ft/min), and from 1000° to 1250° F at low sliding velocities (6 ft/min). Because of very good friction properties, good endurance properties, and ease of application, MoS_2 coatings were excellent at temperatures up to about 500° F.

SUMMARY OF RESULTS

Friction and endurance experiments with solid lubricant coatings gave the following results:

1. Bonded lead monoxide (PbO) coatings were shown to be useful as low-friction bearing surfaces over a wide range of temperatures and sliding velocities. A downward trend in friction was obtained when either temperature or sliding velocity was increased. This trend applied up to the maximum useful ambient temperature of 1250° F and up to the maximum velocity studied (10,000 ft/min).

2. Endurance life increased with increasing temperature up to a maximum at about 1000° F and then decreased somewhat at 1250° F.

3. Run-in of the sliding surfaces at gradually increased loads did not appear to have any beneficial effect on the endurance of PbO coatings. On the other hand, the endurance life of the particular resin-bonded molybdenum disulfide (MoS_2) coatings used as a standard in this investigation was improved by run-in. At room temperature, the endurance life of the PbO coatings was about the same as that of resin-bonded MoS_2 coatings that had not been run in. At 500° F, endurance of the PbO coatings was superior to that of MoS_2, regardless of the run-in procedure. 4817

4. Bonded PbO coatings are intended primarily for high-temperature applications. High friction was obtained at room temperature, except at sliding velocities in excess of 1000 feet per minute. However, the reasonable endurance life at room temperature indicated that the coatings can be useful in many high-temperature applications that require starting at, or cycling through, room temperature.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 17, 1958

REFERENCES

1. Sliney, Harold E., and Johnson, Robert L.: Bonded Lead Monoxide Films as Solid Lubricants for Temperatures up to 1250° F. NACA RM E57B15, 1957.

2. Peterson, M. B., and Johnson, R. L.: PbO and Other Metal Oxides as Solid Lubricants for Temperatures to 1000° F. Lubrication Eng., vol. 13, no. 4, Apr. 1957.

3. Johnson, Robert L., Swikert, Max A., and Bisson, Edmond E.: Friction at High Sliding Velocities. NACA TN 1442, 1947.

4. Levin, Ernest M., McMurdie, Howard F., and Hall, F. P.: Phase Diagrams for Ceramists. The Am. Ceramic Soc., Inc., 1956, p. 59.

5. Feng, I-Ming: Lubricating Properties of Molybdenum Disulfide. Lubrication Eng., vol. 8, no. 6, Dec. 1952, pp. 285-288; 306-308.

6. Kingsbury, E. P.: Solid Film Lubricants at High Temperature. Preprint No. 57LC-7, ASLE, 1957.

7. Godfrey, Douglas, and Bisson, Edmond E.: Bonding of Molybdenum Disulfide to Various Materials to Form a Solid Lubricating Film. I - The Bonding Mechanism. NACA TN 2628, 1952.

8. Boyd, John, and Robertson, B. P.: The Friction Properties of Various Lubricants at High Pressure. Trans. ASME, vol. 67, no. 1, Jan. 1945, pp. 51-56; discussion, pp. 56-59.

