6p

N63-12591

NASA TN D-1580

NASA TN D-1580

code-1

5 54248
18p 5

TECHNICAL NOTE

D-1580

BOUNDARY LUBRICATION CHARACTERISTICS OF A TYPICAL

BEARING STEEL IN LIQUID OXYGEN

By William F. Hady, Gordon P. Allen
and Robert L. Johnson

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON February 1963

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-1580

BOUNDARY LUBRICATION CHARACTERISTICS OF A TYPICAL BEARING STEEL IN LIQUID OXYGEN

By William F. Hady, Gordon P. Allen
and Robert L. Johnson

SUMMARY

Experiments were conducted in liquid oxygen to establish the fundamental boundary lubrication characteristics of liquid oxygen and to study the wear and friction mechanisms experienced by a metal-metal combination. A 3/16-inch-radius hemispherical rider was loaded against the flat surface of a $2\frac{1}{2}$-inch-diameter rotating disk. Both rider and disk materials were AISI 440-C chromium martensitic stainless steel heat treated to a Rockwell C hardness of 52 to 54. The loads were varied from 200 to 1500 grams and the sliding velocities from 250 to 8000 feet per minute.

These data demonstrate the boundary lubrication characteristics of a typical bearing material utilizing liquid oxygen as the lubricant. The results indicate that liquid oxygen is potentially a better lubricant than liquid hydrogen, because surface-reaction films that form in liquid oxygen can provide adequate protection of metal surfaces in sliding contact. The results also indicate that the adhesion concept of friction and wear derived from more conventional applications is valid for liquid-oxygen applications.

INTRODUCTION

The trend in liquid-propellant rocket engines has been toward simplicity of design with increased reliability of all component parts as the principal objective. This trend encourages experimental work to determine the feasibility of lubricating metal surfaces in sliding contact with the fuel, oxidant, or both used as the lubricant. Research on fuels and fuel additives as lubricants for bearings (ref. 1) and geared unit turbopumps (ref. 2) shows that they are potential lubricants. The fundamental principles of lubrication that apply for such a system, however, have not been established. Obtaining a better understanding of the basic phenomena of lubrication would greatly reduce the problem of determining the most feasible system. It is, therefore, necessary to determine material compatibility including thermochemical behavior (ref. 3) and to define the "lubrication criteria" over a range of conditions approximating those encountered in liquid-propellant rocket engines.

Previous investigations have shown that, under those conditions where beneficial oxide films can be established and maintained on surfaces in sliding contact, good lubrication is effected (ref. 4). On the other hand, where oxide films are unable to form naturally, as in the case of liquid hydrogen and liquid nitrogen, these films must be preformed to provide effective lubrication (refs. 5 to 7). Liquid hydrogen is being considered as a coolant for geared unit turbopumps; however, it is a reducing medium, and adverse effects such as high wear and high friction are a distinct probability. It seems logical, therefore, that liquid oxygen might provide better lubrication than liquid hydrogen, since the beneficial oxide film frequently associated with good lubrication could form (and reform) naturally.

Factors that are considered important to the role of the oxidizing media in boundary lubrication are (1) the ability of the fluid-material combination to form an adherent low-shear-strength oxide film, and (2) the effect of load and sliding velocity in generating heat at the sliding interface, which encourages the formation of these oxide films.

This investigation was conducted to establish the boundary lubrication characteristics over a range of loads and sliding velocities of a typical bearing metal (AISI 440-C stainless steel) sliding against itself in liquid oxygen. In friction and wear studies, a 3/16-inch-radius hemisphere contacted the flat surface of a rotating $2\frac{1}{2}$-inch-diameter disk. The loads employed ranged from 200 to 1500 grams, and the sliding velocities ranged from 250 to 8000 feet per minute.

APPARATUS

The apparatus used in this investigation is shown schematically in figure 1. The basic elements are a rotating disk specimen ($2\frac{1}{2}$-in. diam.) and a stationary hemispherically tipped rider specimen (3/16-in. rad.) in sliding contact with the disk (see inset). The disk is rotated by a variable-speed electric motor through a gearbox speed increaser coupled to the specimen shaft. Disk speed is monitored by a magnetic pickup whose output is fed into a digital readout instrument.

The rider specimen is loaded against the disk specimen by a pneumatically operated piston on the end of a gimbal-mounted arm. Through this arm, pressurizing gas (dry helium) is supplied. The arm is linked to a strain-gage assembly for measurement of frictional force.

The apparatus consists of two sections that may be separated for changing specimens. The lower section consists of four separate chambers: The inner chamber, or test chamber, is located within a "jacket" that may be filled with liquid nitrogen for cooling. This cooling jacket is surrounded by a vacuum chamber to reduce the boiloff rate of the cooling and test fluids. The outermost chamber, or spill chamber, surrounds the three chambers providing safe operation in the event excess amounts of the test fluid should escape. The upper section is a vacuum jacket through which the disk specimen drive-shaft housing and the rider specimen arm assembly pass. A series of carbon face seals are employed around the drive shaft, and flexible bellows are used on the rider arm assembly.

Fluorinated hydrocarbon oils are used to lubricate the gearbox and the support bearings in the shaft housing to prevent a reaction of the oil with the liquid oxygen in case the shaft seals fail.

The test fluid, liquid oxygen in this investigation, passes through a coil within the cooling jacket before entering near the bottom of the test chamber. In tests where the test fluid initially is in the gaseous state, the coil would condense the gas into the liquid state. Excess liquid and vapor are vented by a line leaving from a point near the top of the chamber. The liquid level within the test chamber is monitored by a capacitance probe and recorded on a circular chart capacitance recorder.

