NASA TECHNICAL NOTE

NASA TN D-5916

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NASA TN D-5916

FRICTION AND WEAR OF STEELS IN AIR AND VACUUM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1970

1. Report No. NASA TN D-5916	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Friction and Wear of Steels in Air and Vacuum		5. Report Date October 1970
		6. Performing Organization Code
7. Author(s) Roamer Predmore, Jane Jellison, and Charles L. Staugaitis		8. Performing Organization Report No. G-983
9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771		10. Work Unit No. 604-31-75-01-51
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

Submitted to the American Society of Lubrication Engineers, Aerospace Technical Sessions, Chicago, Illinois, May 1970.

16. Abstract

Metal alloys were tested for sliding friction and wear characteristics in vacuum and in air. One purpose was the analysis of variations in the coefficient of friction with changes in air pressure, hardness, and type of alloy. Another purpose was the evolution of a scheme for description of wear patterns. With a Bowden-Tabor apparatus, sliders of various alloys were revolved in contact with a steel plate. Soft and hard steel, titanium, aluminum, copper, and copper-beryllium alloys were tested. Hardness of steel in the plate was varied. Visual and metallographic inspection, as well as study of microhardness traverses from below the wear interface, provided the results. Photomicrographs showing wear in the metal alloys are presented. This paper also provides graphical description of variations in the coefficient of friction. A description of observed wear patterns is accomplished by a scheme of four categories: prow formation, severe rider wear, intermediate rider wear, and mild rider wear. In each category, wear pattern is correlated with a mechanism responsible for its formation.

17. Key Words Suggested by Author Wear mechanisms Friction	18. Distribution Statement Unclassified—Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	19	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
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CONTENTS

FRICTION AND WEAR OF STEELS IN AIR AND VACUUM*

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INTRODUCTION

The sliding friction and wear of steel on steel in air and vacuum has been measured in previous studies (References 1, 2, and 3), and a wide range of friction coefficients (0.4 to 4.9) has been reported for several test conditions. A number of friction and wear mechanisms have been identified by Antler (References 4 and 5), Cocks, and the present authors (Reference 7). The major ones are prow formation, sliding seizure, wedge flow, and various forms of rider wear.

Prow formation is a severe wear mechanism that results in the growth on the tip of the rider of a prow of work-hardened metal that separates the rider from the plate. Sliding seizure results when the slider welds to the disc, abruptly stopping all sliding motion. The wedge flow mechanism entails plastic shearing of slider metal to the trailing edge of the slider without removal from the slider. There are, according to Antler (Reference 5), several forms of rider wear mechanism which have not been fully separated and defined. Their common characteristic is that metal is removed from the slider.

This systematic investigation of steel and other alloys sliding on steel was undertaken to measure the effect of vacuum, hardness, and slider metal on friction in order to explain the wide disparity in friction coefficients reported earlier and to characterize the types of wear mechanism responsible for these variations. Examination of the wear surface characteristics permitted classification of the wear into four groups: prow formation and three heretofore undefined rider wear mechanisms.

EXPERIMENTAL PROCEDURE

A Bowden-Tabor disc-and-slider apparatus (Reference 7) was utilized for this study. A Hertz stress of about 158,000 psi was induced on the plate by a 1-lb load on the slider,

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which was tipped with a hemisphere of 1/4-in. diameter. The friction force was continuously recorded by means of a strain gauge located on the slider arm. Values plotted in the figures are the maximum levels for each test. Tests of 25 revolutions each were conducted at pressures of 760, 10^{-4}, and 10^{-8} torr for each combination of materials, with a different area of the plate and a fresh slider for each test. All specimens were finished to a metallographic polish in the contact area and were cleaned in acetone and alcohol immediately prior to testing. No attempt was made to remove the naturally occurring surface oxides.

The sliders and plates were examined visually at about 15X for evidence of gross metal transfer and surface wear characteristics. Metallographic cross sections of sliders and plates were examined optically and by electron probe analysis in cases where metal transfer was not distinguishable visually. A measure of surface strain or work hardening resulting from interfacial wear damage was obtained by DPH microhardness traverses under the wear surfaces, using a 15-g load.

The steel plate materials were AISI 1020, 4130, or 4340 heat treated to various hardness values ranging from DPH 90 to 600. Structures were tempered martensite except for the 1020 steel that was used in the mill-annealed condition (ferrite plus pearlite). Slider materials were copper (DPH 75), heat-treated copper beryllium (DPH 350), alpha titanium 5A1-2.5Sn (DPH 320), 6061-T6 aluminum (DPH 100), 1020 steel (DPH 190, ferrite plus pearlite), and 1095 steel heat treated to two hardness levels (DPH 350 and 700, both tempered martensite).

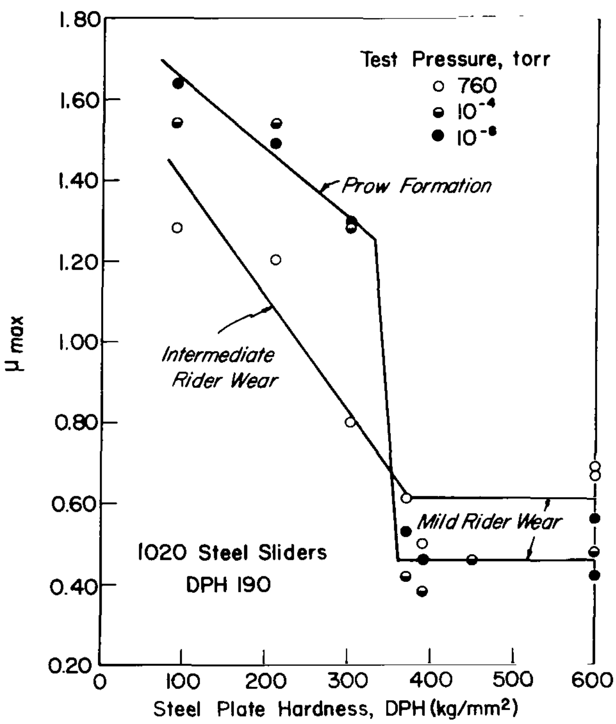


Figure 1–Maximum coefficient of friction versus plate hardness for soft (DPH 190) steel sliders on steel plates.

TEST RESULTS

Steel Sliders on Steel Plates

The friction coefficients for soft 1020 steel (DPH 190) sliders on steel plates ranging in hardness from DPH 90 to DPH 600 are shown in Figure 1. For the softer plates, up to about DPH 350, the maximum friction in vacuum is substantially higher than that in air, and both decrease with increase in plate hardness. The friction in vacuum drops abruptly from 1.3 to 0.45 at a plate hardness of DPH 350 and remains constant at this level with further plate hardness increase. At the same time, the coefficient in air also levels off, but at a somewhat higher value of 0.6.

Examination of the wear surfaces showed that each segment of the curve could be associated with one primary wear mechanism, with a transition from one to another at the inflection points in the friction curves.