9. Milne, A. A.: Lubrication of Steel Surfaces with Molybdenum Disulfide. Research, vol. 4, 1951, p. 93.

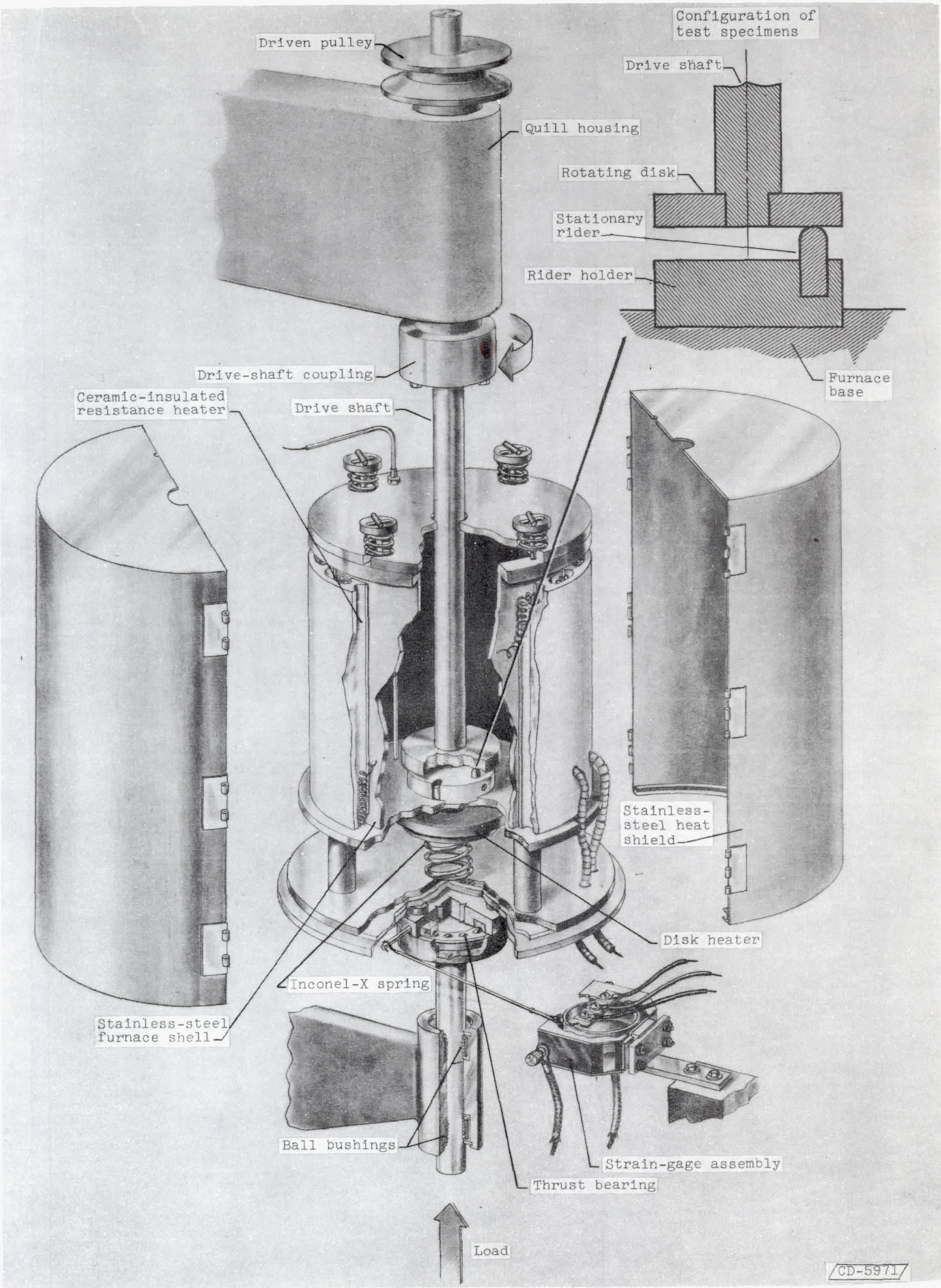
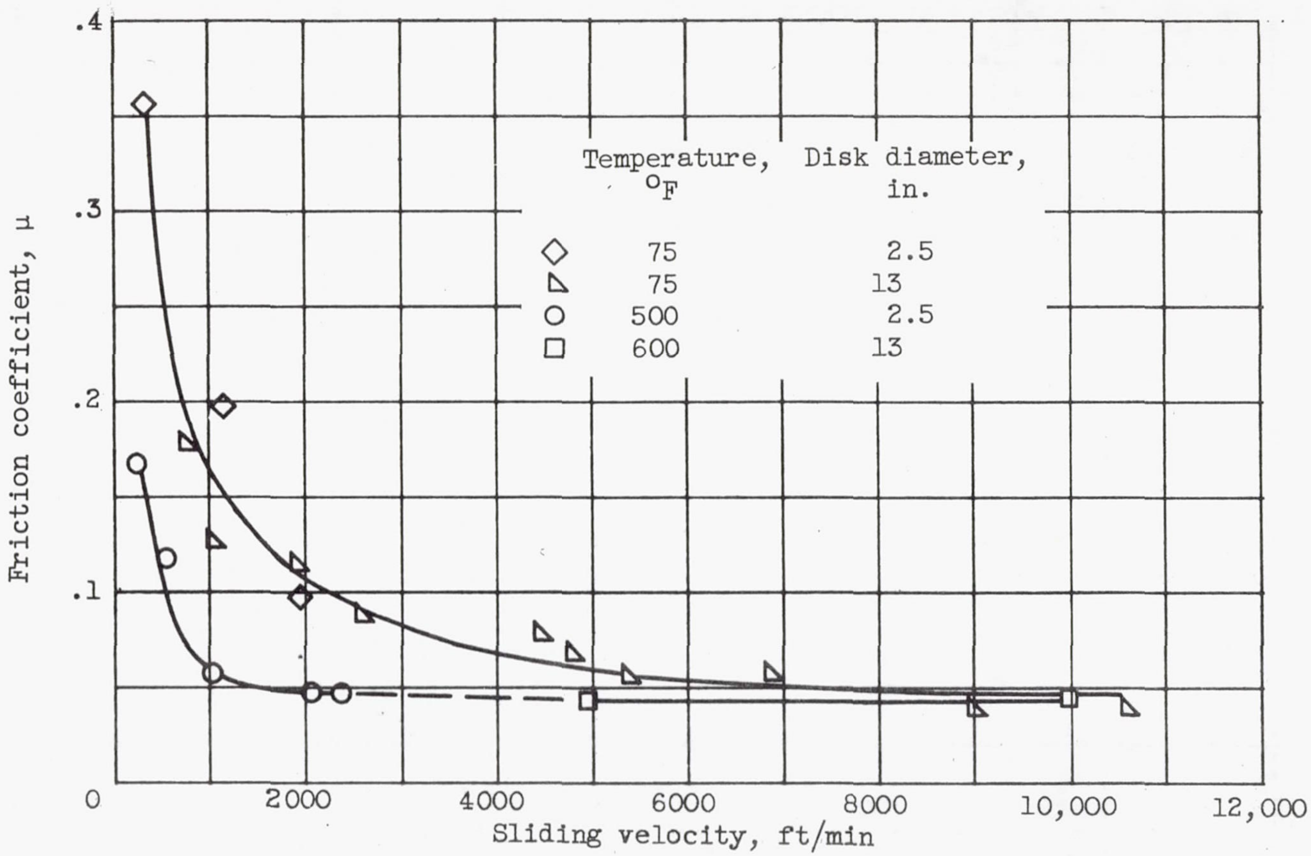


