WADC-TR-59-603
PART IV

FRICTION AND WEAR

AT ELEVATED TEMPERATURES

Directorate of Materials and Processes
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio
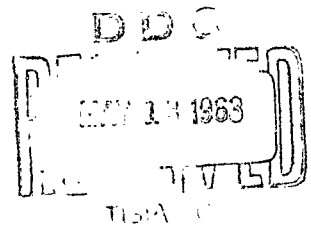
NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, (ASTIA), Arlington Hall Station, Arlington 12, Virginia.

This report has been released to the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C., for sale to the general public.

Copies of this report should not be returned to the Aeronautical Systems Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

C

FOREWORD

ABSTRACT

Measurements have been carried out of the friction coefficient as a function of temperature using surfaces of stainless steel covered by low-melting metals and non-metals applied in powder form. Some work has also been done with a few other metal and non-metal surfaces. In cases where the interaction between the low melting substance and sliding surface is high, as revealed by the occurrence of wetting, the friction reaches a peak just below the melting temperature of the substance, and then drops to considerably lower values just above the melting point. The peak below the melting temperature is associated with the formation of large adhering fragments of the low melting substance on the sliding surface. When there is no wetting, the low-melting substance has, either below or above its melting point, essentially no effect on the friction.

This technical report has been reviewed and is approved.

W. G. Ramke
Chief, Ceramics and Graphite Branch
Metals and Ceramics Laboratory
Directorate of Materials and Processes

TABLE OF CONTENTS

LIST OF FIGURES

I INTRODUCTION

This is the fourth report of an investigation of frictional behavior at elevated temperatures. The aim of this investigation is not, primarily, to discover materials and lubricants suitable for use under sliding conditions at high temperatures, but rather, to discover general criteria which will make it possible to select such materials and lubricants on the basis of their bulk and surface properties. Past investigations have been concerned with glass-forming lubricants, layer lattice materials, and the development of experimental and statistical techniques for interpreting high temperature frictional behavior. During the past year, we have concerned ourselves mainly with low melting metals and their possible use as high temperature lubricants.

Our main method of studying frictional properties at high temperatures has involved the friction-temperature test, in which we measure the friction of sliding surfaces while the temperature is continuously raised. This method dates back to 1922, when Hardy and Doubleday (1) found that when organic materials were used as lubricants, there was a sudden increase of friction at the melting point of the materials and that the friction remained high thereafter. This work has been often repeated and extended, most prominently by Bowden, Gregory, and Tabor (2) who showed that, if the lubricant could react with the surfaces, then it was at the melting point of the products of reaction that the rise in friction was observed.

A second class of materials which has been studied in detail consists of glass-forming materials. It has been shown by Peterson, Murray and Florek (3) and by Rabinowicz and Imai (4) that with these materials there is a pronounced peak in the friction at the softening point of the glass, with the friction much lower on either side of the softening temperature.

1

In view of the fact that these two types of materials behave so differently, it was decided to study other materials which could possibly be used as boundary lubricants, to see how their frictional behavior varied at their melting point.

Most of our work has been done using, as lubricants, various low melting metals, as in this way we can work with materials of simple chemical structure, not subject to thermal decomposition or degradation. Unfortunately, low melting metals do react with an air environment, and this does produce some difficulty.

There have been but a limited number of studies reported of the lubricating properties of metals. Thus, Vinogradov et al (5) have made observations on the use of liquid Wood's metal and mercury as lubricants, while Campbell (6) has investigated liquid sodium and Coffin (7) has studied liquid NaK, the sodium-potassium eutectic. In none of the cases apparently were observations made at the melting point of the metals. In addition Umeda and Nakano (8) and Rabinowicz and Kingsbury (9) have studied the frictional properties of unlubricated unlike metals which form eutectics. In this case, a striking drop in the friction was observed as the temperature was raised to the eutectic melting temperature. On the other hand, a few observations we have reported (4) were not so clear cut. Used as lubricants on stainless steel, tin and cadmium gave an increase in friction at their melting temperature, while lead and zinc showed a decrease. Clearly, this situation deserved further investigation.

In part III of this report, some results of the friction tests using low-melting metals have been reported. This work has been extended and reported in this report.

II APPARATUS

The friction apparatus used in this study utilizes the geometry of three pins of one material contacting a rotating plate of the other material, the region of contact being inside a furnace. The plate is mounted on a shaft which extends outside the furnace and is connected

through a pulley system to a variable-speed electric motor. The pins
are mounted in a self-aligning holder which is connected to another shaft,
the far end of which is outside the furnace and is restrained from
rotation by means of strain gage rings. The loading is by means of
weights applied to this shaft. The furnace is made of welded steel
plate and is air-tight except for the front door, which is bolted on and
supplied with a cooling system to protect the Neoprene gasket, and the
two holes for the shafts, which are covered by rotating seals and also
cooled. The chamber is electrically heated, using resistance wires.
A schematic drawing of the apparatus is shown in Figure 1. Further
details are given by Mamin (10).

For the runs described in this paper, the temperature was gradually
raised from room temperature, during which time sliding was continuous
and the friction was monitored by an electrical recorder. The temper-
ature was measured by a thermocouple connected to one of the pins,
whereas in previous studies the thermocouple was attached to the holder.
This modification in temperature measurement has improved the accuracy
of the data considerably compared to our previous data, since the
temperature of the test specimen is considerably lower than that of the
holder.

The pins were of 1/4 in. diameter and were normally given a
slightly rounded end (radius about two inches). The flat specimen was
of dimensions 2.25 x 2.25 x .5 in.with a recess of two in. diameter and
1/4 in. depth (Figure 2). Low-melting metal powder of commercial purity
was applied to this recess in excess quantity, so that the effect of the
oxidation of the metal power could be minimized. This preparation
differs from that in previous tests, in which limited amount of the soft
metal, in powder form, was applied to the flat surface. The electric
contact resistance of the contacts was also monitored in some of the
tests in order to detect both physical and chemical changes occuring on
the sliding surface. This measurement was made using a Wheatstone-
bridge circuit, in which the electrical contact resistance was shunted
across a 10 ohm resistor, and the signal was fed into an electrical
recorder of time constant 1/5 sec.

3

Atmospheric control of the furnace was carried out by replacing the air with argon of commercial purity. In this process, the argon was slowly introduced from its cylinder into the furnace while the air was pumped out by a vacuum pump. After fifteen minutes, the pump was shut off and the friction run was started. During the test, argon was continuously fed into the furnace at a slight positive pressure in order to prevent back flow of air into the furnace.

III RESULTS

A) Frictional Properties of Low-Melting Pure Metals

Friction data, using stainless steel riders on a stainless steel flat covered with powder of the low-melting metal, are shown in Figure 3. These data are similar to those reported in part III, but the improvement in temperature measurement has made it possible to assign those changes in frictional behavior which arise at the melting point. It is seen that atmosphere has some effect on the friction of these metals. This indicates that the results were affected by the formation of oxides during the tests. Hence, for purposes of comparison tests were also made using the oxides of the metals. These results are also plotted in Figure 3.

The friction-temperature plots of lead and of lead monoxide are quite similar, giving a friction coefficient of about 0.5 at room temperature and of 0.15-0.20 at higher temperatures. A possible explanation is that lead was oxidized rapidly during the test, so that the plot obtained in the test using lead was actually that characteristic of lead monoxide (PbO). It is considered likely that lead was oxidized even in argon, owing to residual traces of oxygen impurity in our apparatus.

The friction plots of tin and stannic oxide (SnO_2) sliding in air are also similar, and this suggests that tin was oxidized during this test. However, the friction plot of tin in argon is quite different from that in air. It showed a peak below the melting point and a very sharp decrease at the melting point. The test was stopped at 300 C,

4

and a photograph of the sliding surface was taken after the specimen was brought down to room temperature (Figure 4). It may be seen that material in metallic form is adhering to the sliding surface, although a portion of the metal powder had become oxidized during the test.

The friction plots of zinc and cadmium also gave a peak below the melting point, while the oxides of these metals showed little change at this temperature. The examination of the sliding surface after the tests in argon revealed that zinc and cadmium remained in the metallic form, as in the case of tin, although again a portion of the metal powder had become oxidized during the test.

There is a distinct difference between the friction-temperature curve of lead and that of the other metals shown in Figure 3. As was discussed above, lead was presumably oxidized rapidly, and the curves using lead as a lubricant merely show the frictional properties of the oxides. On the other hand, the other metals remained metallic above the melting point, at least in argon. The friction-temperature curves of these metals show a peak below the melting point and a sharp decrease at that temperature. The friction above the melting point becomes lower than that of the oxides (or of unlubricated stainless steel), suggesting that the molten metal has some lubricating capacity. The oxides of these metals, as might have been expected, did not produce any change in frictional properties at or near the melting point of the metals.

In order to generalize the above results, tests were also made using titanium surfaces. Figure 5 shows the friction-temperature plots for titanium surfaces covered with cadmium and tin. The plots again give a peak and a dip at the melting point.

The above results show that metal powders give a peak in friction just below their melting point, if the metals have not become oxidized. Above the melting point, the molten metal has some lubricating capacity. In order to study these effects under conditions which could be more readily controlled, it was decided to carry out another series of

5

tests using a metal of still lower melting point, namely the familiar alloy of cadmium, tin, lead and bismuth, namely Wood's metal.

