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NASA Technical Memorandum 81396

MECHANISMS OF LUBRICATION
AND WEAR OF A BONDED
SOLID LUBRICANT FILM

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ABSTRACT

To obtain a better understanding of how bonded solid lubricant films lubricate and wear (in general), the tribological properties of polyimide-bonded graphite fluoride films were studied (in specific. A pin-on-disk type of testing apparatus was used; but in addition to sliding a hemispherically tipped rider, a rider with a 0.95-mm-diameter flat area was slid against the film. This was done so that a lower, less variable contact stress could be achieved. Two stages (regimes) of lubrication were found to occur. In the first, the film supported the load and the lubricating mechanism consisted of the shear of a thin surface layer (of the film) between the rider and the bulk of the film. The second occurred after the bonded film had worn to the substrate, and consisted of the shear of very thin lubricant films between the rider and flat plateaus generated on the metallic substrate asperities. The film wear mechanism was found to be strongly dependent on contact stress.

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INTRODUCTION

The friction, film wear life, and rider wear for AISI 440C HT stainless-steel riders sliding on polyimide-bonded graphite fluoride films have been previously studied with a pin-on-disk friction apparatus (refs. 1 and 2). Long wear lives (approximately 3000 kilocycles of sliding) and low friction coefficients (0.12 to 0.20) were obtained at 25° C in a moist air atmosphere (50% relative humidity). Rider wear rates were also found to be very low (3.5 to 4.7×10^{-17} m^3/m) (ref. 3).

In a Falex testing apparatus, similarly formulated films failed after 15.8 minutes (4.6 kilocycles of sliding) (ref. 4). Loads up to 227 kilograms (500 lb) were used in their study. The authors of reference 4 have attributed this short wear life to the films apparently poor loading carrying capacity, and they concluded these films were not suitable for the high concentrated load applications. This may be true, but there are also many applications for lighter loads. One example is in foil bearings where loads of 2.6×10^2 kPa (37 psi) are typical (ref. 5).

It is puzzling why much longer wear lives were obtained with the pin-on-disk tester than with the Falex tester. Is this due simply to load capacity or do other factors enter into it? In general, the mechanisms by which bonded solid-lubricant films lubricate, wear, and fail are not well understood. Therefore, this investigation was conducted to obtain a more fundamental understanding of the mechanisms by which bonded solid lubricant films lubricate and wear, and of the phenomena controlling the wear life.

The scope of the investigation included studying the effect of film thickness and contact stress on the tribological properties of polyimide-bonded graphite fluoride films applied to sandblasted 440C HT stainless-steel disks. The procedure used was to stop the tests at preset sliding intervals and then to examine what had occurred on the sliding surfaces by optical microscopy at magnifications to 2000×. Four film thicknesses were studied: 10, 18, 45, and 62 micrometers.

A pin-on-disk type of testing apparatus was used; but in addition to sliding a hemispherically tipped rider (as is normally done), a rider with a 0.95-mm-diameter flat on it was also used. Since the hemispherically tipped rider imparted very high initial stresses in the film (exceeding 1.7×10^5 kPa (25 000 psi)), the flat was used to determine if a lower, less variable contact stress would alter the lubricating and wear mechanisms. The flat imparted a projected contact stress of 1.4×10^4 kPa (2000 psi).

Wear life, friction coefficient, film wear, rider transfer, and rider wear were studied and compared for the hemisphere and the flat sliding against a 45-μm thick film in a moist air atmosphere (approxomately 50% R.H. at 25° C) at a sliding speed of 2.6 m/s (1000 rpm) under a 1-kilogram load.

MATERIALS

Pyralin polyimide (PI-4701) was used in this study. The polyimide was obtained as a thick precursor solution containing 43% solids. For a sprayable mixture, a thinner consisting of N-methyl-pyrrolidone and xylene was added to it. The polyimide-bonded graphite fluoride films were prepared by mixing equal parts by weight of polyimide solids with graphite fluoride powder. The graphite fluoride used had a fluorine-to-carbon ratio of 1.1. The films were applied to AISI 440C HT steel disks (1.2 cm thick by 6.3 cm in diam) that had a hardness of Rockwell C-58. The riders used in the friction and wear tests were also made from the AISI 440C HT steel with a hardness of Rockwell C-58.

FRICTION APPARATUS

A conventional type of pin-on-disk friction and wear apparatus was used in this study (fig. 1). The riders were either hemispherically tipped pins with a radius of 0.476 cm or the same hemispherically tipped pins with at 0.95 mm-diameter flat worn on the hemisphere (see insert fig. 1). They were loaded with a 1-kilogram deadweight against the film which was applied to a flat, 6.3-cm-diameter disk. The disk was rotated at 1000 rpm, and the rider slid on the disk

at a radius of 2.5 cm which gave it a linear sliding speed of 2.6 m/sec. The friction specimens were enclosed in a chamber so that atmosphere could be controlled. To obtain a controlled air atmosphere of 10 000 ppm H_2O (approximately 50% relative humidity), dry air and dry air bubbled through water were mixed. Humidity was monitored continuously.