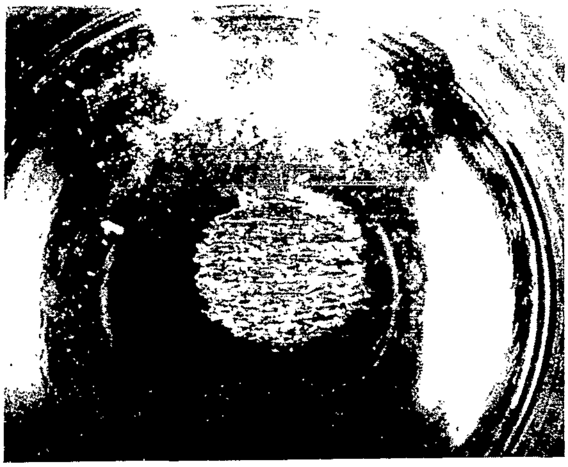
The sliders tested in vacuum on the softer plates wore by prow formation. This is a severe wear mechanism associated with high friction levels, characterized by a build-up on the leading edge of the slider of work-hardened metal which elevates the slider and separates it from the plate. The sliding interface is in the plate and subsurface deformation is great. Since the prow is usually composed of plate metal transferred to the slider, the friction depends on plate, rather than rider, metal characteristics and thus tends to decrease with increasing plate hardness. The same hardness combinations tested in air resulted in a form of rider wear that is herein termed intermediate rider wear.

Characteristics of this mechanism are as follows: (1) metal is removed from the slider (as in all forms of rider wear); (2) surface oxides of the plate are penetrated but little, if any, metal transfer occurs either from rider to plate or from plate to rider; (3) the sliding interface is intermittently in the rider or in the plate; (4) the worn tip of the slider is flat but fairly rough; (5) wear scars on the plate are moderately shallow and straight; (6) a cross section of the slider reveals evidence of some plastic deformation and strain hardening under the worn surface; and (7) for constant slider hardness, friction decreases with increasing plate hardness.

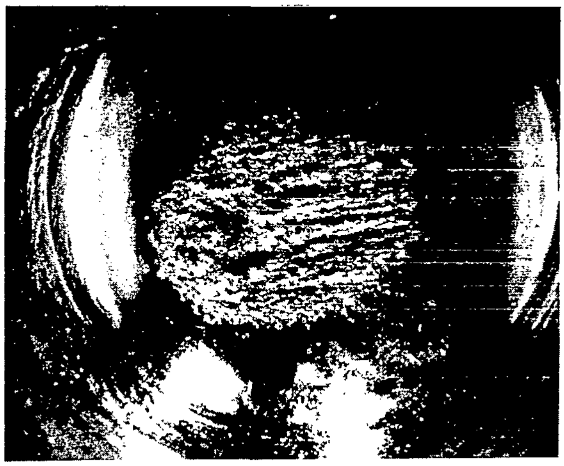
As the plate hardness increased above DPH 350, both the vacuum and air tests showed a wear mechanism transition to another form of rider wear, which is designated mild rider wear. This wear mechanism is typified by the following characteristics: (1) small amounts of metal are removed from the slider; (2) surface oxides of the plate are not significantly penetrated and no metal transfer occurs; (3) the sliding interface is between the rider tip and the surface of the plate; (4) the worn tip of the slider is flat and smooth; (5) wear scars on the plate are light, straight, and, at times, barely visible; (6) a cross section of the slider reveals very little subsurface deformation or work hardening; and (7) for constant slider hardness, friction is relatively low and constant for increasing plate hardness.

Examples of intermediate rider wear and prow formation are illustrated in Figure 2. The slider in Figure 2a shows the rough, worn area associated with intermediate rider wear, and the corresponding track (Track 1) is shallow relative to the tracks produced by the prow formation mechanism (Tracks 3 and 4). This is particularly evident in Figure 2d where the illumination has been adjusted to emphasize the comparative roughness of the tracks.

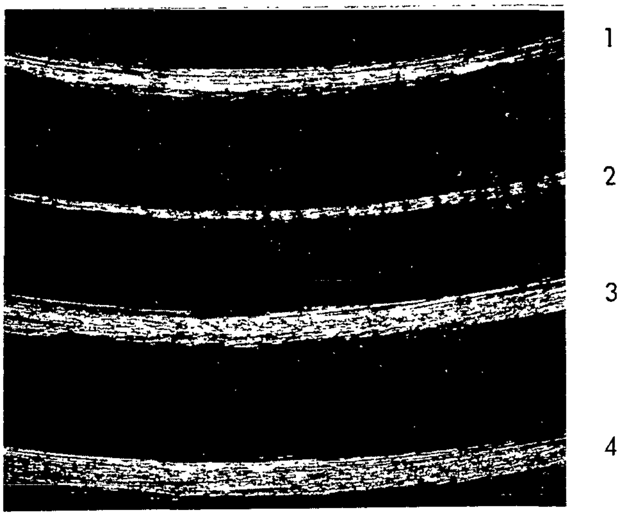
Cross sections of Tracks 1 and 4 (Figure 3) show the extensive plastic deformation and metal removal caused by the prow formation mechanism, while the metal underlying the intermediate rider wear track is much less disturbed. Microhardness traverses below the wear interface for these pairs of test specimens are plotted in Figure 4. The prow material itself was work hardened to DPH 550, and the plate showed hardening to a depth of about 20 micrometers below the wear interface. The plate for the rider wear



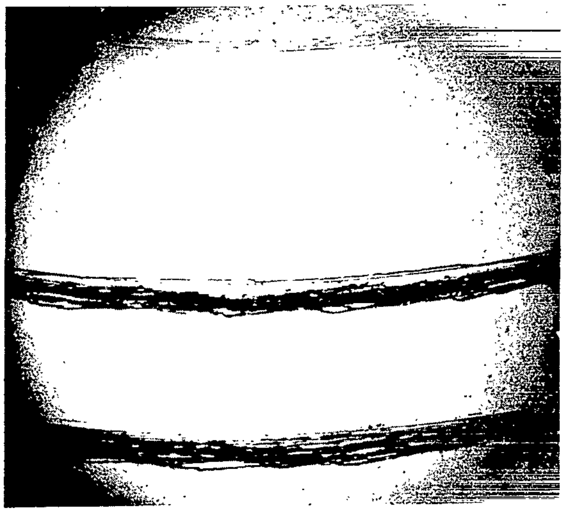
a–Slider tested at 760 torr, 25 revolutions. Intermediate rider wear ($\mu = 0.80$). (20X)



b–Slider tested at 10^{-8} torr, 25 revolutions. Prow formation ($\mu = 1.29$). (20X)