Figure 1. - Apparatus for all endurance tests and for friction tests at medium sliding velocities of 300 to 2400 feet per minute.

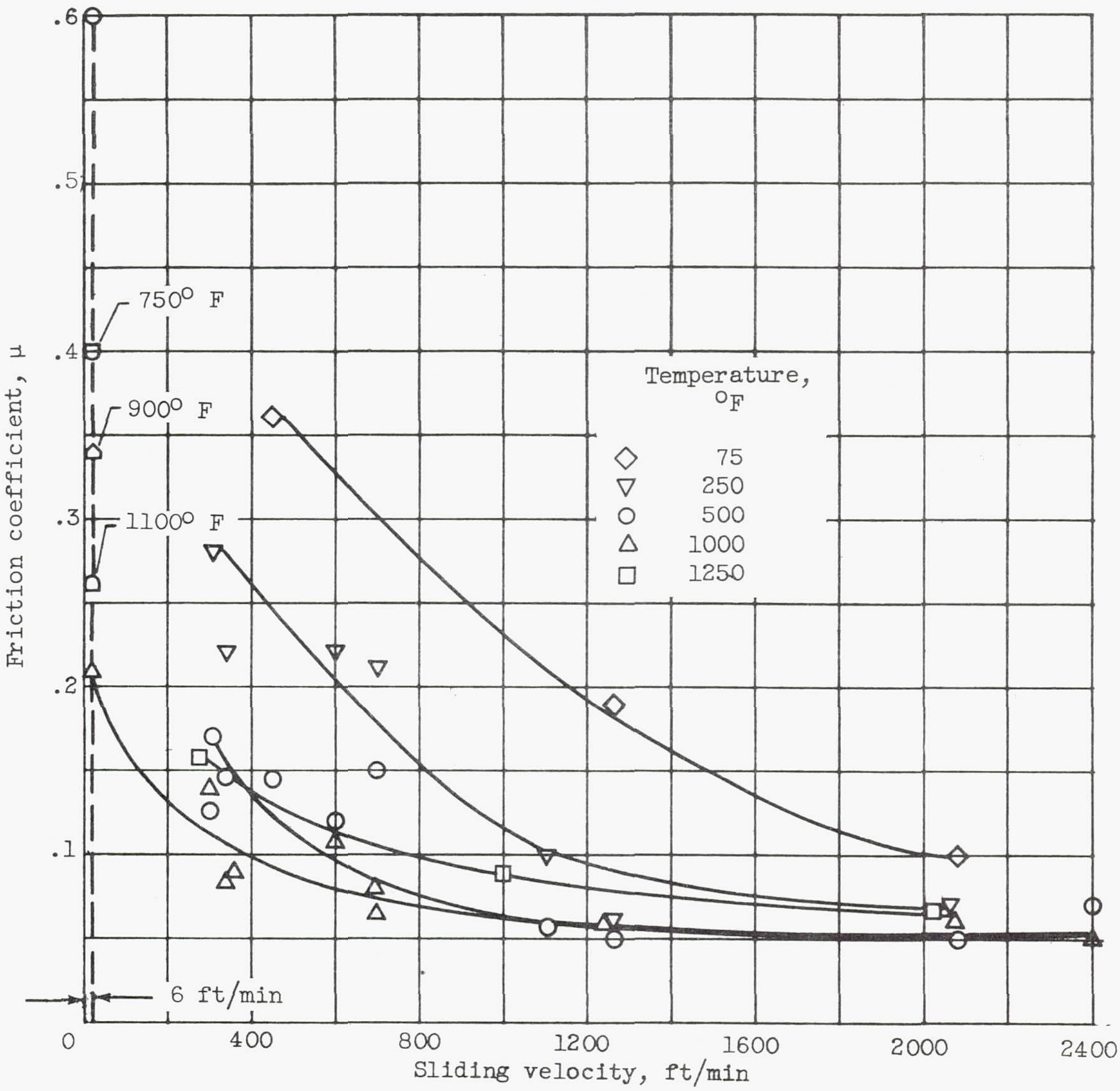
4817



(a) Medium-to-high sliding velocities.

Figure 2. - Friction coefficient of bonded lead monoxide coatings at various sliding velocities. Load, 1000 grams; rider, cast Inconel hemisphere (3/16-in. rad.); coatings, 0.001 inch thick on type 440-C stainless-steel disks.

4817



(b) Low-to-medium sliding velocities.

Figure 2. - Concluded. Friction coefficient of bonded lead monoxide coatings at various sliding velocities. Load, 1000 grams; rider, cast Inconel hemisphere (3/16-in. rad.); coatings, 0.001 inch thick on type 440-C stainless-steel disks.

