SLIDING CHARACTERISTICS OF METALS AT HIGH TEMPERATURE

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INTRODUCTION

A program has been under way at the General Electric Company to gain a better understanding of friction, and wear processes at elevated temperatures. In this report, some of the results of the program are presented with particular reference to sliding contact bearings.

It is recognized that the principal requirements of any bearing system are minimum power loss and adequate life under the specified operating conditions. The bearing material, lubricant, and the system must be chosen consistent with these requirements. Surface damage in itself is generally not specified, but implied, since surface damage would give both high friction and high wear.

The type of bearing system depends upon the operating conditions. The bearing designer generally considers either a fluid film or rolling contact bearing. Also a fluid is provided to cool the bearing and to lubricate effectively those portions where contact is encountered. If the specified operating conditions exclude fluid film or rolling contact bearings, then a sliding contact bearing system must be designed so that the load will be fully supported by the bearing material. Only this type of bearing system will be covered by this discussion.

In this type of bearing (so called dry or boundary-lubricated bearing), various applications place different demands on the bearing. For example, in application where differential thermal expansions cause occasional relative slip, a considerable amount of damage can be tolerated. However, in a main shaft seal, there can be no surface damage since this will result in ineffective sealing.

Another aspect of an application which must be considered is whether the sliding will be confined to a certain clearance. In a journal bearing, where the shaft cannot be displaced to ride over a damaged area, transfer or damage will cause seizure. And when sliding is not confined, the damaged area can possibly be repaired if surface damage is not regenerative. In other words, the requirements of a bearing material for dry or partially lubricated bearings cannot be defined without knowing the type of application under consideration.

When considering bearings that must operate at extremely high temperatures the factors which have the most profound effect on these sliding characteristics are: the lack of suitable lubricants; the oxidation of the surfaces; the loss of strength of the materials; and the increase in the weldability of the surfaces. The most important of these factors is, of course, the lack of lubricants which will be effective over the entire temperature range. This means that at least within certain temperature ranges, it may be necessary for the bearing to operate unlubricated. This requirement coupled with the fact that
the bearing must be oxidatively stable and must possess high temperature strength puts very stringent demands on the bearing material.

Some of the information which has been assembled for low temperature bearing systems can be used as a guide for the selection of high temperature unlubricated bearings. In the most general sense, effective sliding will result if the cohesion of the material is much greater than the adhesion at the sliding interface. Actually, cohesion is a measure of the strength of the material, and adhesion is a measure of weldability. This subject is discussed in reference 1. It has also been shown (2,3) that those combinations of materials whose phase diagrams indicate that they have limited solubility make the most effective sliding contacts.

Another factor which modifies the adhesion at the interface is the formation of surface films. This film can be formed by reaction with the environment or by transferring material from one sliding surface to the other. Sliding then takes place between one of the surfaces and the transferred film.

Based on the above, friction, wear, and surface damage is determined by three factors:
1. Strength
2. Weldability
3. Film formation
   a) Reacted
   b) Transferred

The changes in these factors with temperature should then determine the high temperature sliding characteristics of materials.

The loss of strength of a material, accompanied by an increase in the weldability as the temperature is increased, should have a detrimental effect on the sliding. This has been shown by Marchant (4) for copper and magnesium where increased friction is associated with the relaxation temperature of the metal. This effect has also been for perfectly clean surfaces of gold and nickel (5), where again, the rise in friction is associated with the marked thermal softening of the metals.

The loss of strength or hardness of the material should also be accompanied by an increase in the wear rate. This has been substantiated (6) for various materials such as aluminum and brass sliding against tool steel. Lancaster reported that an increase in wear was found to correlate directly to the loss of hardness. Although such effects are extremely important in choosing high temperature sliding contacts, the role of surface films, mainly oxides, would seem to be a more important factor, especially for contacts which must operate at elevated temperatures.

There has been considerable discussion of the effect of oxides and other surface films in the literature. It has been shown that certain metal couples, if cleaned perfectly by heating in a vacuum,
seize completely upon contact and have essentially an infinite coefficient of friction. However, if even a trace of oxygen is present, the coefficient of friction is reduced considerably to values of 1.0 or lower. It has also been shown that even when operating in air the presence of an oxide is beneficial in preventing seizure and galling of metal pairs\(^{(7,8)}\).