B) Frictional Properties of Wood's Metal

The eutectic temperature of Wood's metal is 69-72 C, and this makes it possible to study phenomena associated with its melting in a temperature range near room temperature, before the effects of oxide formation or of thermal degradation of sliding surfaces become serious. Tests were carried out using Wood s metal powder applied to metallic and non-metallic systems, and the results are shown in Figure 6. The solid lines are the plots obtained simply by applying Wood's metal powder to the sliding surface. However, in some cases, Wood's metal formed droplets on the sliding surface and did not cover the surface completely. In order to ensure the presence of enough Wood's metal to fully cover the surface, tests were made in which the surface was flooded with molten Wood's metal to a depth of 1/4" through the addition of a chunk of Wood's metal just above the melting point. These flooded tests were made while the specimen was heated and then cooled, and mean values of the results, obtained respectively during heating and cooling, are plotted in dotted lines. Also, the frictional properties of the bulk sliding surfaces, without Wood's metal, are shown in the same figure for comparison.

Copper on copper with Wood's metal gave a peak below the melting point. Above the melting point, the friction dropped to 0.2 and the low friction persisted up to 200 C, at which temperature the test was stopped. Stainless steel on stainless steel with Wood's metal also gave an increase and decrease in friction when passing through the melting point, but the friction went up again as the temperature was raised further. The Bakelite system and CP Alundum with Wood's metal gave a friction curve similar to that of stainless steel but with the maximum and minimum less pronounced. It is noted that the friction curve for these four sliding surfaces is quite different in the absence of Wood's metal.

6

On the other hand, the Nylon on Nylon system was quite unaffected by the presence of Wood's metal, showing neither the increase nor the decrease at the melting point of the latter. This result is important, because it shows that the peak just below the melting point is not a property only of the soft metal, but that it is strongly dependent on the nature of the sliding surfaces.

C) Interaction of Wood's Metal and the Sliding Surfaces

Interesting changes were noted in the physical form of the Wood's metal film on the sliding surface during the course of the tests. Figure 7 shows the sliding surface of copper, stainless steel, Bakelite, Nylon and CP Alundum at 100 C and 200 C respectively. It is seen that the sliding surface of CP Alundum is covered by a film of Wood's metal at 100 C, but the film is broken at 200 C. A similar change in the film formation was also observed in the test using stainless steel and Bakelite systems. However, the copper surface was covered by the film both at 100 C and at 200 C, while the Nylon surface was never covered by the molten Wood's metal film.

These changes in the appearance of the Wood's metal film were paralled by changes in the friction. Thus, the friction of the stainless steel, CP Alundum, and Bakelite systems were low at 100 C but increased at 200 C. The friction of copper was always low above the melting point of Wood's metal and that of the Nylon system was not affected by the presence of Wood's metal at all. Hence, it would seem that there is a very good correlation between the friction and the film formation.

The correlation between the friction and film formation was not very straight forward in the test using cadmium on cadmium with Wood's metal. (Figure 6) Since cadmium is a component of Wood's metal, molten Wood's metal formed a very strong film over the cadmium specimen. However, friction increased near 200 C. It was observed that the end of cadmium riders were severly molten and almost welded to the sliding surface. The increase in friction is probably due to this effect.

7

Thus, the frictional behavior of alloy-forming sliding system seems to be more complicated than that of the other class of materials, and needs further investigation. In the absence of such effects, the correlation between friction and physical form of the film appears to be fairly well established.

It might be argued that the change in friction is simply due to the physical disappearance of the Wood's metal film and the consequent exposure of unprotected sliding surfaces. However, the tests with the flooded surfaces show that the same friction changes occur under flooded and unflooded conditions and from this we may deduce that the variation in friction is caused not simply by the presence or absence of the molten Wood's metal film, but by the change in wettability of the liquid-solid system. This change can produce two independent effects, namely a change in the physical form of the film, and a variation in the friction coefficient.

It follows that there is a very good correlation between frictional behavior and wettability; when the molten metal shows poor wettability on the solid surface, the friction curve shows no peak and no drop (e.g. Nylon) but when the wettability is better, as with the other materials, the friction curve shows both a peak and a drop.

D) Frictional Properties of Glass

In order to generalize these conclusions, it was decided to carry out tests with other liquid-forming solids. Tests were carried out using glass-forming powders and the results are shown in Figure 8.

Sodium silicate glass applied to the stainless steel surface gave a friction-temperature plot similar to that of most of the low-melting metals, namely it showed the peak near the softening point (but much more pronounced), and the decrease above that temperature. However, these variations in friction disappeared completely, when sodium silicate glass was applied to a compacted boron nitride surface.

Boron nitride was used since it is a material which is known to have poor wettability with respect to almost all liquids, but which can be wetted by boric oxide. Accordingly, we determined the friction plot for boron nitride when covered by boric oxide, and this system does indeed show the characteristic peak and dip in the friction.

Thus, it is clear that wettability plays a very important role in the frictional behavior, not only of metals, but also of glass-forming materials.

E) Frictional Properties of Sodium Thiosulfate

Another series of experiments have been carried out using 'hypo' as a liquid-forming material applied to metal and non-metal sliding systems. Results are shown in Figure 9.

Dissolution of the 'hypo' in its water of crystallization was observed between 50 C and 60 C. The evaporation of the water became significant near 100 C and was completed between 130 C and 140 C. With all the materials tested, enough 'hypo' solution was present completely to flood the sliding surfaces. The system copper on copper showed a slight increase in friction at the dissolution temperature and the nylon system showed a decrease in friction but the stainless steel and Bakelite systems did not show much change at this temperature.

In all cases, the friction increased when the water evaporated. At this point, the sliding surfaces were covered with dry 'hypo' powder.

An interesting feature of these data is that none of the friction-temperature curves gave the peak at the point where liquid was formed. This is in striking contrast to the friction curves of metal and glass-forming materials which gave the peak in the friction-temperature plot just below the melting temperature.

9

F) Material Transfer

So far, we have related the frictional properties of the various sliding systems to the wettability of the lubricant, which is a property which can be determined only above the melting point. Investigation of the sliding systems below this temperature has also been attempted, with interesting results.

Friction tests were made using Wood's metal riders on copper, stainless steel, Bakelite and Nylon surfaces. The temperature was kept constant at 25 C and 60 C respectively, during each test, and the duration of each test was 20 minutes. Figure 10 shows the photographs of the surface taken after the tests.

It is seen that some material transfer of Wood's metal has taken place on the copper and the Bakelite surfaces at 25 C. The amount of material transfer becomes considerable on the copper and stainless steel surfaces at 60 C, and some transfer to the Bakelite at this temperature. The Nylon surface, on the other hand, does not show any trace of material transfer at either temperature. These results are in striking similarity to the friction results of Figure 6, where the friction curves of copper and stainless steel show a prominent peak at 60 C, while Bakelite shows a less pronounced peak, and the curve for nylon does not show a maximum.

Further tests have been made using the riders of cadmium, lead and boric oxide on a stainless steel surface. The boric oxide rider was prepared by coating a stainless steel pin with a thick layer of boric oxide. The tests were made at constant temperatures, and the duration of each test was one hour. The steel flat specimen was weighed before and after each test, and the amount of material transferred from the riders to the steel surface during the run was calculated. Results are shown in Figure 11 and Figure 12.

The friction results are rather similar to those of steel sliding on steel in presence of cadmium, lead or boric oxide powder. Thus,

10

the cadmium on steel system and the boric oxide on steel system show an increase in friction as the temperature is raised, while the lead on steel system shows a decrease with the increase in temperature.

The amount of cadmium adhering to the steel surface shows a rapid increase as the temperature is raised, which is paralleled by the increase in friction. On the other hand, the lead on steel system gives little change with temperature in the amount of material transfer and rather a decrease in friction. In Figure 12, the amount of boric oxide adhering to the steel surface again shows an increase as the softening point of the boric oxide is approached. The photographs in the figure show that a small amount of boric oxide begins to adhere to the surface at the temperature at which the friction curve shows a rise, and the particles grow larger with the further increase in friction.

The above results show the presence of large adhesive effects in the vicinity of melting or softening temperature. It seems that the frictional behaviors of the sliding system are quite different depending on whether these adhesive effects are present or not, and that the friction peak is associated with these effects.

G) Effect of Load

A friction measurement was made using stainless steel riders sliding on stainless steel surface with boric oxide powders. The load was varied during the test at 500 gr, 1,000 gr and 1,700 gr. Results are shown in Figure 13.

The general pattern of the friction-temperature plot is not changed by the variation of load, but the friction was lower for smaller loads below the peak and this tendency was reversed above the peak.

IV DISCUSSION

The first feature of our data which warrants comment is the fact that, in general, we have found soft metals such as lead and cadmium,

11

in solid form to be poor lubricants for steel, while these materials
have generally been regarded as good lubricants. This distinction can
be explained by the fact that other investigators (11, 12) used a thin
film of the soft metal on the hard sliding surface, whereas we did
not. It is known that the low friction of soft metal film is due to
the ease with which the soft metal may be sheared, while the load is
supported by the hard substrate. In our case the soft metal film
tended to be much thicker, so that this lubricating effect disappeared.
An analysis which gives an order of magnitude estimate of this effect
will be presented in the Appendix.