The cooling jacket is filled with liquid nitrogen and vented by two diametrically opposite lines. The coolant level is monitored with a carbon resistance probe. A full jacket is indicated by a sharp drop in output when the coolant absorbs the heater output.

PROCEDURE

Disk and rider specimens were heat treated to a Rockwell C hardness of 52 to 54 and finished to 4 to 8 microinches rms; the disk specimens were lapped to 2.5 microinches rms. Before each experiment the disk and the rider were given the same preparatory treatment. All the disk specimens were then given the following cleaning treatment: (1) immersed in an ultrasonic cleaning tank filled with water for 1/2 hour, (2) thoroughly rinsed with ACS certified acetone; (3) polished with moist levigated alumina on a soft cloth, and (4) thoroughly rinsed with distilled water. The remaining water was removed using filter paper. Each disk specimen was prepared just prior to being placed in the test chamber.

After the desired liquid-oxygen level was attained, the disk specimen was brought up to speed and the normal load was applied. Duration of runs was 60 minutes or less and was dependent on the stability of operation. The frictional force was measured continuously by resistance strain gages mounted on a dynamometer ring whose output was fed into a recording potentiometer. Rider wear was obtained by measuring the wear scar diameter and calculating the wear volume.

RESULTS

Effect of Sliding Velocity on Friction and Wear

Friction and wear data obtained for 440-C stainless steel sliding against itself in liquid oxygen at speeds up to 8000 feet per minute are shown in figure 2. The coefficient of friction decreased sharply from 0.84 to 0.32 as the sliding velocity was increased to 1500 feet per minute and gradually approached a value of 0.20 at 8000 feet per minute.

Chart recordings of friction against time may give some explanation of what occurs at the interface of the mating surfaces when a run is made in liquid oxygen. Over the entire range of sliding velocity at a load of 1000 grams, the initial frictional force was greater than the stabilized value as reported herein.

The peak value of the frictional force and the time required for stabilization were dependent on sliding velocity; the lower sliding velocities required a longer stabilization time. This peak value is indicative of nascent metal friction, while the lower stabilized value indicates that the oxide film was formed during the experiment because of continued frictional heating. Friction traces at the lower sliding velocities (250 to 1500 ft/min) appeared very ragged; the friction coefficient varied as much as ±0.10. Above 1500 feet per minute up to and including 3500 feet per minute, the friction traces became more smooth. At sliding velocities of 3500 feet per minute or higher, however, instantaneous increases in friction began to occur (fig. 3). The frequency of these sharp rises in friction increased as the sliding velocity increased from 3500 to 8000 feet per minute.

In the tests with a 1000-gram load the ability to form and maintain an oxide film appeared to be optimum in the range of 1500 to 3000 feet per minute. At sliding velocities less than 1500 feet per minute, the oxide film was not easily formed because of insufficient frictional heat. At sliding velocities above 3000 feet per minute, the oxide film was worn away at a rate exceeding its ability to reform. Visual inspections of test specimens showed that the oxide film was formed and maintained best in the range of 1500 to 3000 feet per minute. The film in this range had a reddish brown color. The test specimens showed that little or no film was formed on the surfaces at the lower sliding velocities. Above 3500 feet per minute, the film became black, which indicated a probable change in oxide composition and thickness. As the sliding velocity was increased from 3500 to 8000 feet per minute, increased proportions of the black oxide film were removed and more of the nascent metal was exposed.

The color of the films could be misleading in determining the oxide composition. It is possible that the oxide film observed after a test could have changed color between the time it was removed from the test chamber and the time it warmed to room temperature. Water vapor condensed on the surfaces of the disk and rider specimens during this time. Attempts were made to determine the composition of the film at room temperature; however, the results were inconclusive.

X-ray analysis of the powdered wear debris (easily rubbed off the surfaces of the test specimens) indicated that the debris was either ferric oxide (Fe_2O_3) or a solid solution of ferric oxide and chromic oxide (Fe_2O_3 and Cr_2O_3). Because of the quality of the film pattern taken, it was impossible to determine the exact composition of the wear debris. The chromium in 440-C stainless steel (16 to 18 percent) oxidizes quite readily to Cr_2O_3 when the metal is heated to high temperatures in air. Therefore, it is possible that, in the oxygen-rich medium of this investigation and with the frictional heat generated at the interface, a solid solution of Fe_2O_3 and Cr_2O_3 could be formed.

Forward reflection X-ray diffraction studies with low incident-angle beams were made of the film material in situ on the disk specimen to determine film composition; however, the film was so thin that the X-rays gave only characteristic diffraction patterns of the chromium carbides in the underlying base metal. A sample sufficient for powdered X-ray techniques could not be obtained by scraping the film from the disk.

The data of figure 2 indicate that a minimum in rider wear rate occurs at approximately 3000 feet per minute. The increased wear rate above 3000 feet per minute is attributed to a more rapid rate of removal of the oxide film compared with the rate at which the film can reform.

The photomicrographs (fig. 4) show wear areas of disk and rider specimens. The condition on the wear areas points out the importance of forming and maintaining an oxide film on the mating surfaces. Little or no oxide film was formed at 500 feet per minute; thus, little surface protection was furnished and the wear areas showed evidence of distress. At 2300 feet per minute, however, a continuous oxide film that provided adequate protection was noted. At 8000 feet per minute, areas of nascent metal throughout the film track wear area and plastic flow of metal on the trailing edge of the rider indicated that partial breakdown of the oxide film occurred. The size of the rider wear areas is not representative of wear value as reported, since each set was run for a specific time and not a set distance.