However, to be beneficial, it has been found\(^{(5,9)}\) that the mechanical properties of the oxide and its substrate material must be such that the oxide is retained on the surface. For example, Al\(_2\)O\(_3\), which is harder than Al, is completely ineffective in protecting the aluminum surface since under load the deformation of the aluminum causes a breaking up of the oxide.

It is also known that too much oxide is not beneficial and, in many cases, is detrimental to the system. In the cases where the oxide is removed from the surface and remains in the bearing, considerable abrasive wear may be encountered. A discussion of this type of wear has been given in reference 10.

It has been pointed out that in order to select a bearing material for a particular application, the sliding characteristics of the material might need to be compromised with other material requirements such as strength, oxidation resistance, corrosion resistance, thermal expansion, and ease of fabrication. However, to make these compromises between sliding characteristics and other material requirements, it is necessary to have a knowledge of the sliding characteristics of materials. Specifically, it is necessary to know the friction, the wear rate, and the surface damage characteristics of the materials under the various operating conditions expected.

Therefore, a study was made of the sliding characteristics of several types of materials. The data which was presented in this report illustrate the important aspects from the standpoint of friction, wear, and surface damage.
The apparatus used in these tests consists essentially of a hemisphere sliding against a flat plate. This particular configuration was used as one of the specimens in order to confine sliding to a particular area and to allow wear measurements to be made after a much shorter running time. Figure 1 is a schematic of this apparatus. In this apparatus the support table on which the friction arm is mounted oscillates through an angle of 3.5° as the eccentric cam rotates. Since the friction arm is rigidly fastened to the bearing shaft, it will oscillate through this same angle. The bearing shaft that holds the arm is mounted in ball bearings, allowing the arm to move freely in the vertical direction. The same load which is applied to the load arm is transmitted to the specimens.

As the friction arm moves back and forth, part of the friction force is absorbed by the flexure and part is transmitted through the strain gage arm at B in the figure. The force which this arm carries is recorded on a Brush recorder. The magnitude of the friction force is determined by previous calibration of the system with dead weights.

In operation, the friction arm and the sliding specimens are housed in a furnace. The temperature of the wall of the furnace is controlled at a level that will heat the specimen to the desired temperature. Specimen temperature is measured by a thermocouple next to the specimen.

The following procedure was used for these tests. The friction specimens were cleaned by using repeated applications of levigated alumina and water. They were then rinsed with pure alcohol. The cleaned specimens were put into position and a load of 4.14 pounds was applied. The furnace was moved into position, and the specimens were brought to the desired testing temperature. Friction was continuously recorded for the first five minutes; friction readings were then taken every five minutes. After one-half hour the temperature was either increased or decreased as the sliding continued and the friction force was recorded. At the conclusion of the test, the specimens were microscopically examined to determine the amount of wear and the extent of surface damage. Unless otherwise stated, the standard test conditions were a load of 1880 grams (4.14 lbs.) and a speed of 0.3 inch/seconds.

RESULTS

In these experiments friction-temperature curves were first obtained on several pure metals using the procedure previously given for the reciprocating wear rig. Other tests were then run to understand better the role of the oxide in high temperature sliding, and an attempt
was made to relate these results to alloys which contain these metals.

Pure Metals

Friction-temperature cycle tests were run with Fe, Cu, Co, Ni, Cr, Mo, Al and Zr sliding against themselves. These results are shown in Figures 2 through 6.

The following trends were observed for the Fe/Fe couple (See Figure 2). Initially, friction was high at room temperature and galling was noted. Then the friction dropped off markedly as the temperature was increased to 200°F; above this temperature, the friction then decreased to approximately 0.4 at 1000°F. Upon cooling, a similar trend was observed. However, the friction did not rise to the high initial values previously obtained at room temperature.

This test was rerun in order to observe the surface for damage and film formation. The first cycle was run at room temperature, and after a predetermined time, the test was stopped. The temperature was increased to 220°F and the apparatus was restarted. Upon restarting, the friction was initially high (0.91), but after a few minutes friction decreased to a value of 0.65. After this run, the surfaces of the specimens were examined, and a thin dark film, presumably oxide, was apparent in the sliding areas. There was no visual evidence of oxide in any other areas on the specimens. This result indicates that the sliding process itself is, to a large extent, responsible for the generation of the "run-in" film.