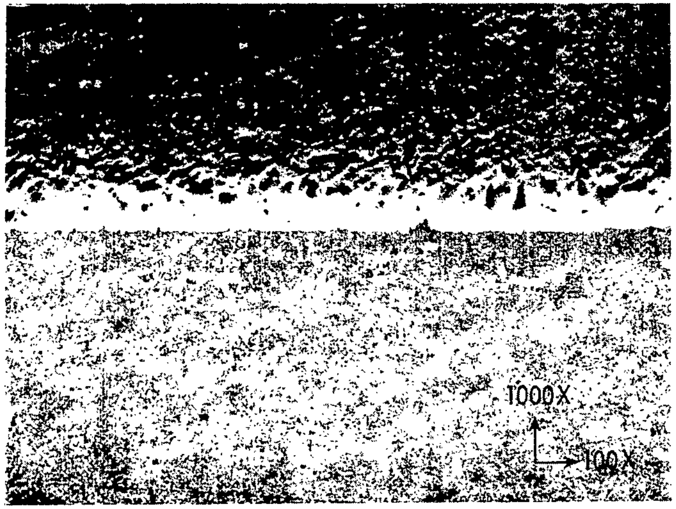


c–Plate tested at 760 torr, 25 revolutions (track 1); 760 torr, 1 revolution (track 2); 10^{-4} torr, 25 revolutions (track 3); 10^{-8} torr, 25 revolutions (track 4). (5X)

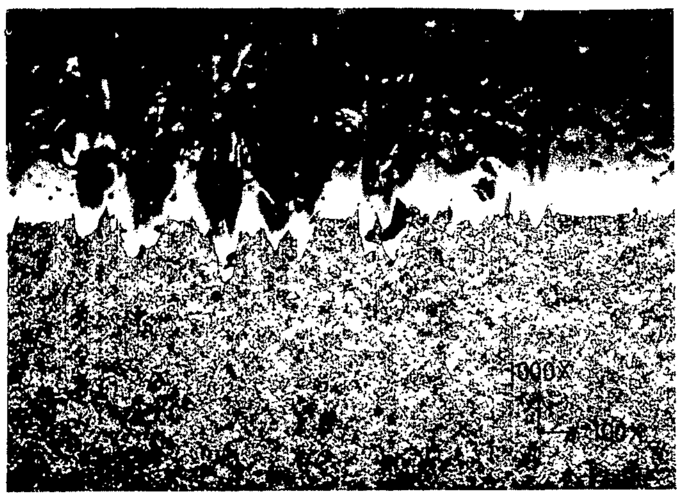


d–Same plate, with illumination adjusted to show depth of tracks. (5X)

Figure 2–Tests of 1020 steel (DPH 190) on 4340 steel (DPH 300).



a–760 torr, 25 revolutions (track 1). Intermediate rider wear.



b–10^{-8} torr, 25 revolutions (track 4). Prow formation.

Figure 3–Taper cross sections of wear plate shown in Figure 2. (Mounting angle 6°, vertical magnification factor 10, horizontal magnification 100X)

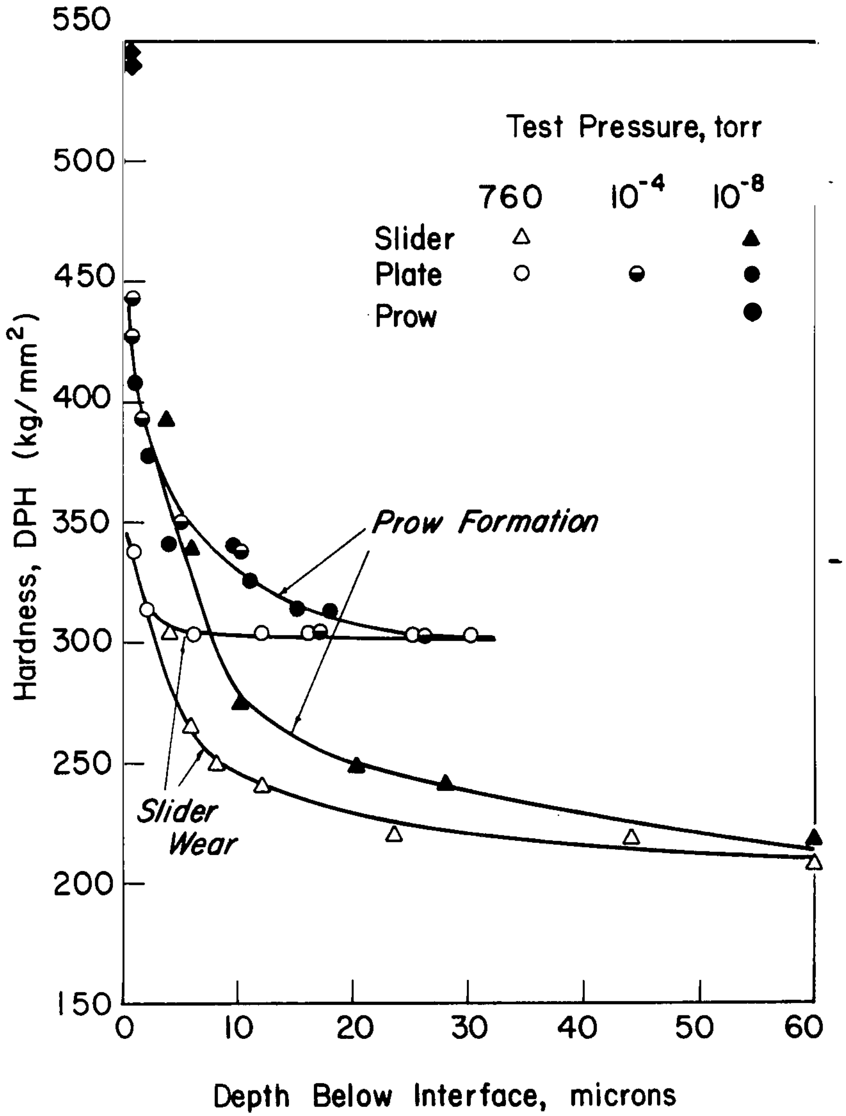


Figure 4–Microhardness traverses across wear interface for 1020 steel sliders (DPH 190) on 4340 steel plate (DPH 300).