As to the results themselves, it has been shown that friction
data obtained with low-melting metals at elevated temperatures are
affected by oxide formation. Among the metals tested lead was most
readily oxidized and this is in agreement with the oxidation data given
in the literature (13). It is shown that the parabolic constant of
the oxidation rate of lead is of the order of 10^{-11} $gr^2/cm^4 sec$, while
that of zinc and cadmium is of the order of 10^{-13} gr^2/cm^4 sec.

When tests are carried out in an argon atmosphere so that the
friction test is but little affected by oxide formation, the friction
plots fell into a general pattern, in which there is an increase in
friction near the melting point and a subsequent decrease above that
temperature. Only surfaces of low wettability, such as Nylon (with
Wood's metal), or boron nitride (with silicate glass), show neither
the peak nor the decrease.

A likely explanation for the friction peak below the melting
point is that, when the lubricating material becomes softer, adhesive
effects between the material adhering to each surface become more
pronounced, and consequently the area that has to be sheared, but is
not supporting the load, becomes larger. It is clear that such an
increase in shear area will result in an increase in friction.

According to recent discussions of the adhesion process, a high
level of adhesion would be expected to result from a high value of

12

the ratio W_{ab}/p, where W_{ab} is the surface energy of adhesion of the materials and p the hardness (14). For materials near their melting point, W_{ab}/p is high (since p is low), consequently, strong adhesive effects are to be expected.

The increased amount of cadmium and boric oxide adhering to the steel surface near their melting or softening point seems to be related to the increase, with temperature, of the W/p ratio. When the surface layer was oxidized as in the case of lead sliding on a steel surface, the decrease in the surface energy of adhesion W resulting from the oxide formation, reduced the adhesive effects in sliding, giving little material transfer and a decrease in friction. The friction curves of sliding systems with 'hypo' did not give any peak, possibly because the softening of the material did not occur prior to the point at which the crystal melted.

As regards the decrease in friction above the melting point, it is clear that this is due to the formation of a lubricating film of the molten metals. The sliding velocity in our tests was 0.1 cm/s, and the viscosity of molten metals is about 2-5 centipoise, so that it is most unlikely that a hydrodynamic lubrication film could have formed. Also, the results using Wood's metal, which have shown the dependence of the friction on the nature of the bulk sliding surfaces, are consistent with boundary lubrication rather than hydrodynamic lubrication.

An adsorbed film of a molten metal is only a few Angstroms thick, compared to values of about 20 A for long-chain organic materials and hence it is natural that molten metals are much poorer lubricants than are long-chain organic liquids. The effectiveness of the molten metals is probably due to the fact that, when adsorbing on a solid surface, they lower its energy of adhesion. This explanation is borne out by the fact that those surfaces on which the molten material did not

adsorb effectively, as indicated by lack of wetting ability, were those
surfaces which the liquid did not lubricate effectively, even when the
liquid was allowed to flood the surface.

In fact, one of the most noteworthy results of these studies is
that they demonstrate the importance of strong interaction between the
interposed material and the sliding surface. Below the melting point,
this interaction leads to the adhesion of large welded particles on
the sliding surfaces, and consequently an increase in the friction,
while above the melting point this interaction leads to the adhesion
of liquid molecules on the solid surfaces, with the consequent occurrence
of boundary lubrication. Neither the peak nor the drop in the friction
was found without the other.

As a final point, it is of interest to consider the relevance of
these results to the problem of selecting good compatible materials
for use under sliding conditions. One well known criterion is that
of miscibility (15). Of the four metals of Figure 3, it is known
that iron and cadmium are immiscible, that iron and lead as well as
iron and zinc are miscible, while iron and tin form intermetallic
compounds. However, the frictional behavior was similar in all cases.

We may take the criterion of miscibility a step further. It does
not seem at all likely that Wood's metal and Bakelite are miscible.
But yet this system gave a friction curve similar to that of miscible
pairs. It would seem that we cannot predict the frictional behavior
of a sliding system only on the basis of miscibility.

However, our tests suggest that wetting ability is a more re-
liable guide to the tendency towards the occurrence of high friction
and high material adhesion in solids, and the tendency for lubri-
cation to occur in systems with liquid lubricants present. Proba-
bly, the wettability which matters in this connection is not that

14

measured in static tests, but rather the tendency for lubricant to wet
the friction track during actual sliding. This can be considered a
dynamic test.

Bondi (16) suggests that wetting ability and miscibility are
highly correlated, so that a selection of material pairs according to
wettability might not differ greatly from one based on miscibility.
However, even given this correlation, the criterion of wettability
still seems to be a better one. During sliding, junctions are made
and broken many times per second, so that there is little opportunity
for the inter-diffusion of metals to occur. However, wettability indi-
cates a high energy of adhesion, and it has been shown that this can
influence friction and wear processes directly (14).

APPENDIX

Estimate for the Limiting Film Thickness in Thin Solid Film Lubrication

Low friction of a surface coated with a soft thin film is attributed to the fact that the contact junctions are easily sheared because the material is soft, but the contact area that has to be sheared is small because the load is supported by the hard substrate. In order that the lubricating effect of the film to be effective, the film has to be thin enough so that most of the load is supported by the substrate.

The limiting film thickness for the effectiveness of thin film may be estimated by assuming that the favorable action of the film is lost when half of the load is supported by the film itself. The load supported by the film can be approximated by the punching force of a thin plate as in Equation (1).

$$\Delta L = 2 \pi r t \tau_s \qquad (1)$$

where ΔL : load supported by the film

   r : radius of the junction

   t : film thickness

   τ_s : shear strength of soft metal

On the other hand, the load supported by the substrate is:

$$\Delta L' = p_H \pi r^2 \qquad (2)$$

where $\Delta L'$: load supported by the substrate

   p_H : hardness of the substrate

Equating these two, and also assuming,

$$\tau = \frac{p}{6} \qquad (3)$$

16

where $\tilde{\tau}$: shear strength

         p : hardness

We obtain:

$$t_c \sim \frac{p_H r}{p_s} \tag{4}$$

where t_c : critical thickness

        p_s : hardness of the film

It is reasonable to assume that the order of magnitude of (p_H/p_s) is 10, and that of r is 10^{-3} cm. Then, we obtain t_c in Equation (4) of the order of 10^{-2} cm.

Measurement shows that the layer of soft metal in our tests is thicker than this value.

REFERENCES

1. W. B. Hardy and I. Doubleday, "Boundary Lubrication, the Temperature
    Coefficient", Proc. Roy. Soc. A, 101, pp. 487-492, 1922.

2. F. P. Bowden, J. N. Gregory and D. Tabor, "Lubrication of Metal
    Surfaces by Fatty Acids", Nature, 156, 97-99, 1945.

3. M. B. Peterson, S. F. Murray and J. J. Florek, "Consideration of
    Lubricants for Temperatures above 1000 F", Trans. A.S.L.E. 2,
    No. 2, 225-234, 1960.

4. E. Rabinowicz and M. Imai, "Boric Oxide as a High-Temperature
    Lubricant", A.S.M.E. paper 61-LUBS-17, 1961.

5. G. V. Vinogradov, Bezborodko, Parlovskaja and Tsuzkan, Discussion
    on p. 807 of the 'Proceedings of the Conference on Lubrication and
    Wear', Institution of Mechanical Engineers, London, 1957.

6. R. B. Campbell, "Liquid Sodium as a Lubricant", pp. 529-533 of the
    'Proceedings of the Conference on Lubrication and Wear', Institution
    of Mechanical Engineers, London, 1957.

7. L. F. Coffin, "Boundary Lubrication, Wear-in and Hydrodynamic Be-
    havior of Bearings for Liquid Metals and other Fluids", Trans.
    A.S.L.E. Vol. 1, No. 1, pp. 139-150, 1958.

8. K. Umeda and Y. Nakano, "Solid-Solubility Effect of Metallic
    Surface Friction", Physical Review, 75, p. 1621, 1949.

9. E. P. Kingsbury and E. Rabinowicz, "Friction and Wear of Metals to
    1000 C", Trans. A.S.M.E., Series D, 81, 118-121, 1959.

10. P. A. Mamin, "Design and Construction of a Vacuum Furnace for
    Friction Tests", M.S. Thesis in the Department of Mechanical
    Engineering, M.I.T., May 1959.

11. F. P. Bowden, and D. Tabor, "The Friction and Lubrication of Solids",
    Oxford, 1950, Chapter V.

12. D. H. Buckley and R. L. Johnson, "Gallium Rich Films as Boundary
    Lubricants in Air and in Vacuum to 10^{-9} mm Hg", ASLE paper 62-LC-1.

13. N. B. Pilling and R. E. Bedworth, "The Oxidation of Metals at High
    Temperatures", J. Inst. Met., 29, 529-591, 1923.

14. E. Rabinowicz, "Influence of Surface Energy on Friction and Wear
    Phenomena", J. Appl. Phys. 32, 1440-1444, 1961.

REFERENCES (cont.)

15. C. L. Goodzeit, "The Seizure of Metal Pairs during Boundary Lubrication", pp. 67-83 of the 'Proceedings of the Symposium on Friction and Wear' Elsevier, 1959.