Surface phenomena responsible for the trend in rider wear rate may be described as follows: In spite of the cryogenic environment, the high temperatures encountered at the interface of the sliding specimens caused localized softening of the materials and led to plastic flow of the metal, as indicated by a buildup of metal on the trailing edge of the rider specimens. With progressive frictional heating at the higher sliding velocities, deformation of the base metal continued so that the inherently brittle oxides were fragmented from the metal because of their inability to deform along with the metal substrate. As these brittle oxides are removed, the proportional amount of contact between the nascent metals is increased, which leads to greater adhesion of the mating surfaces; the result is increased adhesive wear as described in reference 8. The wear debris, shown by X-ray analysis, could be the abrasive oxide Fe_2O_3. Its presence on the surface of or suspended in the liquid oxygen should have a marked effect on abrasive wear. With surfaces that have geometry or other properties conducive to retaining wear debris on contacting surfaces, abrasive wear can be predominantly important.

Effect of Load on Friction and Wear

The data of figure 5 show that a linear relation exists between frictional force and load for the four sliding velocities investigated. Because of this relation, the coefficient of friction is constant for each sliding velocity regardless of load. From this result, it can be deduced that the oxide film formed remains sufficiently thin so that the real area of contact increases proportionally with increasing load (ref. 9). The frictional force is, therefore, directly proportional to load; thus, the coefficient of friction is independent of load.

It is significant to note that when the curves in figure 5 are extrapolated, they pass through the origin. This indicates that hydrodynamic forces, which could be expected, are insignificant over the range of sliding velocities investigated.

Hydrodynamic forces that occur between two members moving relative to one another in fluids increase with increasing velocity (ref. 10). If a hydrodynamic force were experienced, however, a net reduction in the real load at the contacting surfaces would occur. This reduction would displace the line intercept from the origin. The displacement would represent the amount of hydrodynamic force acting in the system with the greater displacement occurring at the higher sliding velocities.

Wear data of 440-C rider specimens at four sliding velocities show an increasing trend with increasing load (fig. 6). The accelerated wear rate noted at 500 feet per minute indicates that the frictional heat required to initiate a reaction and to form a film on the disk surface was not sufficient even under a load of 1500 grams. The curves for 1000, 2300, and 5000 feet per minute show a more linear relation of wear against load. The curve for 5000 feet per minute shows that rider wear for all loads exceeds the wear at 2300 feet per minute. Visual inspection of disk wear areas after experiments at 5000 feet per minute confirmed the fact that even under the lightest load of 200 grams the oxide film was partly removed. Increased proportions of the base metal were exposed as the load was increased to 1500 grams.

DISCUSSION

The practical significance of these data may be deduced for a turbopump designed to utilize one of the propellants as a coolant-lubricant for mechanical components such as bearings and gears. Such a system may employ either the fuel or the oxidant, which in advanced rocket engines would be either liquid hydrogen or liquid oxygen. Liquid hydrogen might be a tempting choice because its lower temperature offers greater cooling ability. In such design choices, the possible use of oxygen should be considered carefully, however, since oxygen is a much better lubricating material than hydrogen and, hence, less cooling would be required. Furthermore, in hydrogen chemical reduction of surface films is apt to occur with the energy for reaction obtained from frictional heating. With the resultant nascent surfaces, interface welds that would render the parts inoperative are apt to occur. In liquid oxygen, however, as described herein, surface oxide films on metals are readily maintained over substantial ranges of operating conditions. These films prevent surface welding and can give low friction. The coefficients of friction of 440-C stainless steel sliding on 440-C stainless steel in liquid hydrogen, liquid nitrogen, and liquid oxygen are compared in figure 7. Materials in sliding contact in liquid oxygen must be selected with caution, however, to avoid the possibility of exothermic reactions that can be activated by frictional energy.

SUMMARY OF RESULTS

Experimental data obtained with a chromium martensitic stainless steel sliding on a chromium martensitic stainless steel in liquid oxygen showed the following basic characteristics of boundary lubrication:

1. There appeared to be an optimum sliding velocity at which rider wear was a minimum. For a 1000-gram load, minimum rider wear occurred at a sliding velocity of 3000 feet per minute. This combination of load and sliding velocity provided the necessary frictional heat required for forming and maintaining an apparent oxide film on the mating surfaces.

2. The coefficient of friction decreased with increased sliding velocity over the entire range. At sliding velocities above 3000 feet per minute for a 1000-g load however, instantaneous increases in the friction trace were observed. These increases indicated that the oxide film on the surface was being fragmented at a rate greater than the rate of formation.

3. Rider wear increased linearly with increasing load for each of the four sliding velocities: 500, 1000, 2300, and 5000 feet per minute.

4. The frictional force was proportional to the load within the range of sliding velocities and loads investigated. Hydrodynamic forces between the two members moving relative to one another in liquid oxygen were insignificant.

5. Within the scope of this investigation, the coefficient of friction was independent of load. This observation and other characteristics noted are consistent with the adhesion concept of lubrication, friction, and wear.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 18, 1962

REFERENCES

1. Butner, M. F., and Rosenberg, J. C.: Lubrication of Bearings with Rocket Propellants. Lubrication Eng., vol. 18, no. 1, Jan. 1962, pp. 17-24.

2. Hartman, Martin A.: Fuel Additive: A New System and Lubricant for Rocket Engine Gear Boxes. Lubrication Eng., vol. 18, no. 3, Mar. 1962, pp. 114-123.