For copper sliding against itself (Figure 3) friction was initially high at room temperature (1.3), then decreased to a lower value, increased at 500°F, decreased to a minimum value of 0.60 at 500°F and increased again above 1000°F. Upon cooling, a low point was reached at approximately 400°F. As previously noted for iron, the original friction value was not obtained upon returning to room temperature.

The coefficient of friction (0.60) found at the higher temperatures was identical to that found by Godfrey(11) for solid copper oxide sliding on copper oxide. These results indicate that when sufficient oxide is formed on the surface, the oxide will support the load itself, and its properties will determine the sliding characteristics.

Several tests were run with this particular combination in order to be assured of the reproducibility of the rise of friction at 300°F. This rise in friction indicated that the oxide was being removed. This may be explained by the fact that the copper becomes softer as the temperature approaches the recrystallization temperature. This softening facilitates the removal of the oxide. At higher temperatures the oxidation is more rapid and more adherent and again forms a protective film.
Figure 2. Effect of Temperature on the Coefficient of Friction for Iron vs. Iron During Temperature Cycling. Load - 1880 G., Velocity - 1.5 Ft./Min.
Figure 3. Effect of Temperature on the Coefficient of Friction for Copper vs. Copper During Temperature Cycling. Load - 1000 G., Velocity - 1.5 Ft./Min.
Numerous tests were run with the cobalt combination (See Figure 4). At room temperature, an initial coefficient of friction value of 0.32 was obtained. A slight decrease in friction was observed up to 700°F but friction then increased to a high value at 1000°F. However, above 1000°F friction decreased again and reached a value of 0.32 at approximately 1400°F. Upon cooling, a maximum friction value was obtained in the vicinity of 1000°F and the original friction was obtained on returning to room temperature.

The reason for the increase in friction is not precisely known. It is interesting that the rise in friction takes place at a temperature where there is a phase change in the cobalt (788°F). This may result in a disruption of the surface oxide or the formation of detrimental oxides.

Another test was also run several hours at room temperature. At the conclusion of this test there was a thick film build up on the slider in the wear area; however, there was no film apparent on the flat.

The same general trends were also apparent with chromium, nickel, and molybdenum pairs. That is, high friction was obtained up to a certain temperature, then followed by a reduction in friction (See Figure 5). With these metals the reduction in friction took place at 800°F for chromium at 900°F for molybdenum, and at 1100°F for nickel. As with the other metals which galled, a hysteresis effect was noted. Once the oxide was formed, the low friction would persist to lower temperatures upon cooling. It is also noteworthy that with molybdenum an increase in friction was found to occur at approximately the sublimation temperature (1460°F) of MoO₃.

The friction-temperature cycle tests for 24S aluminum and zirconium are shown in Figure 6. For aluminum, a large increase in friction resulted as the temperature approached the recrystallization temperature (650°F) of this alloy. As previously mentioned, the hard Al₂O₃ would not be expected to have much effect with a soft substrate and the rise in friction would be due to the thermal softening of the metal.

For zirconium, low friction was obtained at room temperature, then friction gradually increased above 500°F. This particular test was not cycled, but stopped at the highest temperature. At the conclusion of the test there was a considerable amount of loose powdered oxide in the sliding area.

Based on the results attained in these tests, the following general conclusions can be drawn. As the temperature is increased, a large increase in friction and surface damage will occur as the material softens. This persists until a temperature is reached whereby an oxide film will be continually reformed at the sliding surface. At this temperature, the sliding characteristics will then be markedly improved.
Figure 4. Effect of Temperature on the Coefficient of Friction for Cobalt vs. Cobalt During Temperature Cycling. Load = 1500 G., Velocity = 1.5 Ft./Min.
Figure 5. Effect of Temperature on the Coefficient of Friction for Various Material Combinations During Temperature Cycling. Load - 1880 G., Velocity - 1.5 Ft./Min.
Figure 6. Effect of Temperature on the Coefficient of Friction for Various Materials Sliding Against Themselves.
Load - 1880 G., Velocity - 1.5 Ft./Min.
With metals such as cobalt and zirconium, sufficient oxide is generated at room temperature to be beneficial. With the other material pairs, an increase in the ambient temperature is necessary to promote sufficient oxide formation. Any temperature effect which tends to remove the oxide such as softening (in the case of Cu), scaling, or sublimation will cause a rise in friction. A similar effect may also be hypothesized for cobalt where the volume change could disrupt the oxide.