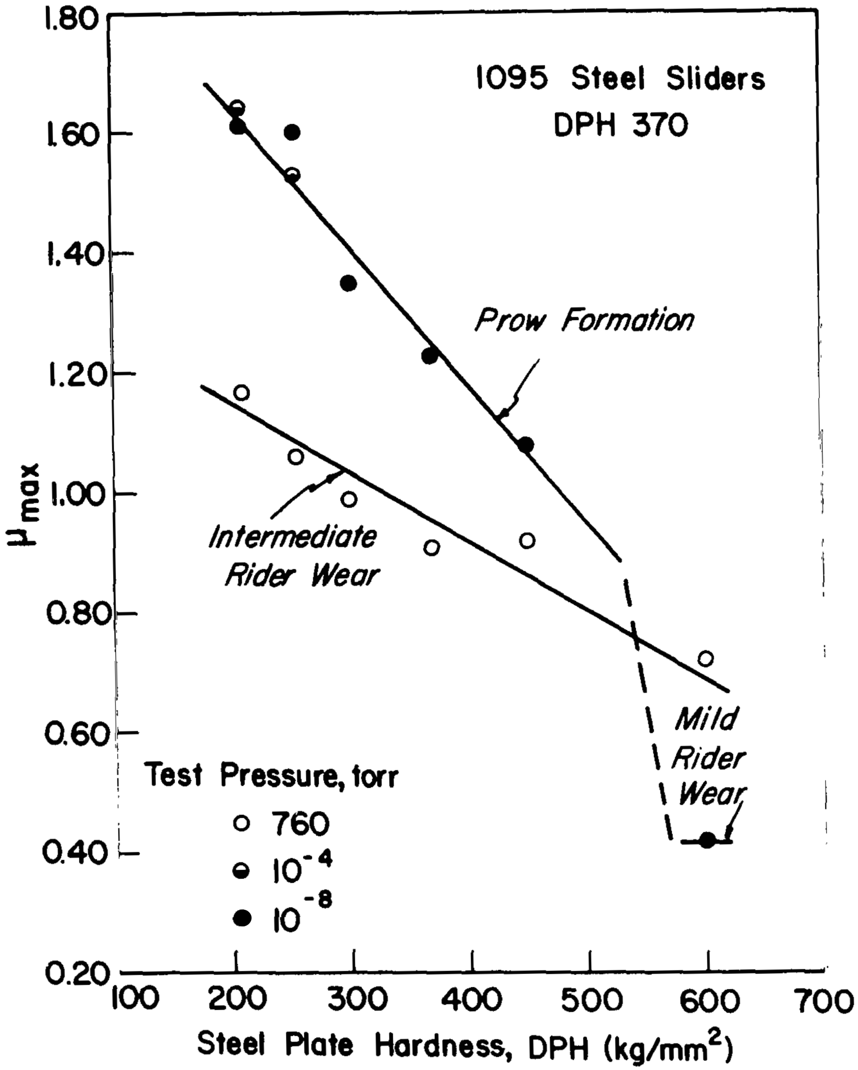


Figure 5–Maximum coefficient of friction versus plate hardness for moderate hardness (DPH 370) steel sliders on steel plates.

a–Slider tested at 760 torr, 25 revolutions (μ = 0.72).

b–Slider tested at 10^{-8} torr, 25 revolutions (μ = 0.42)..

Figure 6–Tests of 1095 steel sliders (DPH 370) on 4340 steel (DPH 600). Mild rider wear in both air and vacuum. (20X)

case, on the other hand, showed no effects deeper than 5 micrometers. Traverses for mild rider wear are not plotted, but consist of horizontal lines with exiguous hardening confined to within two micrometers of the surface.

The same form of friction versus plate hardness curve in air and vacuum was generated for a series of tests with the steel slider hardness increased from DPH 190 to 370 (Figure 5). The friction coefficient decreases in air and vacuum as plate hardness increases up to a critical plate hardness. For this slider hardness, the transitions from prow formation to mild rider wear in vacuum and from intermediate rider wear to mild rider wear in air were shifted from a plate hardness of DPH 370 to DPH 500 to 600. The sliders in Figure 6 show the typical appearance of mild rider wear on hard plates in air (6a) and in vacuum (6b). Wear surface characteristics are similar, but the extent of wear is less in vacuum. Buckley's results (Reference 2) for 52100 steel (DPH 515) sliding on itself in air and in vacuum showed this type of behavior: friction dropped from 0.5 to 0.4, and less wear was observed in vacuum, indicating the mechanism transitions had taken place for this hardness combination.

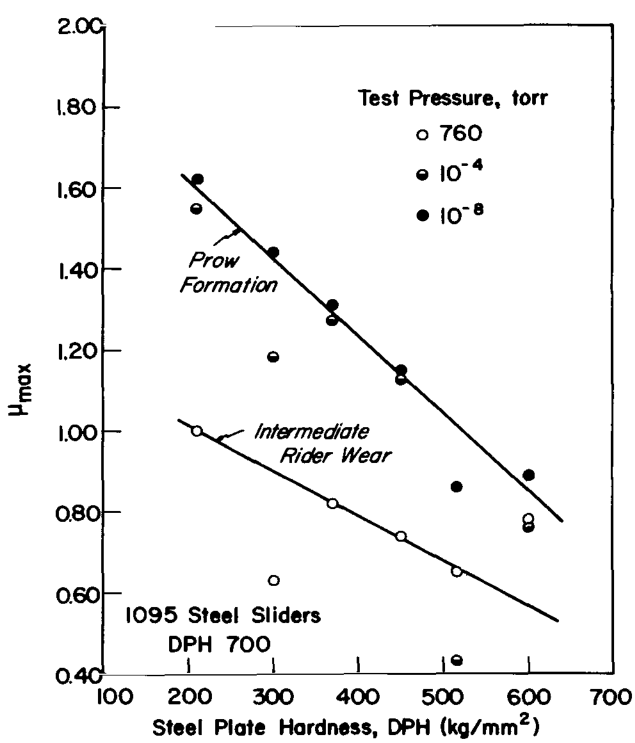
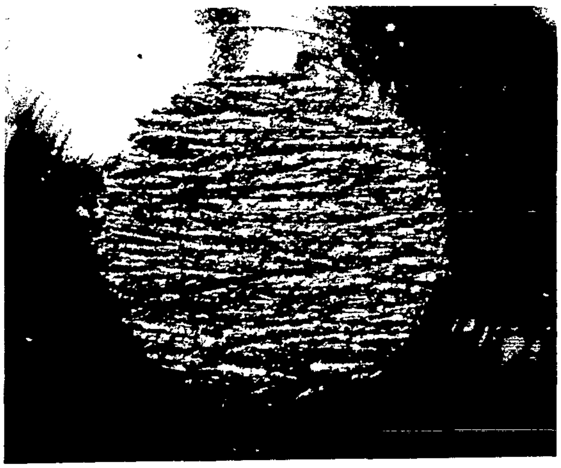


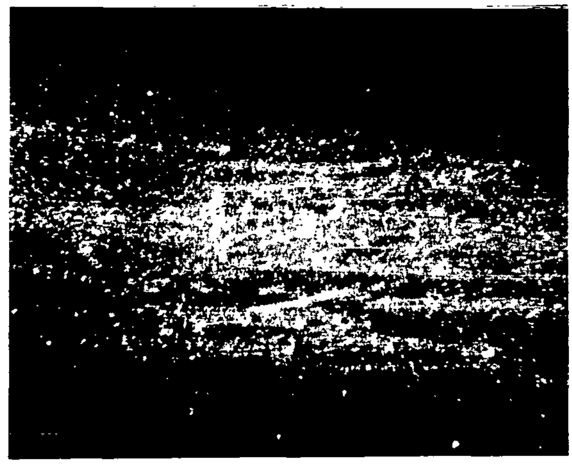
Figure 7–Maximum coefficient of friction versus plate hardness for hard (DPH 700) steel sliders on steel plates.

When the slider hardness was further increased to DPH 700, no wear mechanism transitions as a function of hardness were observed; the wear in all cases was by prow formation in vacuum and by intermediate rider wear in air. As expected, in both cases the friction decreased with increasing plate hardness (Figure 7).