16. A. Bondi, "The Spreading of Liquid Metals on Solid Surfaces", Chemical Review, 52, 417-485, 1953.

Weight

Glass Cover

Strain Gage Ring

Ball Bushing

Spindle

Holder

Thermocouple

Insulation

Heating Coils

To Inert
gas Tank

Riders

Flat

Spindle

Water Cooling

Electric Motor and
Speed Reducer
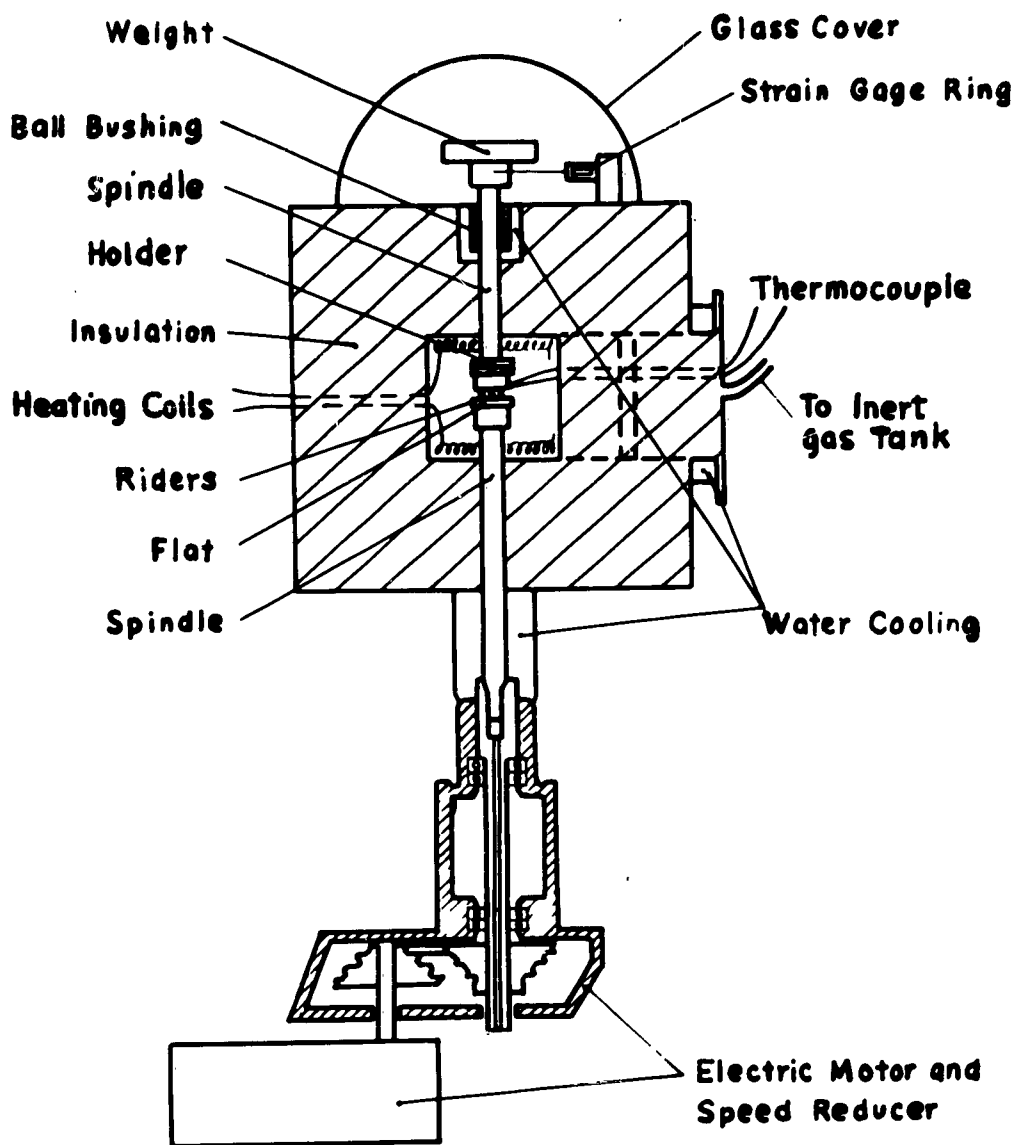
FIGURE 1

Schematic Illustration of the High-Temperature Friction Apparatus
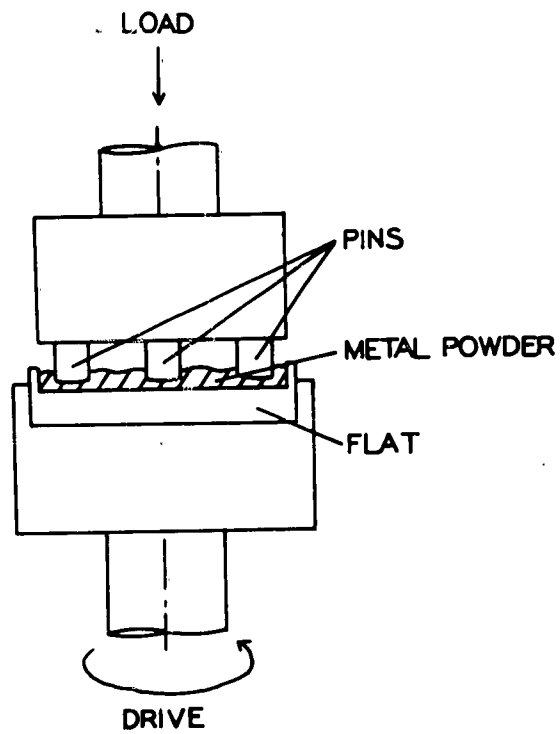
FIGURE 2

Schematic Illustration of the Test Geometry and the Test Specimens

21
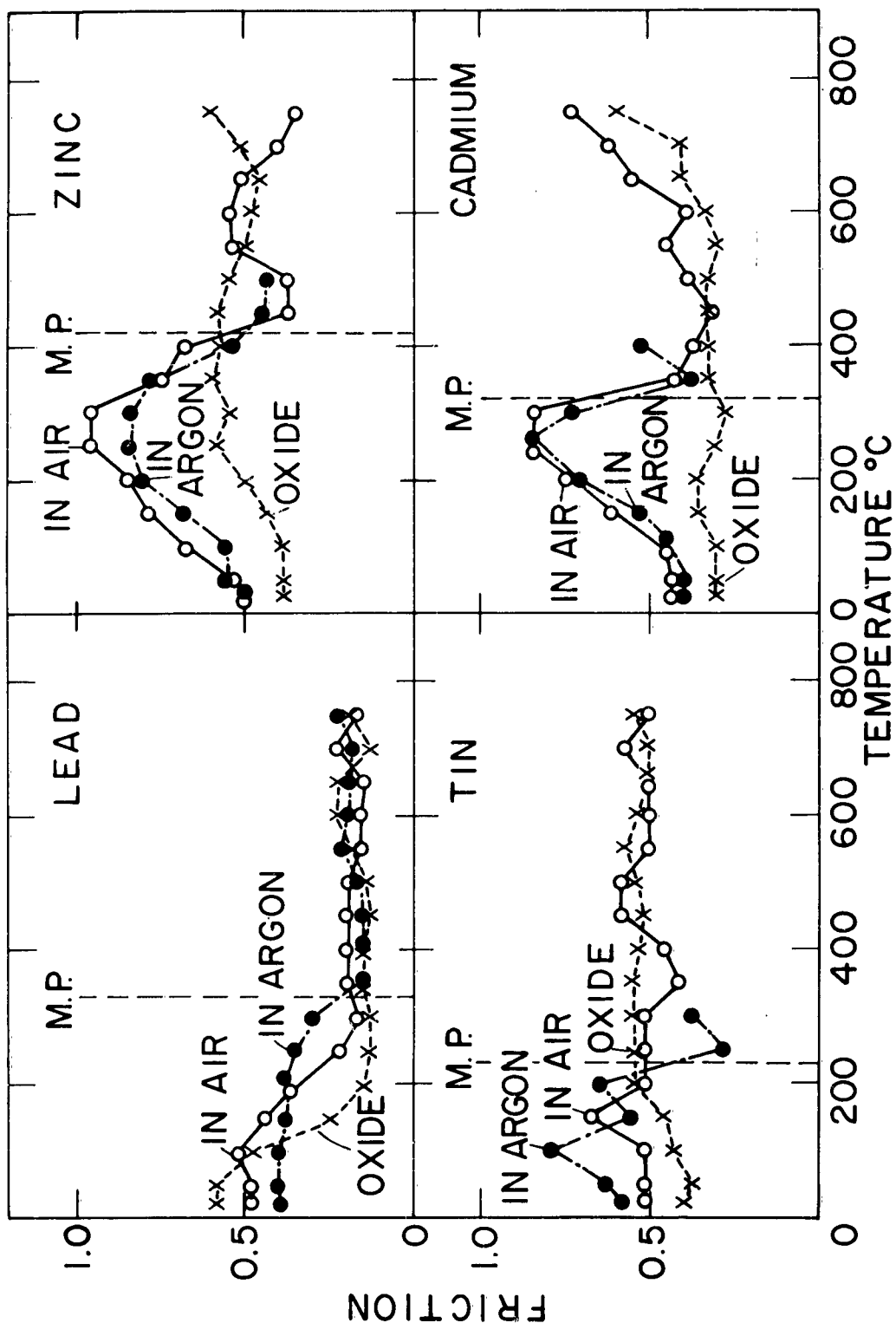
Figure 3. Friction-Temperature Plot for Stainless Steel on Stainless Steel with Metal Powders: Load 1700 g, Speed 0.1 cm/s