When the oxide on the surface is retained during sliding (e.g. Cu sliding across Cu), the coefficient of friction is essentially the same as for oxide sliding on itself. Such data are not available for the other oxides; therefore, a test was run with a compress of zirconium oxide sliding against zirconium silicate. The friction for this combination was 0.46 as compared with 0.43 for zirconium sliding against zirconium. These data indicate that for these two compounds, at least, the oxide may be thick enough to support the load. If this is so, then, in essence sliding is taking place between oxide surfaces.

There are, however, several other ways in which the oxide could be acting. The oxide could be causing an increase in the hardness of the surface layer of metal\(^{(12)}\). Also, the oxide could be decreasing the effective shear strength of the surface by the formation of a reaction film. This latter explanation would not seem feasible for compounds like nickel and zirconium which form hard oxides. A fourth possibility, but a more remote explanation, is that the loose oxide particles reduce friction by rolling between the surfaces.

In order to check the effectiveness of the oxides as soft lubricant coatings, several tests were run with the powdered oxides as lubricants for an Inconel hemisphere sliding against an Inconel X surface. The bonding of the powdered oxide was, of course, much poorer than that of surface reaction film. If, however, an oxide were effective in this test, it would certainly be effective if formed on the surface.

The friction coefficients using various oxides as solid lubricants at 1300°F are shown in Figure 7 along with the sliding conditions. Each of these oxides except chromium, nickel, and iron flowed into a continuous solid film and prevented the Inconel surfaces from coming into contact. When NiO, Fe\(_3\)O\(_4\), or Cr\(_2\)O\(_3\) was placed on the surface, the sliding action brushed them from the surface and considerable galling resulted. The lowest friction (0.12) was obtained with PbO. This result is consistent with other reported results. This friction was approached by molybdenum trioxide which gave a coefficient of friction of 0.20. Although the friction was high when WO\(_3\) was used, there was no surface damage to the Inconel slider or flat. A photograph of the surface using CuO as a lubricant is shown in Figure 8. The CuO formed a continuous film and prevented metal contact. A similar behavior was observed in the case of cobalt oxide (Figure 9). Again the cobalt formed a continuous film and prevented surface contact.

These results show that considerable benefit can be gained by using alloys which form a soft continuous type of oxide on the surface.
Figure 7. Effect of Sliding Cycles on the Coefficient of Friction Using Various Oxides as Lubricants. Inconel Sliding Against Inconel X, Load - 17 Lbs., Velocity - 16.7 In./Min.
Figure 8. Track of Inconel X Sliding on Inconel X using CuO as Lubricant.
Temp. - 1600°F  Mag. - 20X

Figure 9. Track of Inconel X Sliding on Inconel X using Co₃O₄ as Lubricant.
Temp. - 1300°F  Mag. - 20X
These results are also in agreement with previous experience obtained with alloys which contain a major portion of those elements which form these soft oxides.

The formation of a soft oxide film, however, would not explain the data obtained for metals such as nickel and zirconium whose oxides are harder than the base metals, especially at high temperatures. For those metals which form the hard oxides, it is hypothesized that oxide is sliding on oxide much the same way as when two solid pieces of oxide are sliding together.

**Alloys**

The friction data for these pure metals were compared with values of friction obtained with several typical alloys which contain these pure metals. The coefficients of friction for nickel are compared with those obtained for Inconel in similar temperature cycling tests in Figure 10. The friction trends were nearly identical except that Inconel had a lower friction than nickel at the low temperatures where galling took place. These frictional changes are considered within the reproducibility of the experiments. It should also be mentioned that the temperatures where these frictional changes occurred were also sensitive to load and time. A similar drop of friction occurred after a 30-hour run at 1000°F.

The type of surface damage that occurred above the transition temperature is compared to that which occurred below the transition temperature. The photograph (Figure 11) indicates that some initial surface damage occurred at 1600°F, but subsequent sliding on the oxide was smooth with very little surface damage. At room temperature under identical conditions (Figure 12), there was considerable damage with many small welds.

The data for tool steel and SAE 1020-steel are shown in Figure 13. This chart shows the coefficient of friction obtained using the temperature cycling procedure. For soft SAE 1020-steel the friction was nearly identical to that of the pure iron with a few exceptions. The drop-off of friction to a value of 0.4 was at 600°F instead of 400°F, and there was a friction increase above 800°F.