The effect of normal load on the friction and wear transitions was measured by applying a 3-lb normal load to a 1020 steel slider (DPH 190) on a 4340 steel plate (DPH 450). For this higher load, the maximum friction coefficients were 0.97 in air and 1.04 in vacuum. The wear mechanisms were intermediate rider wear in air and prow formation in vacuum (Figure 8), whereas for the couple tested at the lower load both test environments resulted in mild rider wear. In effect, the wear mechanism transition was shifted to higher plate hardness levels by increasing the normal load. Mild rider wear did not occur because the increase in stress was sufficient to penetrate the surface contaminant layers of the plate and lead to



a–Slider tested at 760 torr, 25 revolutions (μ = 0.97). (20X). Intermediate Rider Wear.



b–Wear track for slider in 8a. (10X)

c–Slider tested at 10^{-8} torr, 25 revolutions (μ = 1.04). (20X). Prow Formation.

d–Wear track for slider in 8c. (10X)

Figure 8–Tests of 1020 steel sliders (DPH 190) on 4340 steel (DPH 390) with the normal load increased to three pounds.

sufficient plastic deformation to promote prow formation in vacuum and intermediate rider wear in air.

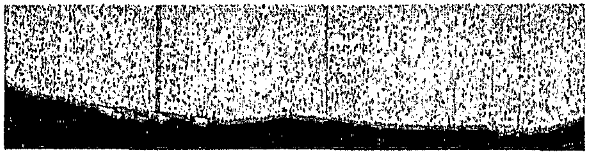
Wear mechanism transition phenomena can also occur in the course of a single test. The specimens discussed above exhibited a transition from intermediate slider wear to prow formation during the vacuum runs. The slider tested in air exhibited intermediate rider wear. Figure 9a shows a cross section of this slider with its typical flat wear profile. The metal removed from the slider accumulated in the form of loose wear debris on the plate, Figure 8b, and no metal transfer occurred. Plastic deformation resulting from the shearing of rider metal can be seen all along the wear surface, the leading edge of which is shown at higher magnification in Figure 9d. As the test pressure was reduced from 760 to 10^{-4} torr, the test started in the same manner: metal was sheared from the rider and formed loose debris on the plate. However, after several revolutions, the oxide layer was broken up, metal to metal contact occurred, and the prow formation mechanism was initiated. As the test pressure was further lowered to 10^{-8}, the same phenomena were observed, but earlier in the test. Figures 9a, b, and c show the continuous reduction in the extent of rider wear and the increase in prow size resulting from increasingly hard vacuum.

Metallographic examination and electron probe analysis describe the structure and chemical composition of the prow in Figures 9 and 10. A comparison of Figures 9d and e shows a similar depth of shear-strained rider metal at the leading edge of each rider resulting from the portion of the test governed by intermediate rider wear. This wear mechanism prevailed until the end of the test run in air, but Figure 9e shows vortices of slider metal mixing with and cold welding to plate metal to form a prow.

To identify the source of the prow metal, the metallographic sample was submitted to electron probe microanalysis. The area of the rider and prow analyzed is delineated by a series of hardness indentations, as indicated in Figure 10a. The 4340 plate steel contains nickel and chromium, but the 1020 slider does not. Figure 10b is a photograph of the backscattered electron image outlining the sample profile. Figure 10d shows the emission of nickel X-rays in the same area of the sample. The sample had been electroplated with nickel during the metallographic preparation to protect the edge, and this plated film shows up as a bright, white strip covering the prow. The nickel-free slider material appears dark, and the prow in between shows a low but distinct nickel content consistent with that of 4340 steel (about 1.7%). A similar indication is obtained with chromium X-rays (Figure 10c). Clearly the prow is composed primarily of plate metal cold welded to the slider during the test.

Vacuum, or more specifically the lack of oxygen, caused most steels which displayed intermediate rider wear mechanism in air to exhibit prow formation in vacuum. In air, iron oxide formed continuously to produce a barrier to atomically clean metal to metal contact; hence, the initiation of a prow. In vacuum, for sliders and plates of appropriate hardnesses, initial rider wear was of the intermediate type, but after several passes prow formation was initiated and the friction coefficient rose abruptly to a high level characteristic of this mechanism. The higher the rider-plate hardness

a–760 torr, 25 revolutions.



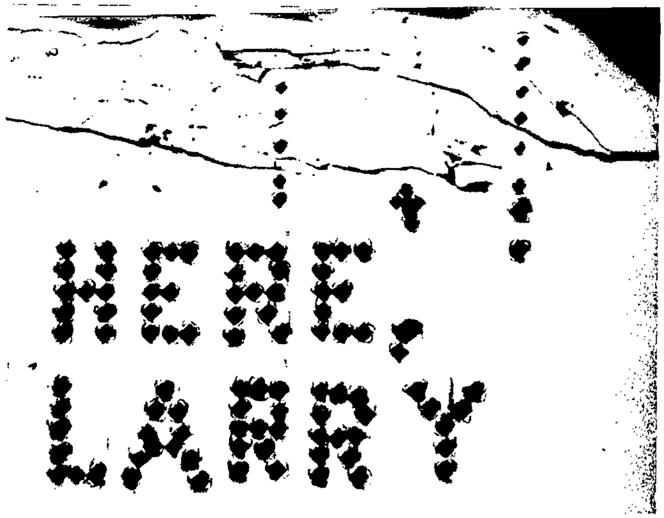
b– 10^{-4} torr, 25 revolutions.

c– 10^{-8} torr, 25 revolutions.

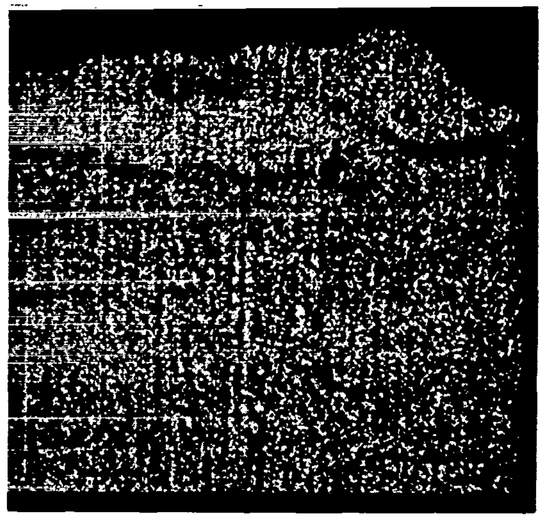
d–Leading edge of slider in a. (500X)

e–Leading edge of slider in c. (500X)

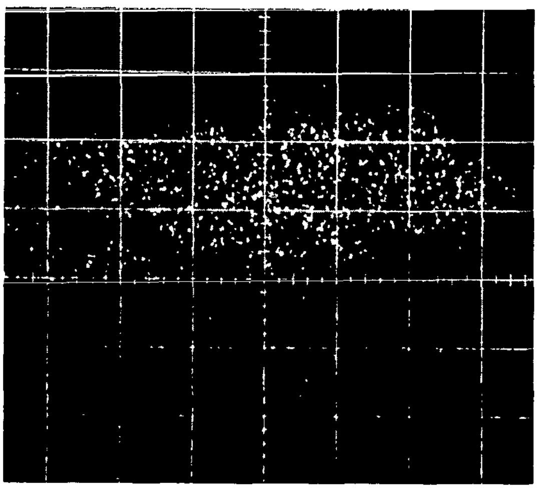
Figure 9–Cross sections of sliders shown in Figure 8.
Progressive reduction in rider wear area and initiation of prow formation at indicated pressures (100X):