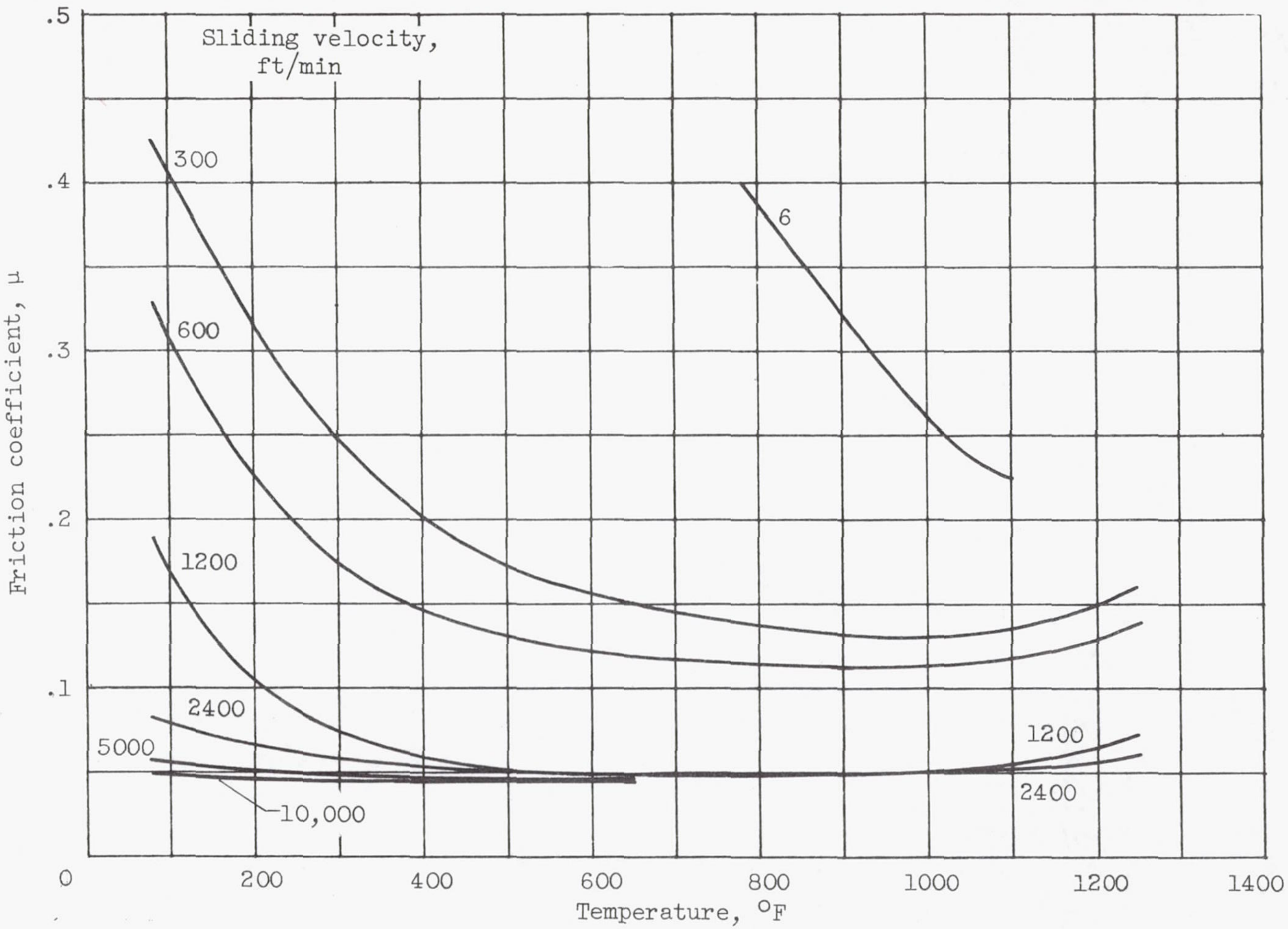


Figure 3. - Cross plots of figures 2(a) and (b), summarizing friction coefficient of bonded lead monoxide base coatings over the complete range of sliding velocities and ambient temperatures investigated. Load, 1000 grams; rider, cast Inconel hemisphere (3/16-in. rad.); coatings, 0.001 inch thick on type 440-C stainless-steel disks.