22

304 SS on 304 SS
with Tin (300°C)

FIGURE 4

Photograph Showing Sliding Surface of Stainless Steel Flat Specimen
Covered with Tin
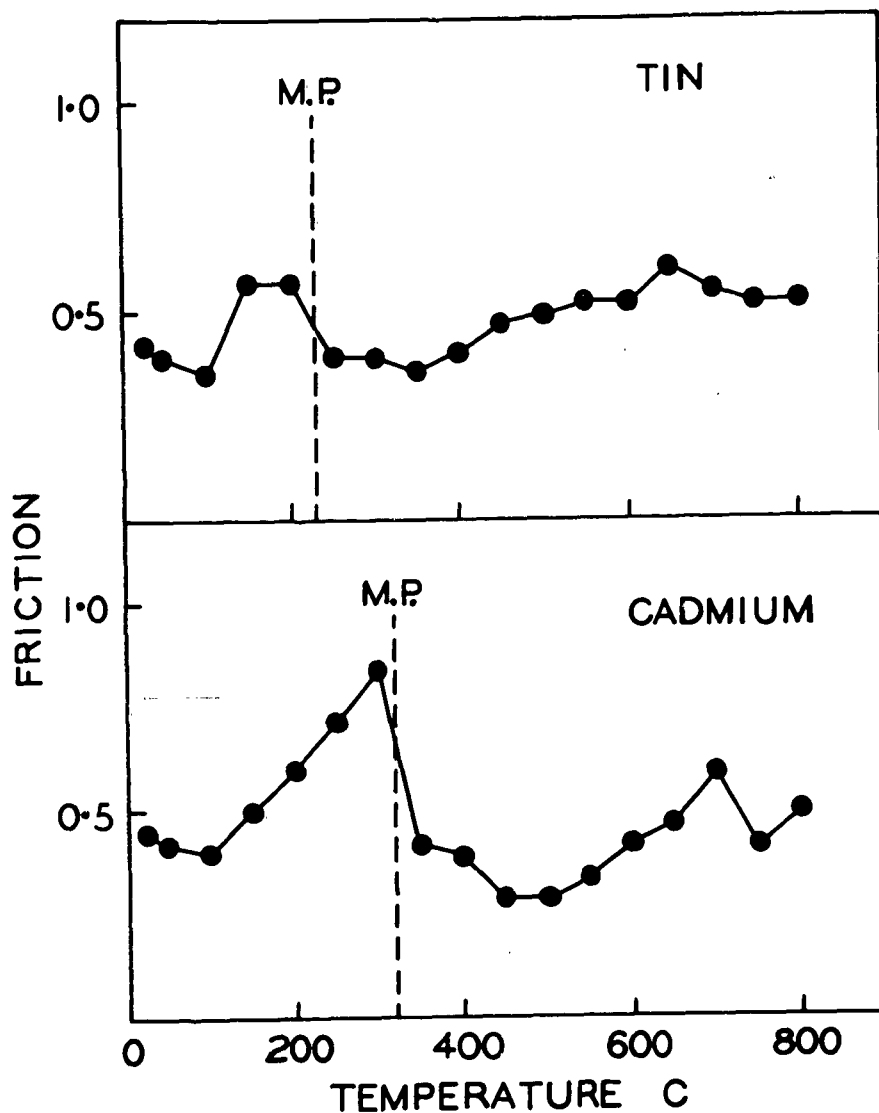
FIGURE 5

Friction-Temperature Plot for Titanium on Titanium with Metal Powders:
Load 1700 g, Speed 0.1 cm/s, in Argon

24
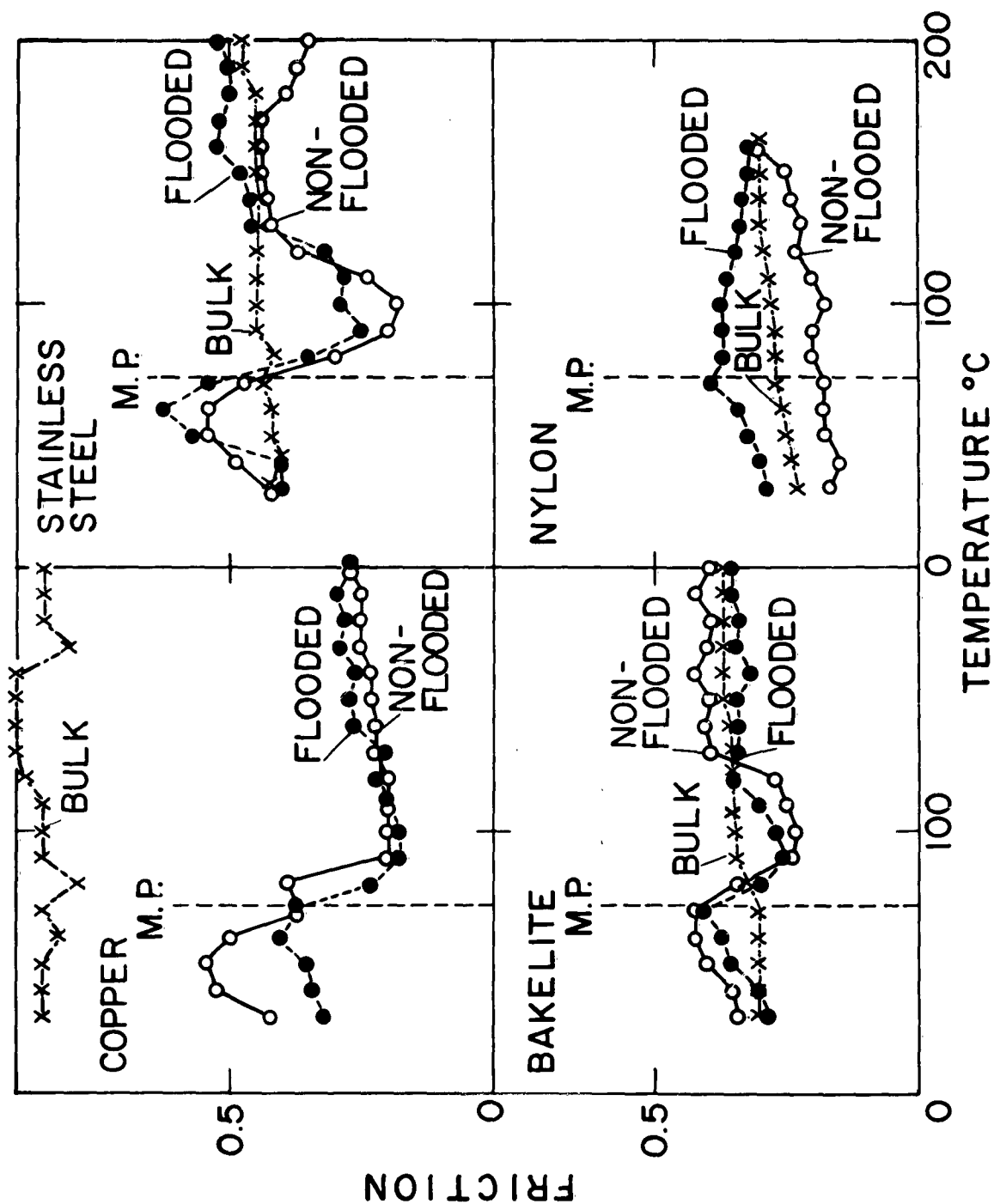
FIGURE 6a. Friction-Temperature Plot for Metal and Non-Metal Sliding Systems with Wood's Metal: Load 1700 g, Speed 0.1 cm/s, in Air
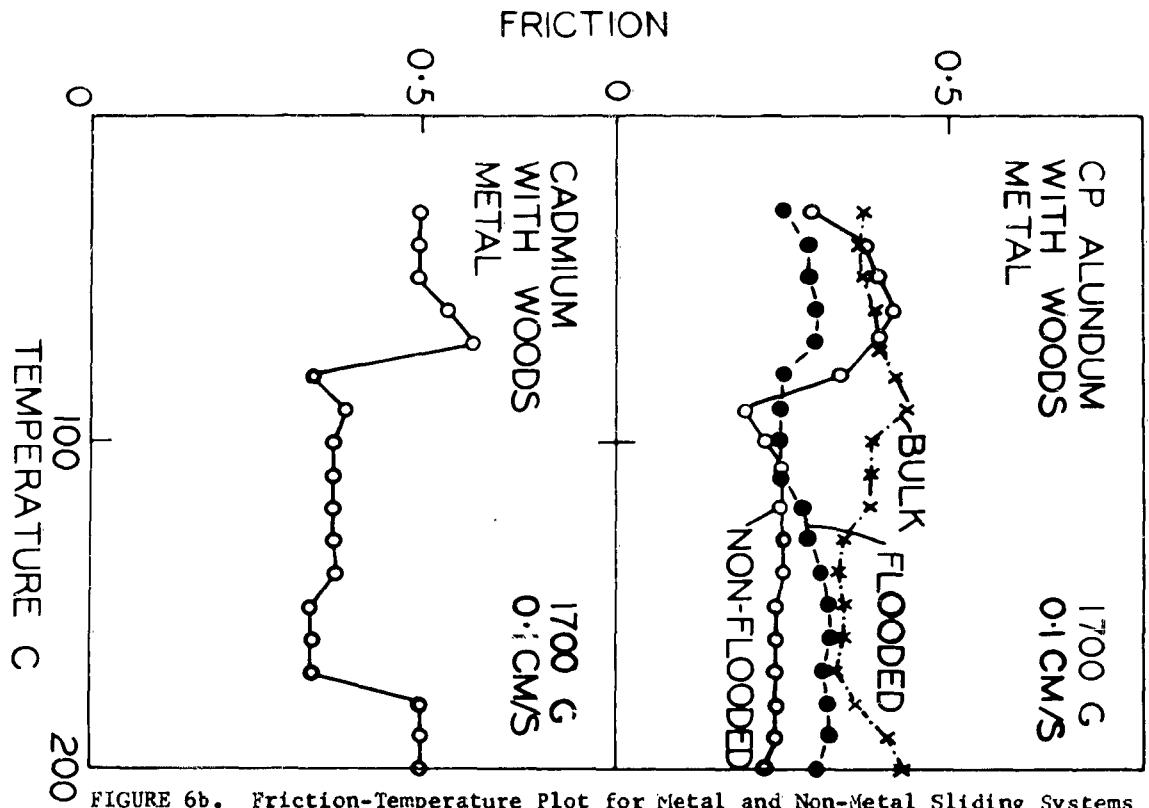
FIGURE 6b. Friction-Temperature Plot for Metal and Non-Metal Sliding Systems with Wood's Metal: Load 1700 g, Speed 0.1 cm/s, in Air