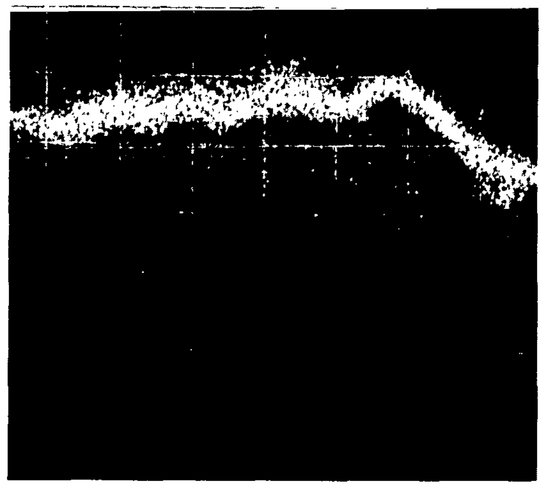
a–Optical photomicrograph indicating area to be analyzed.



b–Image produced by backscattered electrons.



c–Image produced by chromium X-rays emitted by the specimen.



d–Image produced by nickel X-rays emitted by the specimen. White band is a layer of nickel plating applied during metallographic preparation.

Figure 10–Electron probe analysis of 1020 steel slider tested at 10^{-8} torr illustrated in Figures 8c, 9c, and 9e. (250X)

ratio, the sooner the transition took place: almost immediately for very hard sliders. The remainder of the test then continued the prow formation process. For cases characterized in air by mild rider wear, this mechanism also occurred in vacuum, but to a lesser degree.

The transition from intermediate rider wear in air and prow formation in vacuum to mild rider wear for both environmental conditions is dependent on the relative hardness of the slider and plate (Figure 11). This is a plot of the ratio of the vacuum coefficient of friction to that in air versus the slider-to-plate hardness ratio. Values of the coefficient ratio greater than one indicate the first type of behavior, and fractional values, the latter. For all three slider hardnesses tested, the transition occurred at a slider-plate hardness ratio in the range of 0.5 to 0.8. This number, of course, applies only to the particular test geometry and normal load employed, but the nature of the transition would apply to low speed, room temperature tests of steels.

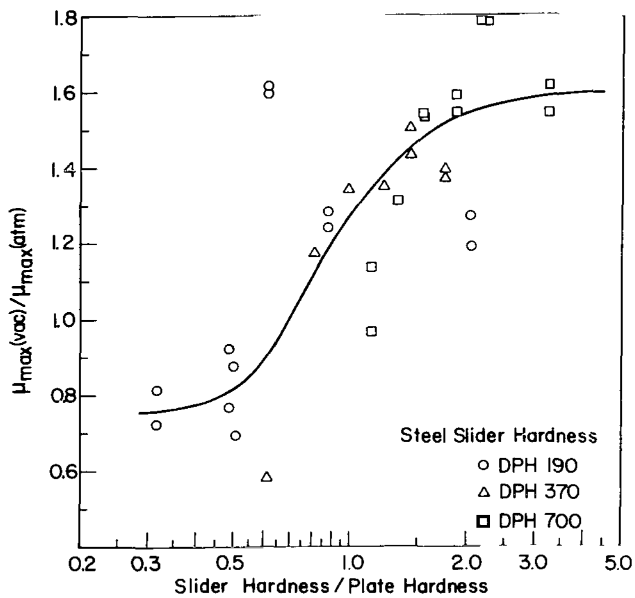


Figure 11—Friction and wear mechanism transitions as a function of slider-plate hardness ratio for steel sliders on steel plates. $\mu_{vac}/\mu_{air} > 1$ indicates the transition from intermediate rider wear in air to prow formation in vacuum. $\mu_{vac}/\mu_{air} < 1$ indicates mild rider wear for both environments.

Titanium, Aluminum, and Copper on Steel

Aluminum, alpha titanium, copper, and beryllium copper sliders were tested on the same series of steel plates. Figure 12 shows the maximum coefficient of friction in air and in vacuum obtained for aluminum and titanium on steel. The titanium sliders behaved like hard steel on steel: friction was higher in vacuum than in air and decreased in both cases with increasing plate hardness. In air, intermediate rider wear was observed, and in vacuum, prow formation. Figure 13 illustrates a typical example of each mechanism. Intermediate rider wear is shown in Figures 13a and 13b, with shear deformation evident on the rider and light wear scars with little subsurface deformation on the plate. The steel prow formed in vacuum (Figure 13c) caused the deep wear scars and deformation indicative of interfacial hardening evident on the plate (Figure 13d).

Aluminum sliding on the same series of plates exhibited a rider wear mechanism that was different from those shown by steel or titanium on steel; it is termed severe rider wear. Both in air and in vacuum, metal was removed from the rider and transferred and cold welded to the plate. The sliding interface thus was primarily in slider

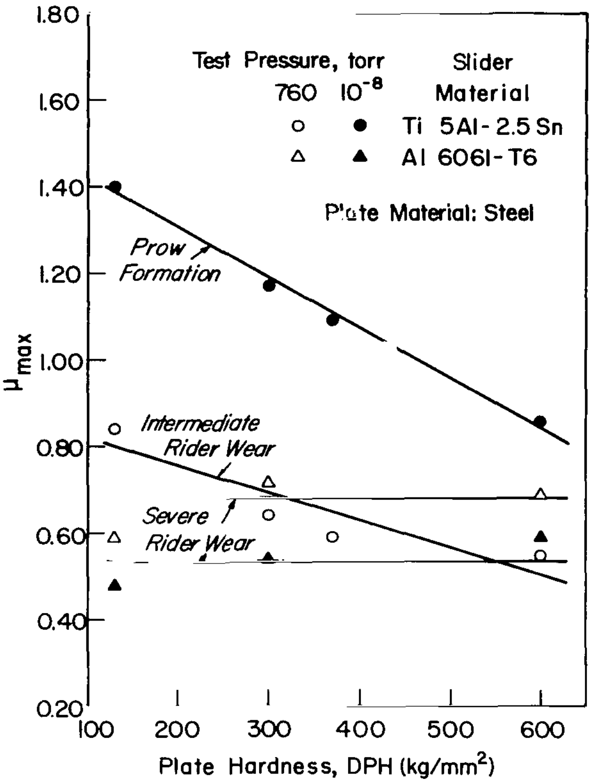


Figure 12–Maximum coefficient of friction versus plate hardness for titanium and aluminum sliders on steel plates in air and in vacuum.