3. Hauser, R. L., Sykes, G. E., and Rumpel, W. F.: Mechanically Initiated Reaction of Organic Materials in Missile Oxidizers. TR 61-324, Aeronautical Systems Div., 1961.

4. Buckley, Donald H., and Johnson, Robert L.: Effect of Inert, Reducing, and Oxidizing Atmospheres on Friction and Wear of Metals to 1000° F. NASA TN D-1103, 1961.

5. Wisander, D. W., Hady, W. F., and Johnson, R. L.: Friction Studies of Various Materials in Liquid Nitrogen. NACA TN 4211, 1958.

6. Wisander, D. W., and Johnson, R. L.: Wear and Friction of Impregnated Carbon Seal Materials in Liquid Nitrogen and Hydrogen. Advances in Cryogenic Eng., vol. 6, K. D. Timmerhaus, ed., Plenum Press, Inc., 1961.

7. Wisander, D. W., and Johnson, R. L.: Wear and Friction in Liquid Nitrogen with Austenitic Stainless Steel Having Various Surface Coatings. Advances in Cryogenic Eng., vol. 4, K. D. Timmerhaus, ed., Plenum Press, Inc., 1959.

8. Burwell, John T., Jr.: Survey of Possible Wear Mechanisms. Wear, vol. 1, no. 2, Oct. 1957, pp. 119-141.

9. Bowden, F. P., and Tabor, D.: The Friction and Lubrication of Solids. Claredon Press (Oxford), 1950.

10. Burwell, J. T., and Strang, C. D.: The Incremental Friction Coefficient - A Non-hydrodynamic Component of Boundary Lubrication. Jour. Appl. Phys., vol. 20, no. 1, Jan. 1949, pp. 79-89.

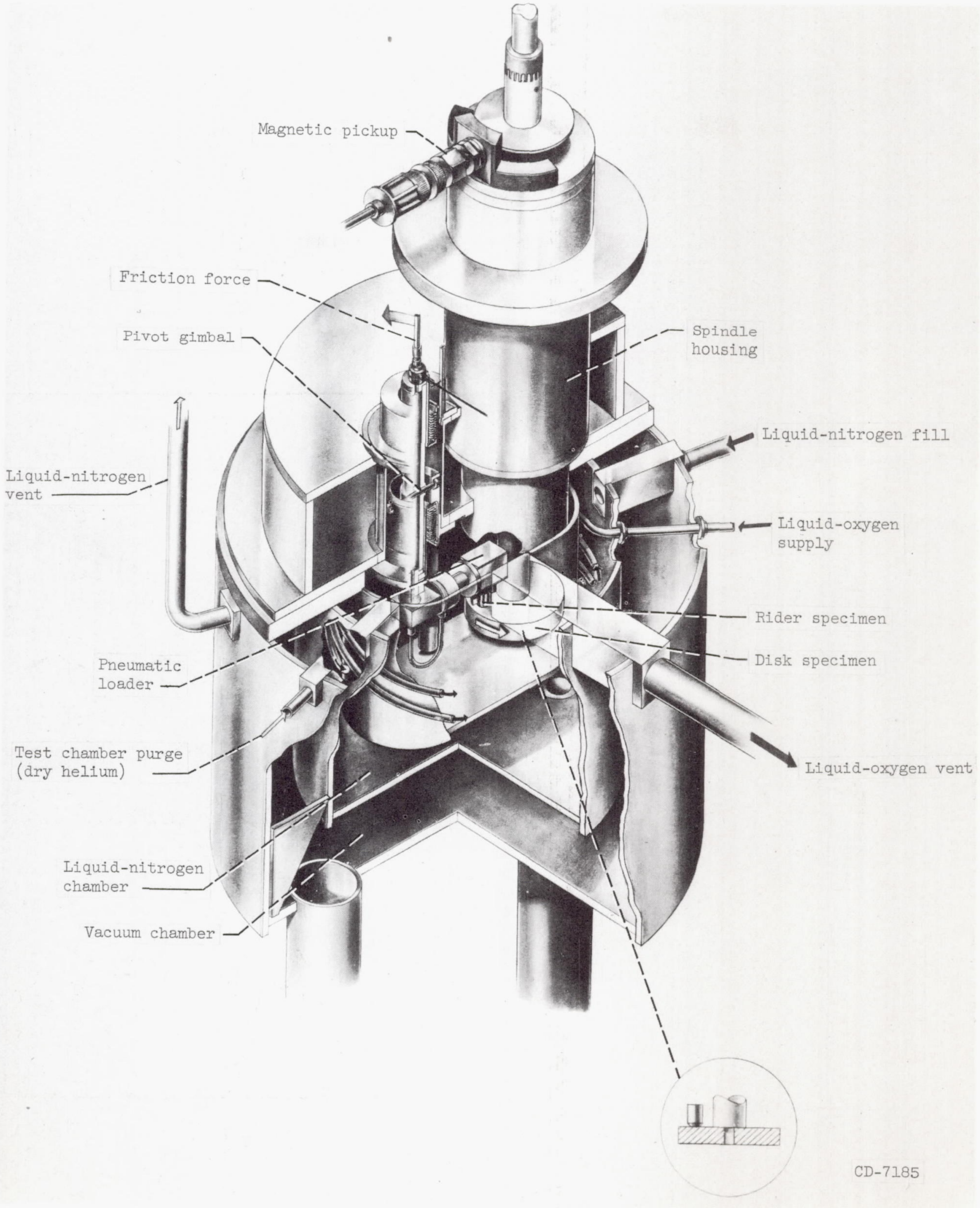


Figure 1. - Liquid-oxygen friction apparatus.