For tool steel a curve identical to the 1020-steel was obtained; however, no rise in friction was noted above 1000°F. The reasons for these variations in friction behavior have not been determined at the present time. The important point is that above 250°F the frictional behavior of each of these materials is almost identical. This indicates the important role played by the oxide in high temperature sliding.

The frictional values obtained with Hastelloy B (62 Ni 28 Mo) are compared with those of Ni and Mo (Figure 14). It is noted that no similarity exists for the Hastelloy B and the Ni curves, but there is a marked similarity for the Molybdenum and the Hastelloy B curves.
Figure 10. Effect of Temperature on the Coefficient of Friction for Various Material Combinations During Temperature Cycling. Load - 1880 G., Velocity - 1.5 Ft./Min.
Figure 11. Track of Inconel Sliding on Inconel.
Mag. - 20X

Temp. - 1600°F  Sliding Time - 1/2 hr
Load - 4.14 lbs  Velocity - 3.7 ft/min
Figure 13. Effect of Temperature on the Coefficient of Friction for Various Material Combinations Sliding Against Themselves During Temperature Cycling. Load - 1880 g., Velocity - 1.5 Ft./Min.
Figure 14. Effect of Temperature on the Coefficient of Friction for Various Material Combinations Sliding Against Themselves During Temperature Cycling. Load - 1880 G., Velocity - 1.5 Ft./Min.
The reduction in friction for this alloy occurred at 600°F, with an increasing trend above 1000°F. Thus, the frictional behavior of Hastelloy B is more related to that of Mo than Ni, even though the alloy only contains 28% Mo. A much greater hysteresis effect was noted for Mo than for Hastelloy B. This is understandable since Mo oxidized faster than Ni, and considering the large quantity of molybdenum oxide which can be formed at 1500°F.

The friction curves for S-Monel (65 Ni, 28 Cu) are compared with Cu and Ni in Figure 15. For S-Monel, friction decreased slightly around 400°F and upon cooling retained this low value. This behavior is not similar in any regard to the nickel curve. About the only similarity to the copper curve in the reduction is friction about 500°F. Of course, there is considerable difference between the properties S-Monel and copper. S-Monel is a hardened cast alloy while copper is relatively soft.

For austenitic stainless steels a change in the friction and surface damage was not noticeable as the temperature was increased. If anything, it was higher due to thermal softening at the high temperatures. A photograph of the sliding specimens of 310-stainless steel is shown in Figure 16.

For the 440-series of stainless steel, initial surface damage made subsequent sliding very rough; however, a reduction in friction was noted at the higher temperatures.

This data is, of course, limited but it does show that there is a correlation between the sliding characteristics of the alloys and the oxide formed on the surface. The data obtained to date indicates that it is related to the less noble major constituent of the alloy.
Figure 15. Effect of Temperature on the Coefficient of Friction for Various Material Combinations Sliding Against Themselves During Temperature Cycling. Load - 1880 g., Velocity - 1.5 Ft./Min.
SUMMARY OF RESULTS

Based on data available in the literature and from these experiments, the following conclusions may be drawn concerning materials for high temperature sliding contacts.

1. Extremely high friction, surface damage, and greater wear will result with metals sliding against themselves at a temperature where the material softens appreciably, if no protective oxide is formed.
2. If an oxide is formed, the galling tendency will be reduced and effective sliding will result as long as the oxide film adheres to the surface.
3. If the formed oxide is hard, the sliding is essentially oxide on oxide; however, if the oxide is removed from the surface, abrasive wear will result.
4. If a soft oxide is formed on the surface, a beneficial effect is achieved by preventing surface damage and reducing abrasive wear. Too much soft oxide, however, can increase the rate of wear.
5. There is a relation between friction properties of alloys and that of the major constituents. Based on limited data, a reduction in friction occurs at a temperature sufficient to promote oxidation of the least oxidation-resistant component. With several alloys such as cobalt, Cu, and Fe, this reduction takes place at low temperature.
REFERENCES


11. Godfrey, Douglas and Bailey, John M., "Coefficient of Friction and Damage to Contact Area During Early Stages of Fretting," I Class, Copper, or Steel Against Copper, NACA TN 3011, September, 1953.