CP Al_2O_3 on CP Al_2O_3
with Wood's Metal
(100°C)
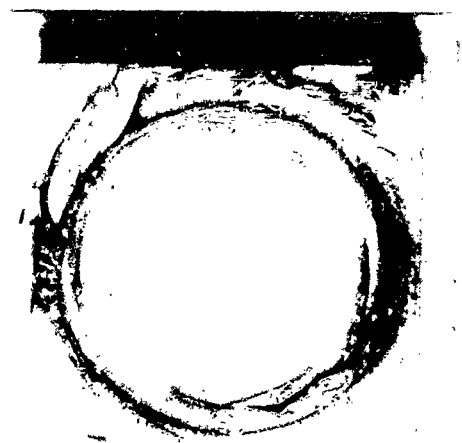
CP Al_2O_3 on CP Al_2O_3
with Wood's Metal
(200°C)

FIGURE 7a. Photograph Showing Sliding Surface of Flat Specimens Covered with Wood's Metal, at 100 C and 200 C

Copper on Copper
with Wood's Metal
(100°C)

Copper on Copper
with Wood's Metal
(200°C)

304 SS on 304 SS
with Wood's Metal
(100°C)

304 SS on 304 SS
with Wood's Metal
(200°C)

FIGURE 7b. Photograph Showing Sliding Surface of Flat Specimens Covered with
Wood's Metal, at 100 C and 200 C

27

Bakelite on Bakelite
with Wood's Metal
(100°C)
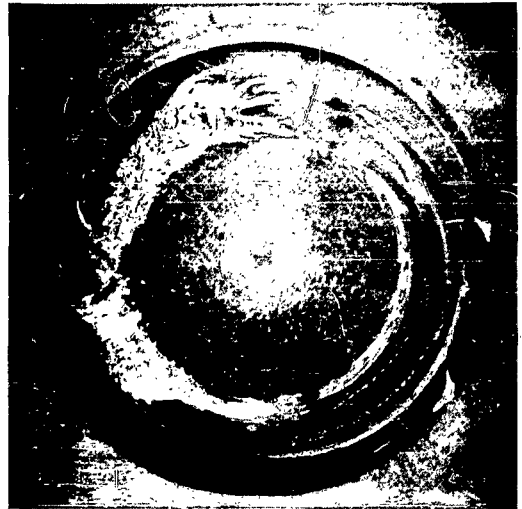
Bakelite on Bakelite
with Wood's Metal
(200°C)
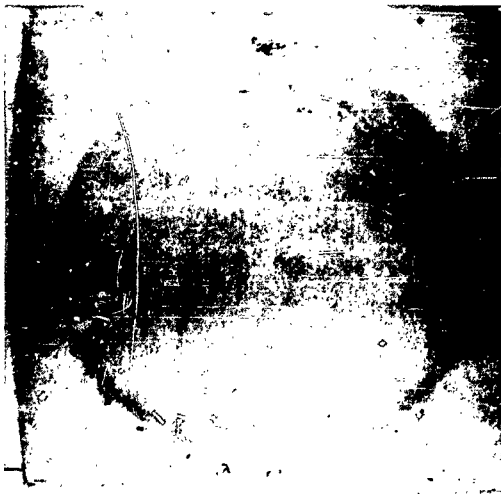
Nylon on Nylon
with Wood's Metal
(100°C)

Nylon on Nylon
with Wood's Metal
(200°C)

FIGURE 7c. Photograph Showing Sliding Surface of Flat Specimens Covered with
Wood's Metal, at 100 C and 200 C
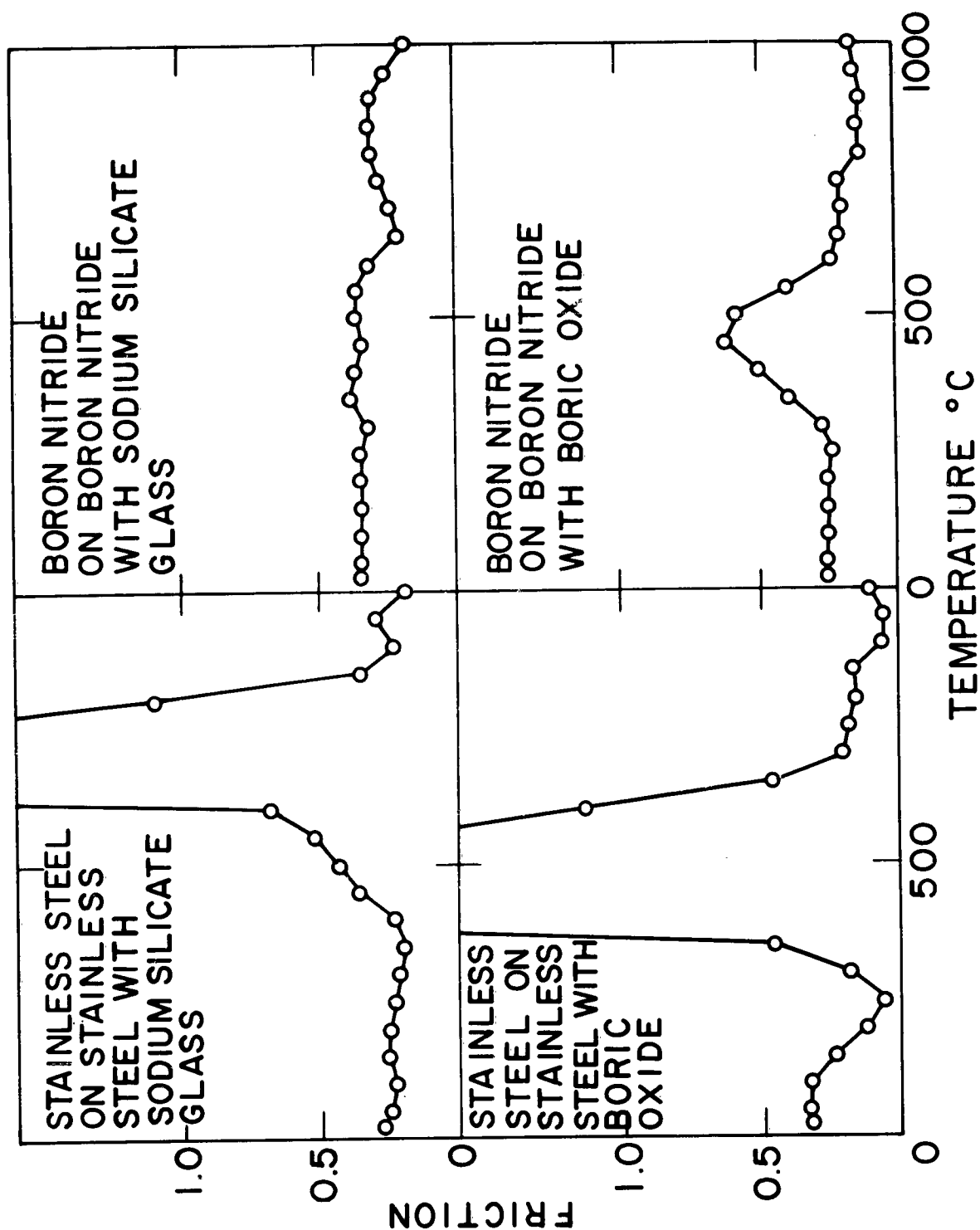
FIGURE 8. Friction-Temperature Plot for Glass-Forming Materials: Load 1700 g, Speed 0.1 cm/s, in Air