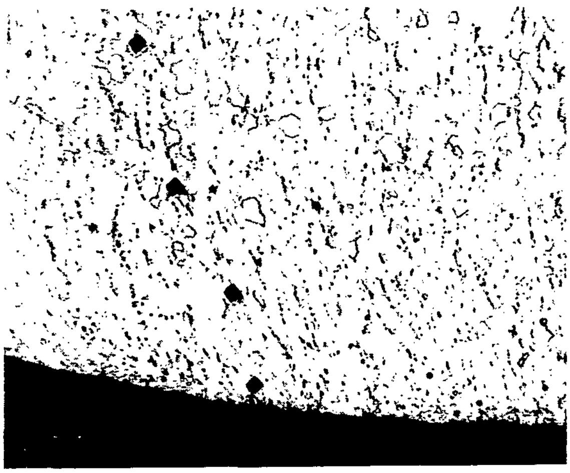
metal, and the friction remained constant for all plate hardnesses tested. The amount of wear was larger and the friction higher in air (0.7) than in vacuum (0.5). During the test, a pseudoprow was formed on the leading edge of the slider. This pseudoprow was composed mainly of back-transferred aluminum with a small amount of steel as shown by electron probe analysis. Examination of the pseudoprow sliding surface in cross section showed it to be in the wear surface plane of the rider, whereas a true prow extends out from the wear surface. (See Figure 9c).

The friction coefficients of copper (DPH 75) and beryllium copper (DPH 350) were measured on 1020 steel (DPH 130) and 4340 steel (DPH 450), respectively, in vacuum and in air. Friction remained constant or decreased in vacuum (Figure 14), and the wear was primarily by severe rider wear. Like the aluminum sliders on steel, the copper alloys showed less wear in vacuum than in air (Figure 15), but without a wear mechanism transition.

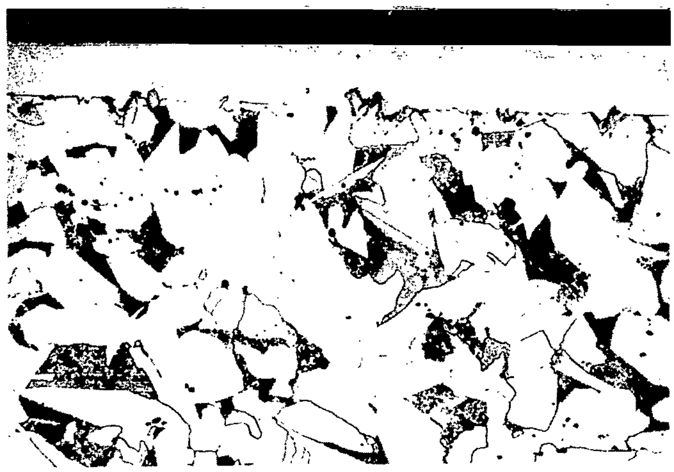
Wear Mechanisms and Transitions

Aluminum and copper alloys manifested the severe rider wear mechanism; the slider cold welded to the steel plate. The slider continued to move forward, causing plastic shearing and eventual fracture in the soft, weak slider material. The slider then moved forward to repeat the process. Milner and Rowe (Reference 8) showed that a compressed metal-oxide-metal sandwich would cold weld after it was plastically stretched. In the process the oxide is broken into particles while the surface area increases. The atomically clean metals then join together between the oxide particles to cold weld. In this investigation, the normal load and consequent friction force were sufficient to initiate this process for aluminum and copper sliders. Since the friction force depended on the fracture strength of the slider metal, it was essentially constant for all steel plate hardnesses.

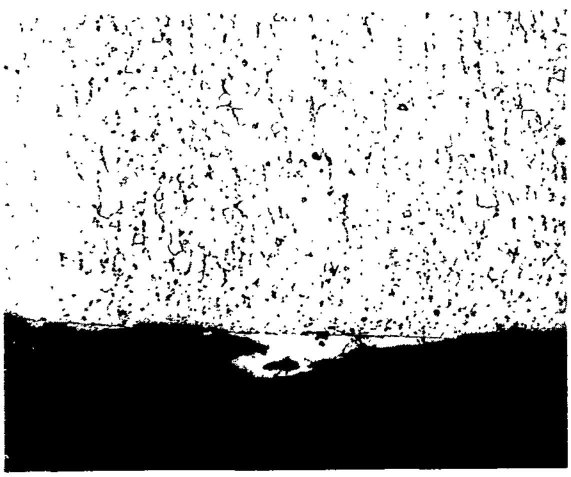
Relatively hard steel and titanium on steel exhibited intermediate rider wear in air. Upon sliding, the metal-oxide-metal sandwich at the slider-plate junction was plastically strained, but before the threshold of deformation for cold welding was achieved, fracture



a–Cross section of slider tested at 760 torr, 25 revolutions. Intermediate rider wear (μ 0.84). (250X)



b–Taper cross section of wear track generated by slider in a. (Mounting angle 13.5°, vertical magnification 750X and horizontal magnification 175X)



c–Cross section of slider tested at 10^{-8} torr, 25 revolutions (μ = 1.40). Prow is steel. (250X)

d–Cross section of wear track for slider in c. (Magnification as for b)

Figure 13–Alpha titanium sliders (DPH 320) tested on 1020 steel (DPH 130).

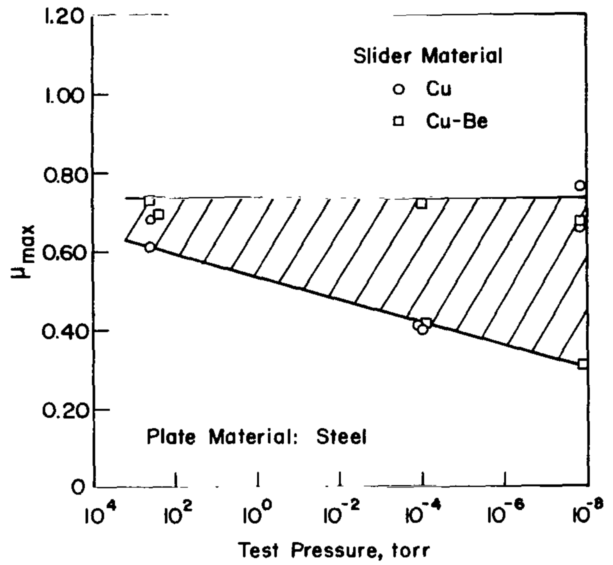


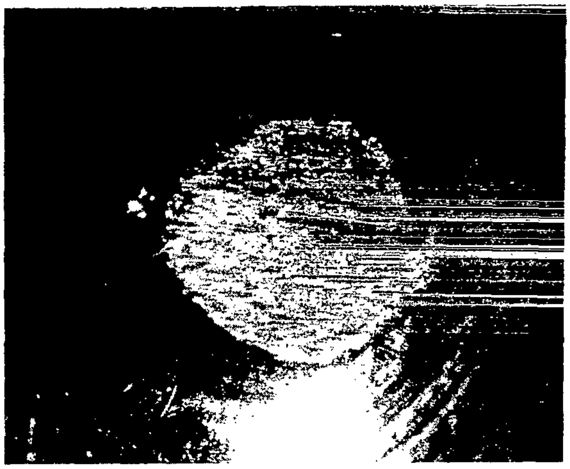
Figure 14—Maximum coefficient of friction versus test pressure for Cu and Cu-Be sliders on steel plates.

resulted in the slider or in the plate. The slider moved forward to repeat the process, leaving a loose wear particle. The active sliding interface was intermittent between the slider and the plate and the friction and/or junction fracture force depended upon the mechanical properties of both slider and plate. Oxygen in the air reacts with the atomically cleaned fracture surface to form iron oxide, thus precluding extensive cold welding necessary for prow formation.