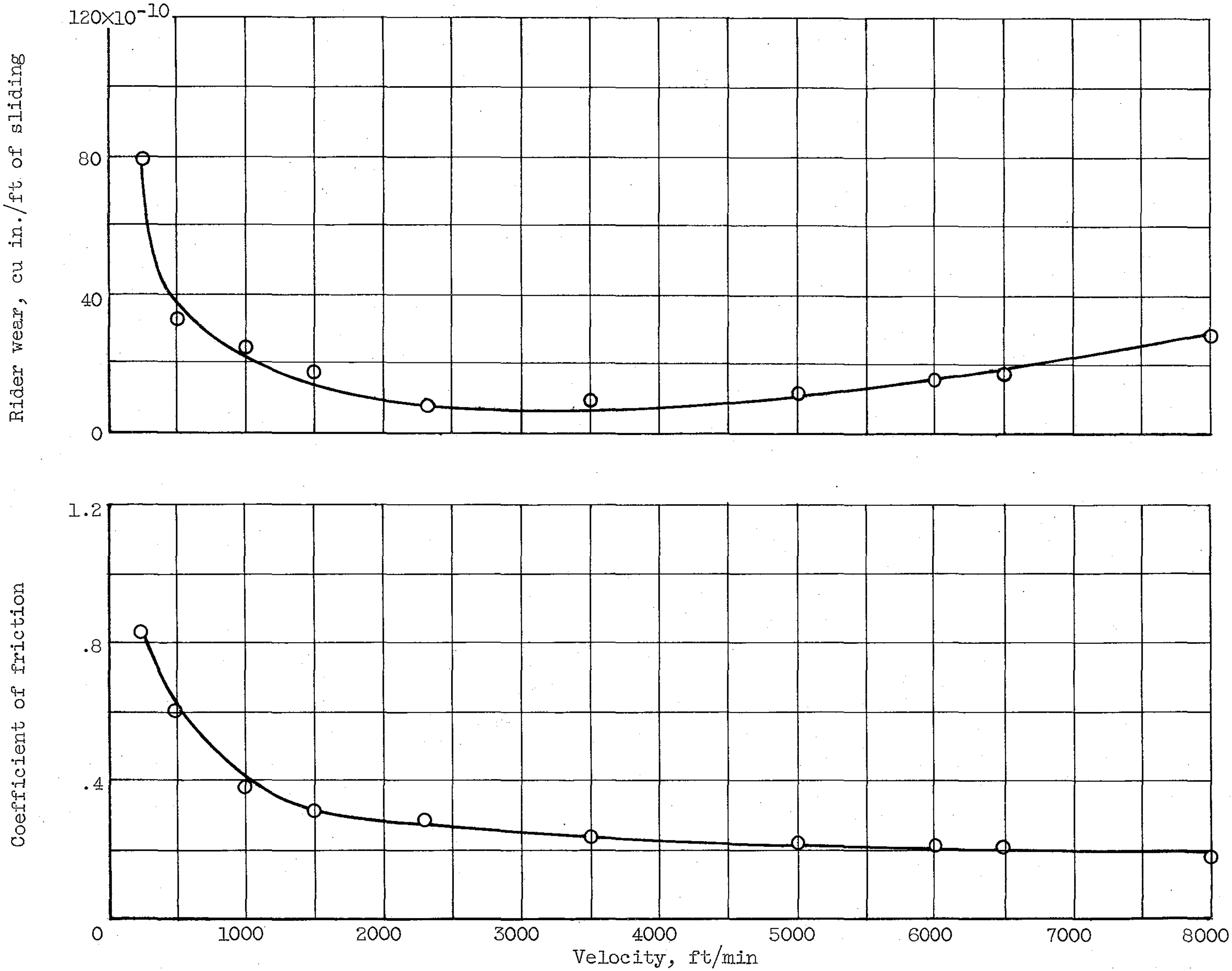


Figure 2. - Variation of rider wear and coefficient of friction with velocity for 440-C stainless steel sliding on 440-C stainless steel in liquid oxygen. Load, 1000 grams; duration, 1 hour.