29
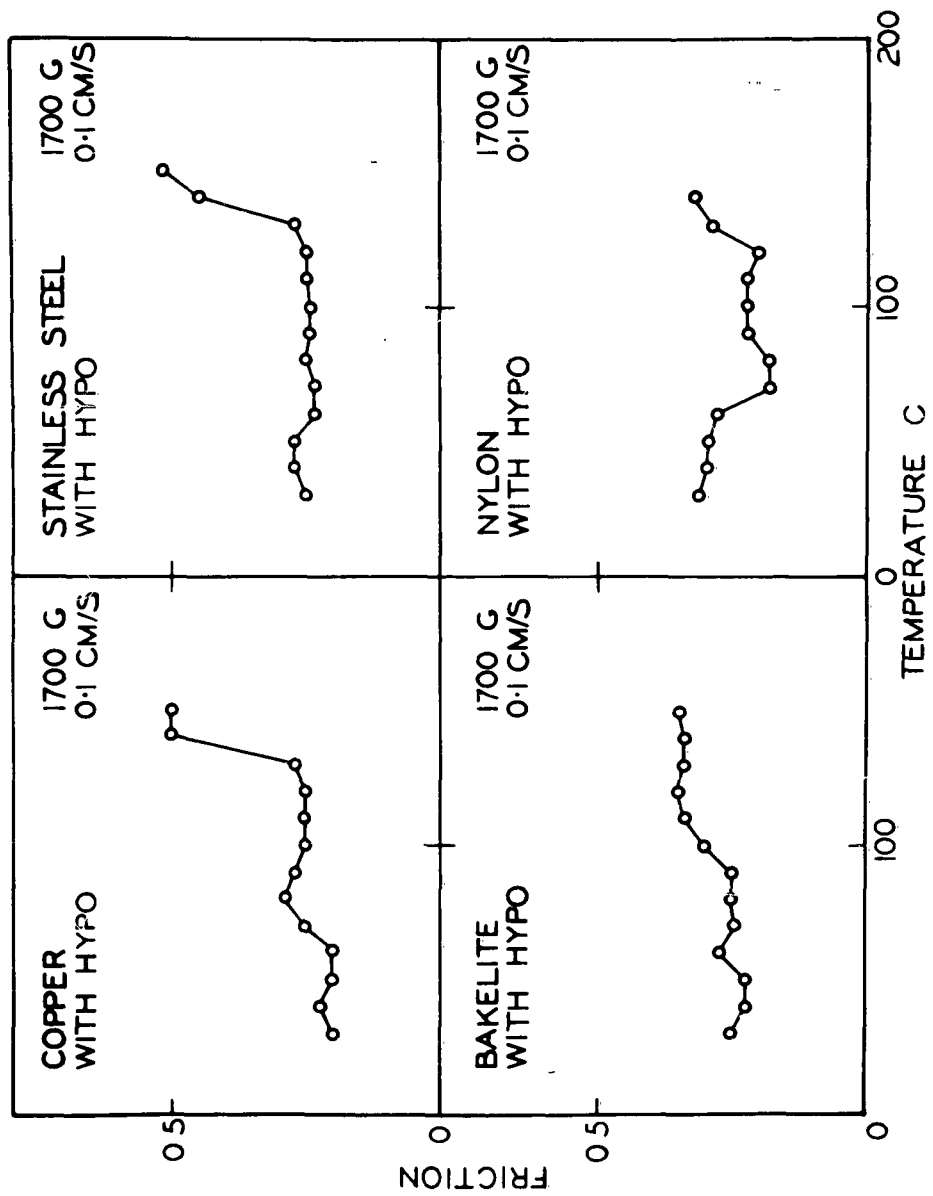
FIGURE 9. Friction-Temperature Plot for Metal and Non-Metal Sliding Systems with Hypo:
Load 1700 g, Speed 0.1 cm/s, in Air

Wood's Metal on Copper
(25°C)
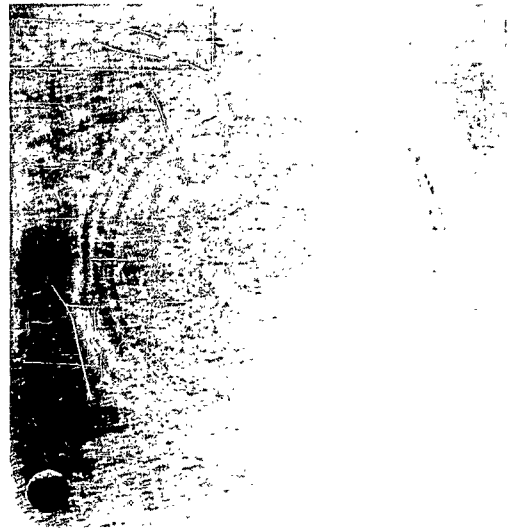
Wood's Metal on 304 SS
(25°C)

Wood's Metal on Bakelite
(25°C)

Wood's Metal on Nylon
(25°C)

FIGURE 10a. Photographs Showing Surfaces of Various Materials Lubricated by
Solid Wood's Metal at 25 C and 60 C

31
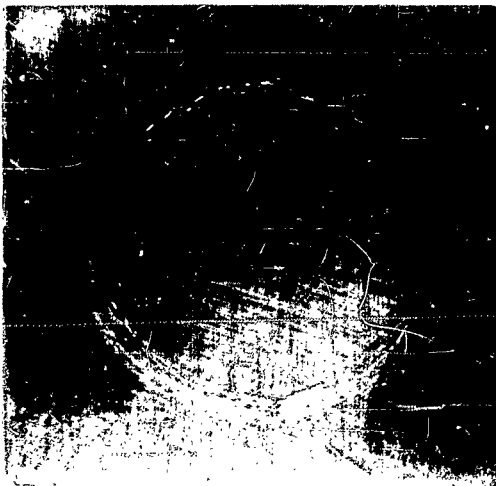
Wood's Metal on Copper
(60°C)
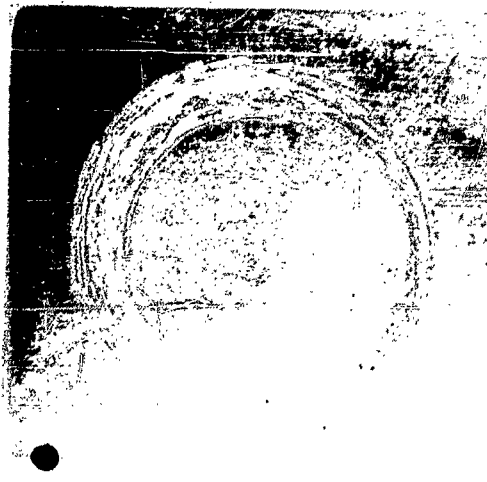
Wood's Metal on 304 SS
(60°C)

Wood's Metal on Bakelite
(60°C)
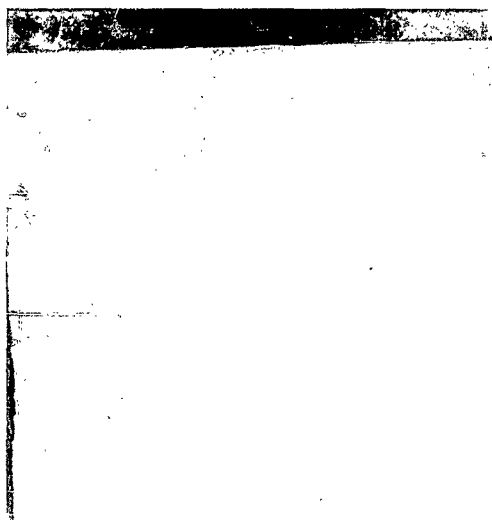
Wood's Metal on Nylon
(60°C)

FIGURE 10b. Photographs Showing Surfaces of Various Materials Lubricated by Solid
Wood's Metal at 25 C and 60 C