4817

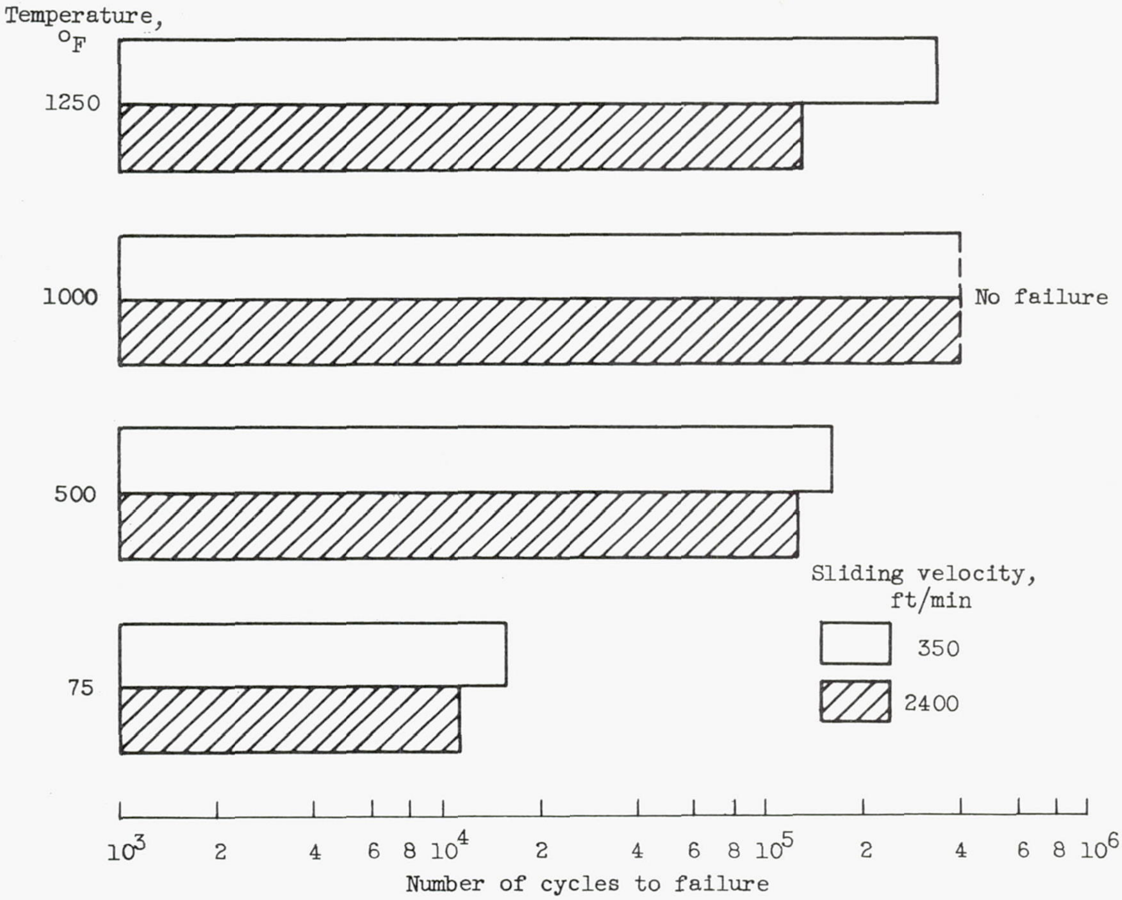


Figure 4. - Effect of ambient temperature and sliding velocity on endurance of bonded lead monoxide base coatings after run-in. Test load, 2000 grams; rider, cast Inconel hemisphere (3/16-in. rad.); coatings, 0.001 inch thick on type 440-C stainless-steel disks.