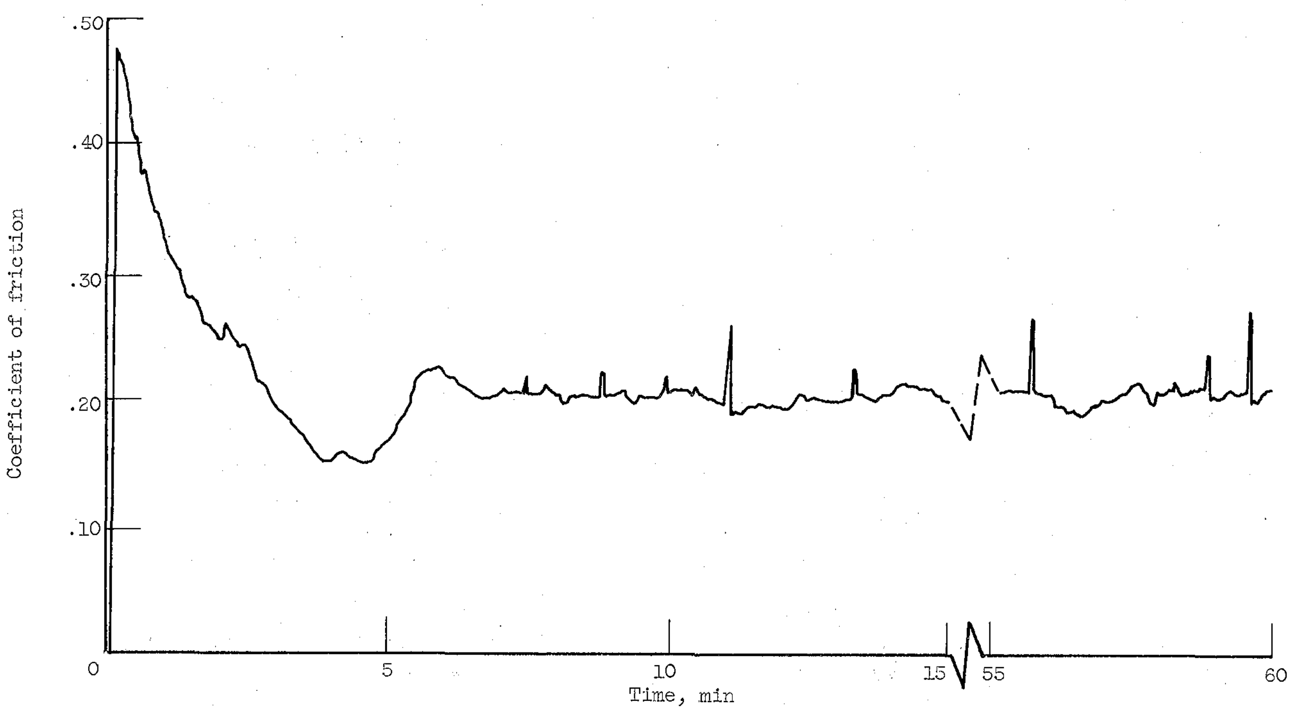
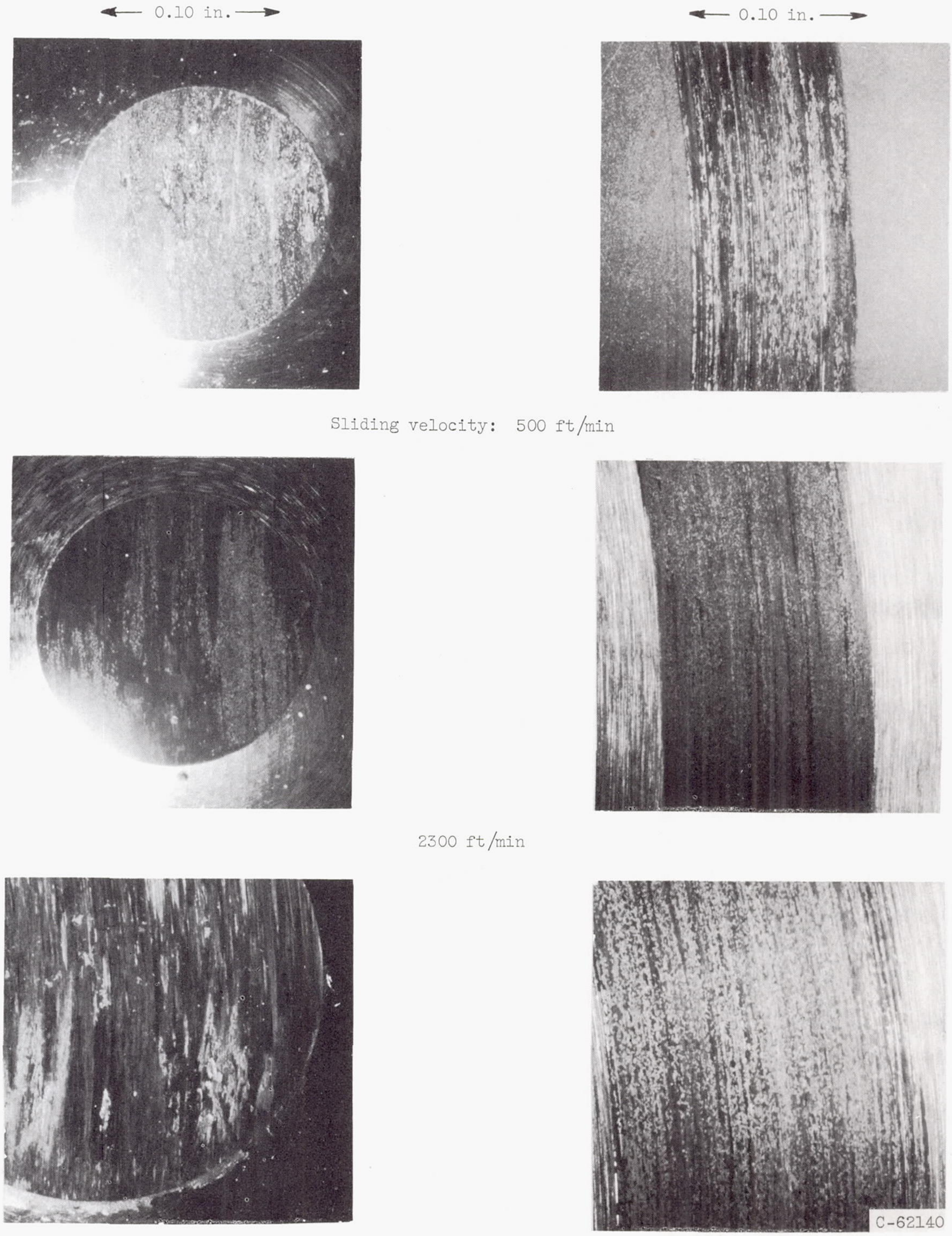


Figure 3. - Friction trace of 440-C stainless steel sliding on 440-C stainless steel in liquid oxygen at a velocity of 3500 feet per minute; load, 1000 grams.



8000 ft/min

(a) Rider wear scar.