32
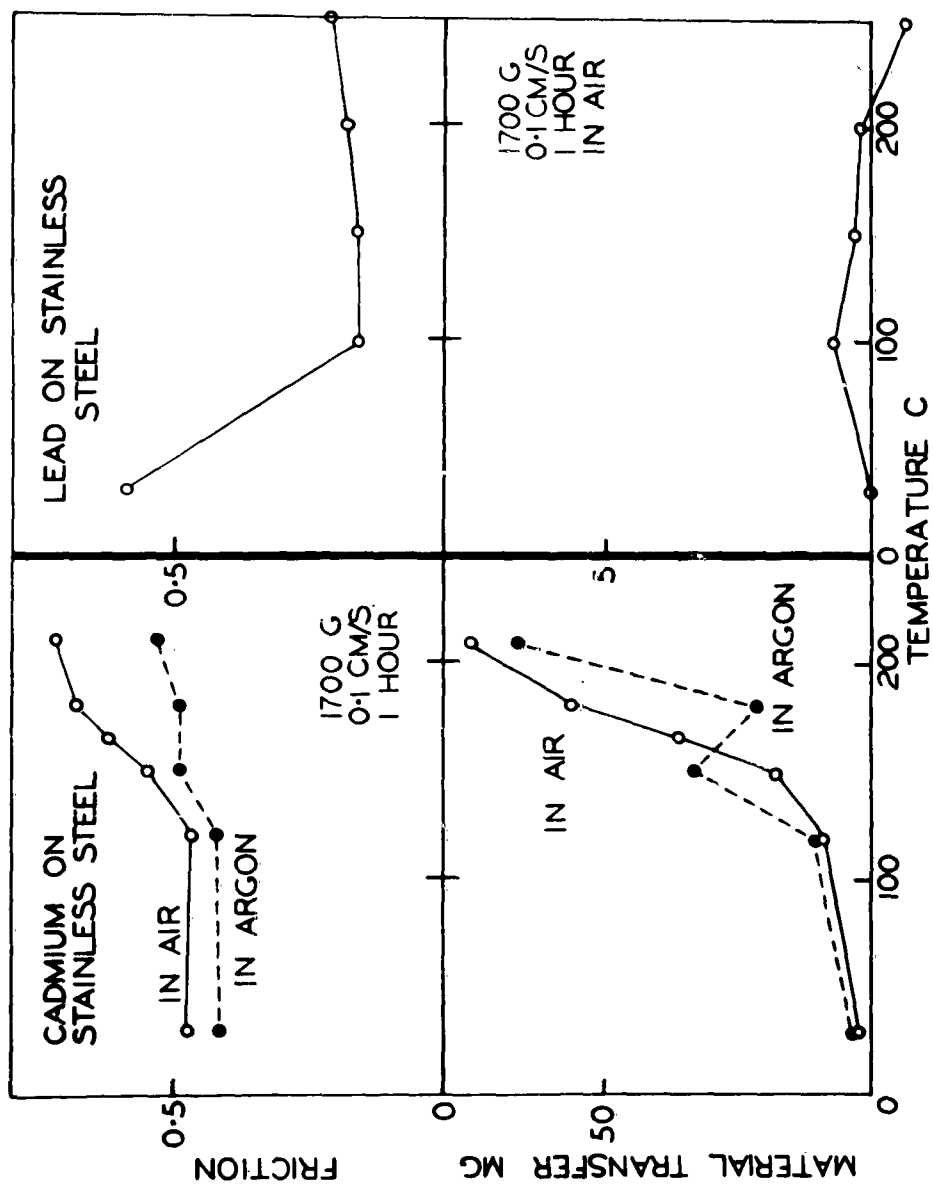
FIGURE 11. Material Transfer and Friction: Load 1700 g, Speed 0.1 cm/s, Duration of Test One Hour

33
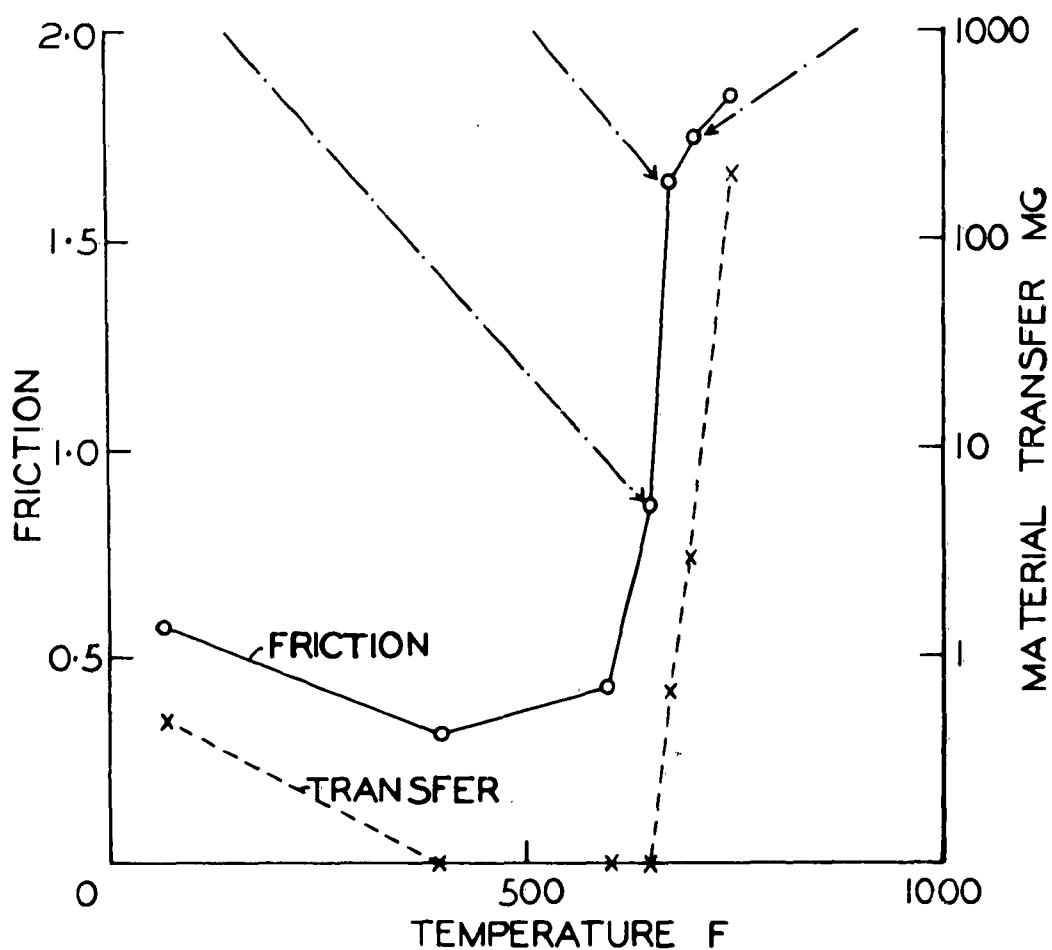
FIGURE 12. Material Transfer and Friction for Boric Oxide on Stainless Steel
Steel: Load 1700 g, Speed 0.1 cm/s, Duration of Test One Hour, in Air
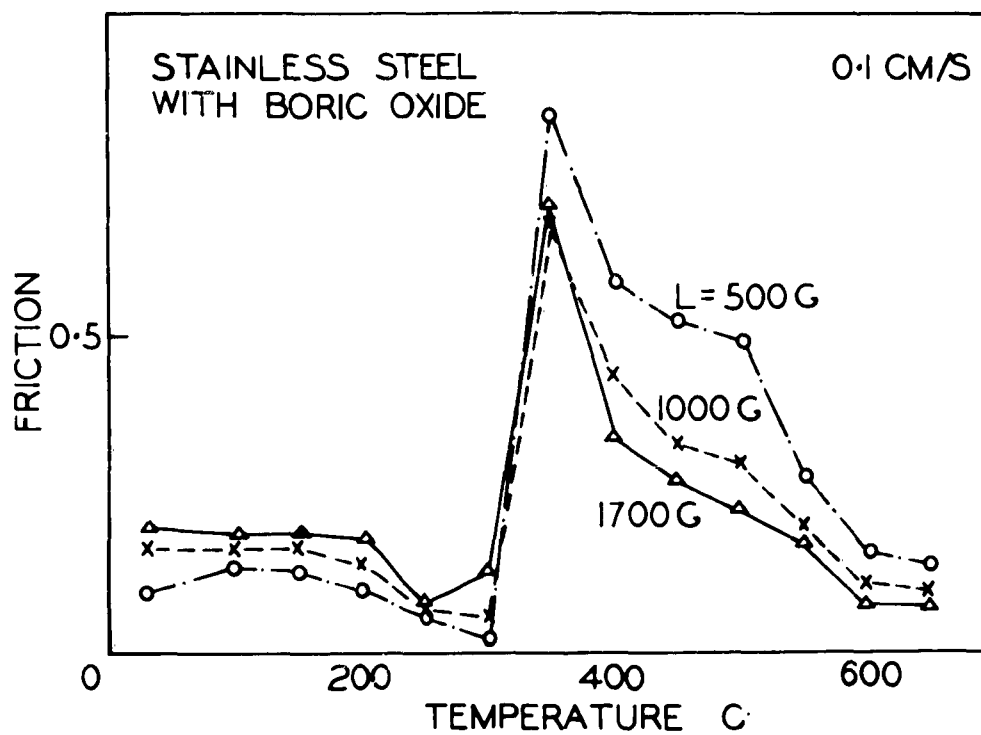
FIGURE 13

Effect of Load for Stainless Steel on Stainless Steel with Boric Oxide

35

Aeronautical Systems Division, Dir/Materials
and Processes, Metals and Ceramics Lab,
Wright-Patterson AFB, Ohio.
Rpt No. WADC-TR-59-603, Pt IV. FRICTION AND
WEAR AT ELEVATED TEMPERATURES. Interim report,
Mar 63, 35p. incl illus., 16 refs.

Unclassified Report

Measurements have been carried out of the
friction coefficient as a function of temper-
ature using surfaces of stainless steel cover-
ed by low-melting metals and non-metals
applied in powder form. Some work has also
been done with a few other metal and non-
metal surfaces. In cases where the inter-

(over)

1. Friction and
   Wear
2. High Temperature
   Research
I. AFSC Project 7342,
    Task 734204
II. Contract AF33(616)-
    7648
III. Mass. Institute of
    Technology,
    Cambridge, Mass.
IV. E. Rabinowicz, M.
    Imai
V. Aval fr OTS
VI. In ASTIA collec-
    tion

action between the low melting substance and
sliding surface is high, as revealed by the
occurrence of wetting, the friction reaches
a peak just below the melting temperature of
the substance, and then drops to consider-
ably lower values just above the melting
point. The peak below the melting tempera-
ture is associated with the formation of
large adhering fragments of the low melting
substance on the sliding surface. When
there is no wetting, the low-melting substance
has, either below or above its melting point,
essentially no effect on the friction.