4817

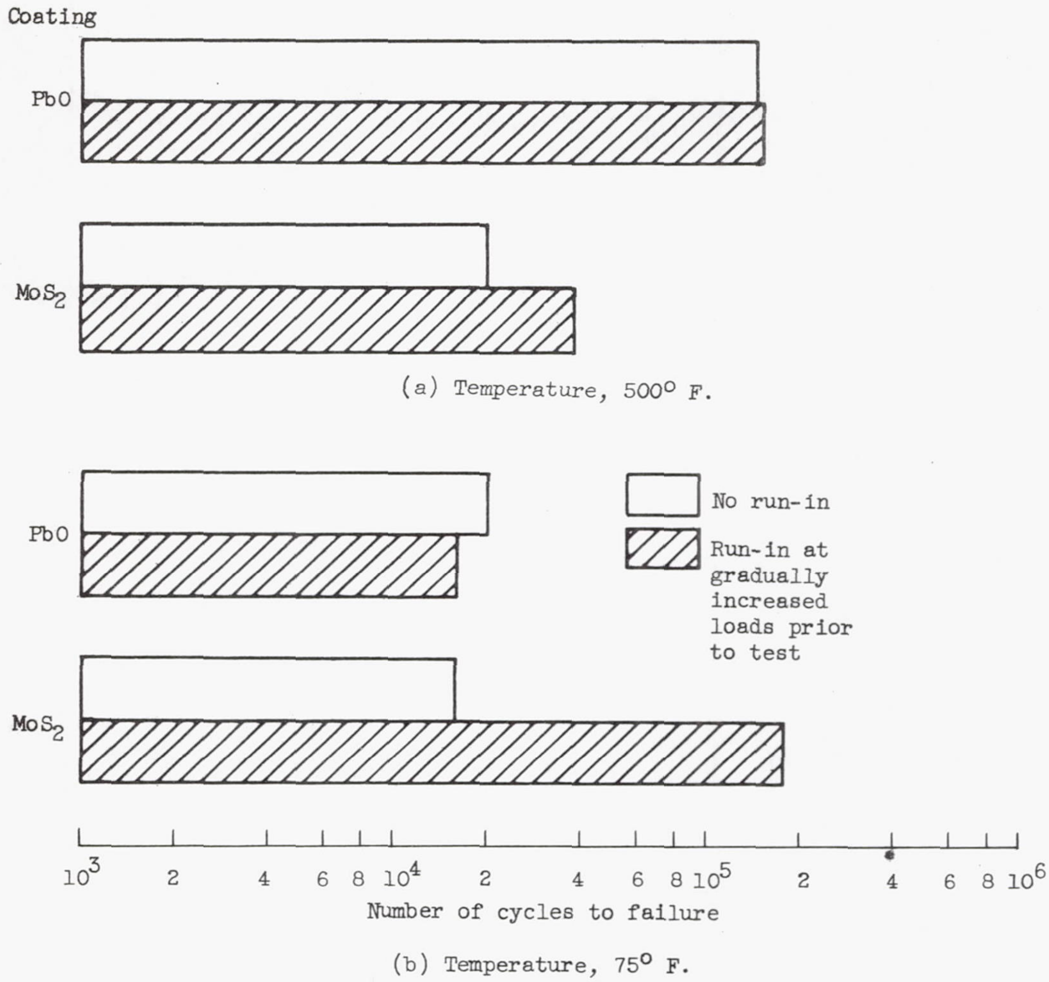


Figure 5. - Effect of run-in on endurance of lead monoxide coatings at 75° and 500° F with reference to standard, bonded molybdenum disulfide coatings (cycles during run-in not included in lines shown). Test load, 2000 grams; rider, cast Inconel (3/16-in. rad.); sliding velocity, 350 feet per minute; coatings, 0.001 inch thick on type 440-C stainless-steel disks.