(b) Disk wear track.

Figure 4. - Rider and disk wear areas of 440-C stainless steel specimens formed at various sliding velocities in liquid oxygen. Load, 1000 grams; duration, 1 hour.

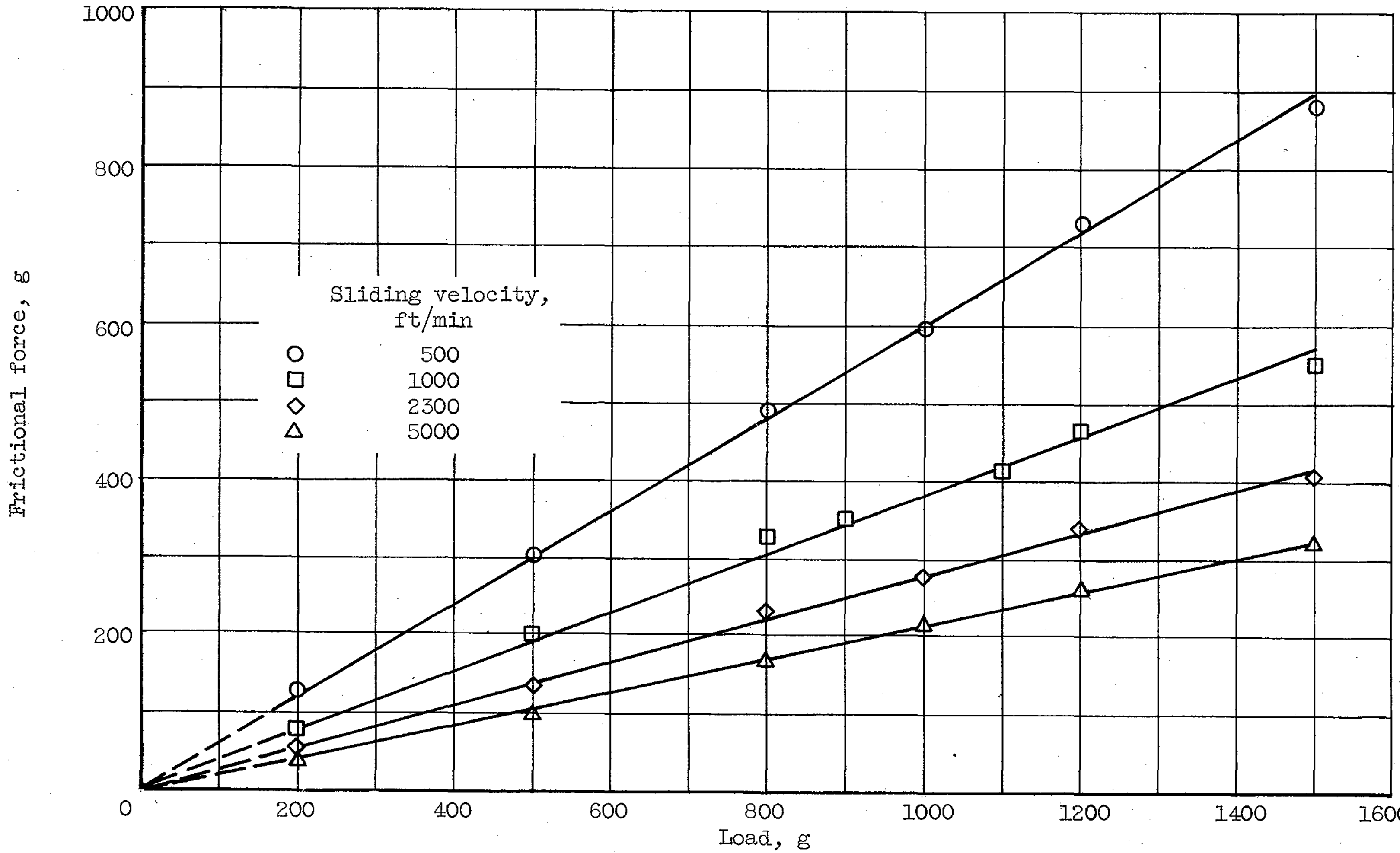


Figure 5. - Frictional force of 440-C stainless steel sliding on 440-C stainless steel in liquid oxygen at various loads and sliding velocities. Duration, 1 hour.