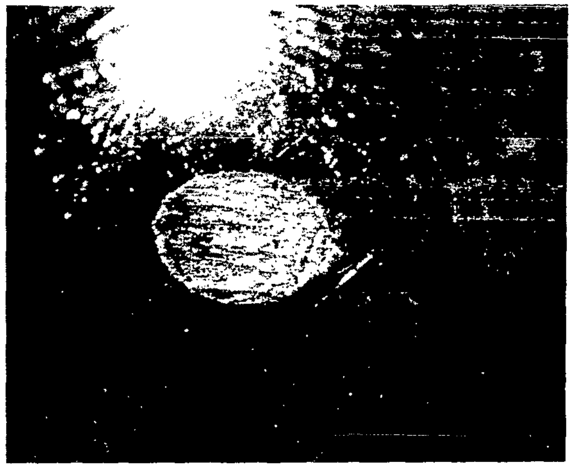
Mild rider wear results when the sliding interface is at the metal oxide layers between the slider and plate. Metal is worn from the rider by the abrasive action of the hard iron oxide, and a smooth or polished surface is produced on the slider. In vacuum, oxide reformation is inhibited, and consequently the extent of wear is less and the friction is lower. In both instances, plate damage is minimal.

Prow formation is a form of severe wear characterized by metal transfer to the slider tip. The prow is composed of plate metal or a mixture of plate metal and back-transferred slider metal (Figure 10). Friction is high and the depth of interfacial work hardening in the plate is extensive. As in severe rider wear, the interface area of the metal-oxide-metal sandwich increases from plastic straining, the oxide breaks into particles and permits metal to metal contact that results in cold welding, but in this case the fracture occurs in the plate rather than the rider. Prow initiation was almost instantaneous when the slider material was substantially harder than the plate. Continuous cold welding of work-hardened plate metal to the slider tip causes the prow to grow with continued sliding. The active sliding interface is thus in the plate metal under the surface.

Wear mechanism transitions have been observed to be a function of metal and oxide properties, normal load, and test environment. For materials that evidence intermediate rider wear in air, a vacuum environment leads to a transition to prow formation. Steel couples that exhibit mild rider wear in air will continue to do so in vacuum. Increasing the normal load can change the latter type of behavior to the former, as can increasing the slider-plate hardness ratio. In all of these cases, the oxide film on the specimen surface plays a key part in determining the wear mechanism.



a–Slider tested at 760 torr, 25 revolutions (μ = 0.67). (25X)



b–Slider tested at 10^{-8} torr, 25 revolutions (μ = 0.51). (25X)

c–Wear plate. Track 1 is wider and has more slider metal deposited on it than do tracks 2 and 3. Tested at 25 revolutions and 760 torr (track 1), 10^{-4} torr (track 2), and 10^{-8} torr (track 3).

Figure 15–Cu-Be sliders (DPH 350) tested on 1020 steel plate (DPH 350) with a normal load of three pounds. Severe rider wear.

The role of the oxide layer in wear mechanism transitions has also been investigated by others with similar results. Powell and Earles (Reference 9), Peterson et al. (Reference 10), and Moeller (Reference 1) showed that high air temperatures produced on the sliding surface a thick iron oxide film that behaved as a metal oxide dry film lubricant. This iron oxide film caused a drop in friction and a wear mechanism transition from intermediate rider wear at low temperature to mild rider wear at high temperature, with no evidence of prow formation. In the present tests, the oxidation of the steel wear surfaces was decreased rather than increased during the tests in vacuum. Friction and wear increased, and the wear mechanism transition was from intermediate rider wear in air to prow formation in vacuum. In air the atomically clean fracture surfaces are continuously oxidized, preventing cold welding, but in vacuum the clean metal surfaces are not readily oxidized, plate metal is cold welded to the slider, and prow formation results.

For steel sliding on steel, load-dependent transitions from intermediate rider wear to mild rider wear in air and from prow formation to mild rider wear in vacuum resulted when the slider-plate hardness ratio dropped below 0.5. Below this ratio, the 1-lb load was insufficient to cause the plastic deformation of the plate metal required to induce the more severe wear mechanisms. Increasing the normal load to 3 lb shifted the critical hardness ratio to a lower value and the wear mechanisms reverted to intermediate rider wear in air and prow formation in vacuum.

CONCLUSIONS

Variations in the Metals Tested

Titanium and relatively hard steel on steel exhibited intermediate rider wear in air, with friction decreasing as plate hardness increased. In vacuum, these metals exhibited prow formation. Friction was higher than for intermediate rider wear but again decreased as plate hardness decreased.

Soft steel on hard steel plates, on the other hand, showed mild rider wear in both air and vacuum, when the rider-plate hardness ratio was less than 0.5 to 0.8. Friction and wear were less in vacuum than in air. For both environmental conditions, friction remained constant with increasing plate hardness.

Aluminum and copper alloys on steel displayed severe rider wear for all conditions tested and friction was independent of plate hardness. Friction and the extent of wear were less in vacuum than in air.

Description of Rider Wear

Mild rider wear results when the sliding interface occurs at the natural oxide layers between the slider and the plate. Straight, shallow wear scars form on the plate. The slider and plate wear surfaces are smooth and very little damage or interfacial hardening is observed. Friction and extent of rider wear are lower in vacuum than in air.

Intermediate rider wear occurs when the sliding interface is intermittent between plate and slider metal. Little metal is transferred in either direction and loose debris accumulates on the plate. The friction force depends on the hardness of plate and slider. The result is shallow interfacial strain-hardening in the plate and somewhat deeper hardening in the rider.

Severe rider wear is characterized by location of the plane of sliding in the slider. Force of friction depends on the fracture strength of the slider, not on plate hardness. Interfacial strain hardening is moderate in the slider and light in the plate. Occasionally, slider metal is transferred to the plate and back to the slider in the form of a pseudo-prow.

Prow formation results when the sliding interface is in the plate. Plate metal is cold welded to the slider tip and forms a severely work-hardened prow which separates the slider from the plate. Rough wear scars and deep interfacial hardening are observed in the plate. In many cases, prow initiation is preceded by intermediate rider wear until the metal oxide layers are rubbed off, allowing metal to metal contact.

Transitions from one mechanism to another depend on vacuum, rider-plate hardness ratio, normal lead, and metal-metal oxide characteristics.

ACKNOWLEDGMENTS

The authors acknowledge the excellent support offered by the following: Dr. Henry E. Frankel, John C. Smith, William B. Latham, Lawrence Kobren, and James R. Jarrett.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, April 3, 1970
604-31-75-01-51

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