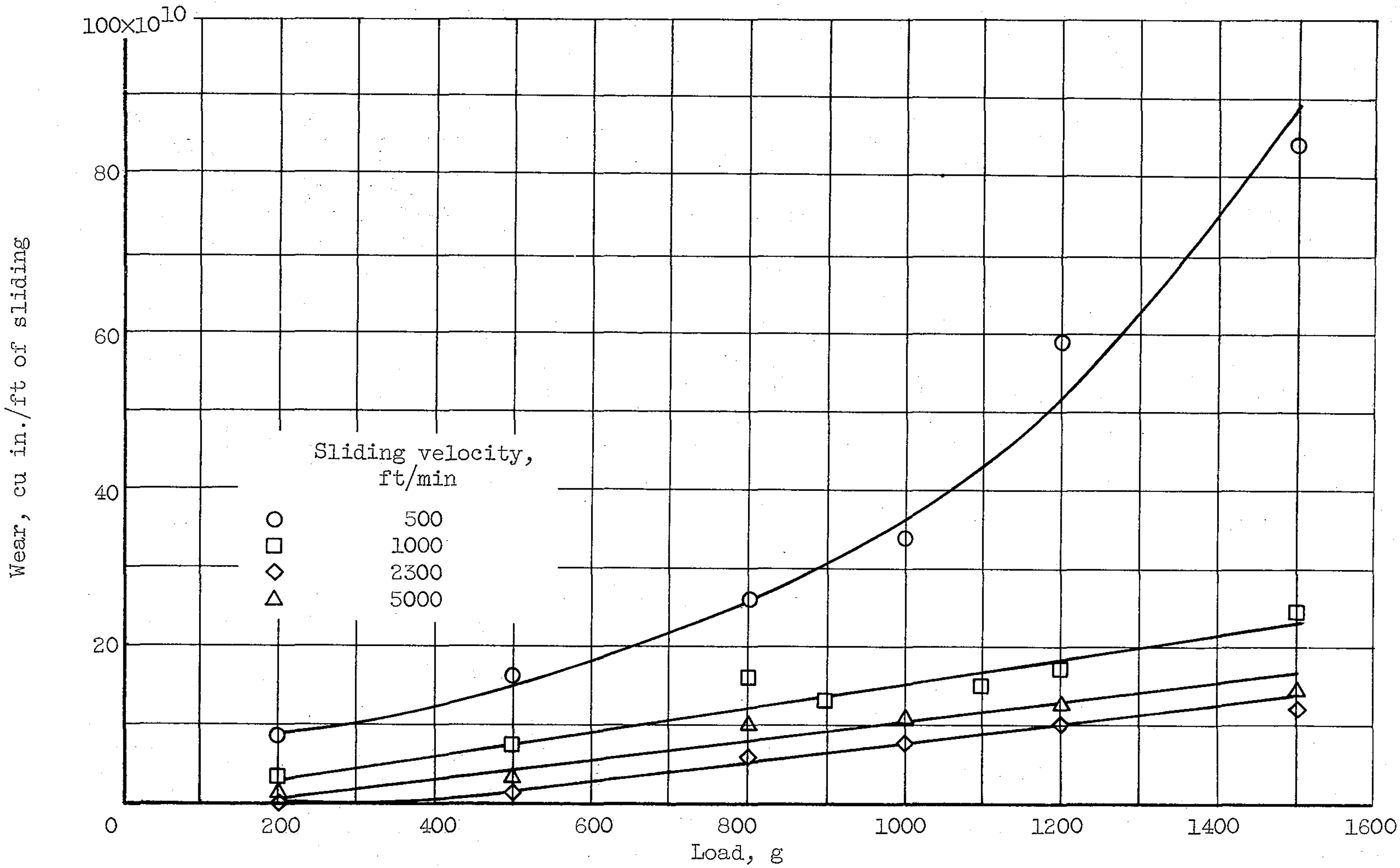


Figure 6. - Wear of 440-C stainless steel sliding on 440-C stainless steel in liquid oxygen at various loads and sliding velocities. Duration, 1 hour.

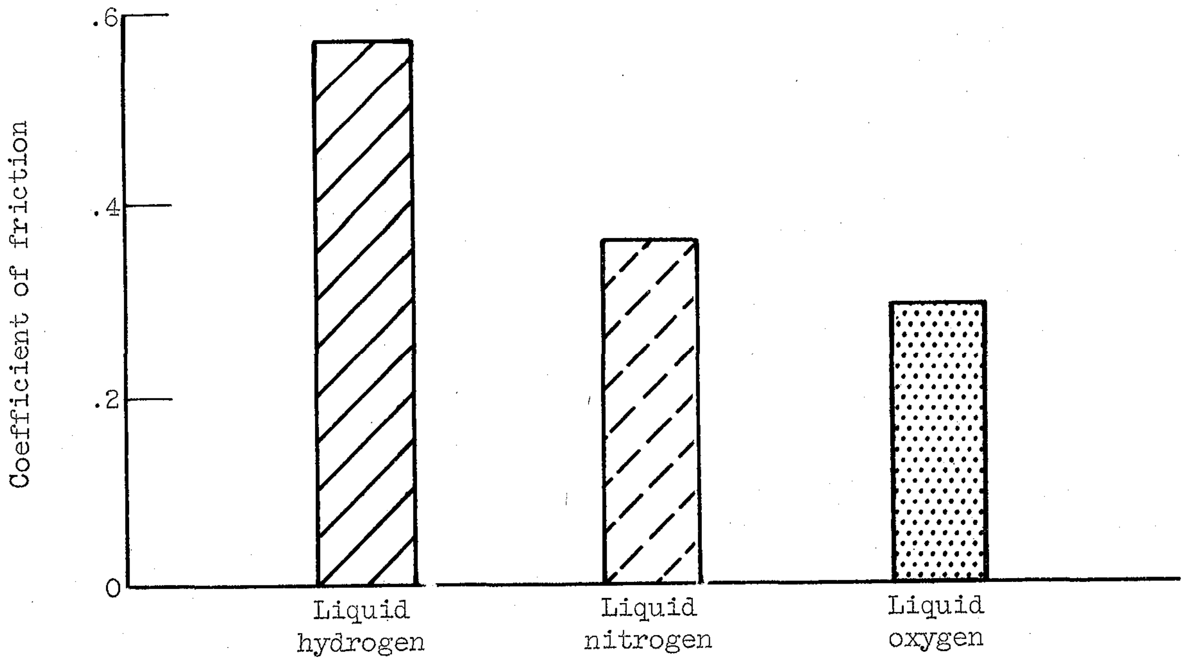


Figure 7. - Coefficient of friction of 440-C stainless steel sliding on 440-C stainless steel in reducing, inert, and oxidizing cryogenic liquids. Sliding velocity, 2300 feet per minute; load, 1000 grams; duration, 1 hour.