PROCEDURE

Generation of Rider Flat

The flat on the 0.476 cm-radius hemispherically tipped rider (pin) was generated prior to conducting the friction and wear experiments by sliding it against a rubbed graphite fluoride film which was applied to a sandblasted AISI 440C HT stainless steel sandblasted disk. The rider was not removed from the holder after the flat was generated or while it was cleaned; and it and the disk (with applied polyimide-bonded graphite fluoride film) were positioned and indexed in the apparatus by using a linear variable differential transformer (LVDT) so that a flat-on-flat configuration occurred with minimal misalignment being introduced (fig. 1).

Surface Preoparation and Cleaning

The disk surfaces were roughened by sandblasting to a centerline avera (cla) roughness of 0.9 to 1.2 micrometers. After surface roughening, the disks were scrubbed with a brush under running tap water. The disks were rinsed in distilled water and then clean, dry compressed air was used to quickly dry the surfaces. The disks were stored in a dessicator until they were ready for coating with the solid lubricant.

The rider was lightly scrubbed with ethyl alcohol and with levigated alumina to remove the graphite fluoride transfer film that originated during the generation of the flat wear area. It was next rinsed in distilled water and dried with compressed air. Lubricant was not applied to the riders.

Film Application

An artist's airbrush was used to apply the polyimide-bonded graphite fluoride films to the disks. Because the film did not dry rapidly, only a thin layer was applied at one time in order to prevent "running." Each thin layer was cured completely before the next layer was applied. The cure consisted of heating the films at 100° C for 1 hour followed by 300° C for 2 hours.

The film thicknesses evaluated in this study were up to 62 micrometers (0.0024 in.). Since each layer applied was from 8 to 13 micrometers thick, up to five applications were needed to achieve the desired thicknesses.

Friction and Wear Tests

The procedure for conducting the friction and wear tests was as follows: The test specimens were inserted into the friction apparatus and the test chamber sealed. A controlled moist air test atmosphere (10 000 ppm H_2O) was purged through the chamber for 15 minutes before each test and continuously throughout the test. After purging, the disk was set into rotation at 1000 rpm and a 1-kg load gradually applied. The test temperature was 25° C.

Each test was stopped after $\frac{1}{4}$ kilocycle ($\frac{1}{4}$ min) of sliding. After the rider and disk were removed from the friction apparatus the contact areas were examined by optical microscopy and photographed. Surface profiles of the disk wear tracks were also taken. The rider and disk were then placed back into the apparatus, and the test procedure was repeated. The rider was not removed from the holder, and locating pins in the apparatus ensured that it was returned to its original position. The same was true for the disk.

Each test was stopped and the test procedure repeated after sliding times of $\frac{1}{4}$, 1, 15, 60, 250, 500, 1500, 2500, 3500, 4500, 6000, and 8500 minutes. Film wear was calculated by measuring the cross-sectional area of the polyimide bonded graphite fluoride film wear track (from the surface profiles) after each sliding interval. Rider wear was determined by measuring the

change in the diameter of the wear scar on the hemispherically tipped rider and then calculating the volume of material worn away.

Analysis of Sliding Surfaces

Optical microscopy techniques were used to study the lubricating films, the transfer films, and the wear particles in this investigation. The surfaces were viewed at magnifications to 2000×. At these high magnifications, the depth of field was very small (approximately 1 μm); thus the focusing distance was used in measuring various features on the sliding surfaces such as film thickness, and wear track depth.

The thin films (1 μm or less) of polyimide-bonded graphite fluoride were transparent. Since illumination and observation of the surfaces were normal to the surfaces, interference fringes could be seen in the films both on the disk wear track and on the rider. Intereference fringes indicated that solid lubricant films were present and that the films were smooth and continuous.

Since the surface of the bonded film was very rough, the rider flat initially only made contact on the highest film asperities. These areas became bright and shiny. Thus a quantitative metallurgical system (QMS), which i· ·n image analysis technique, was used to determine the percentage of the wear ·rack which had the shiny appearance. By assuming that full contact was occurring on the shiny areas, the contact stress on the film asperities was estimated.

RESULTS AND DISCUSSION

Friction and Wear Life

Friction traces for hemispherically tipped 440C HT stainless-steel riders (0.476 cm radius) sliding on polyimide-bonded graphite fluoride films of four thicknesses (10, 18, 45, and 62 μm) are shown in figure 2. The friction traces are discontinuous because the tests were stopped at various intervals to make wear measurements and to observe the sliding surfaces with an optical microscope. The experiments were terminated when the friction coefficient reach··

0.30, and wear life was defined as the number of sliding revolutions to reach this friction coefficient. For all four film thicknesses evaluated, the friction coefficient started out at 0.08 to 0.09 and then rose gradially with sliding duration. Eventually the friction coefficient leveled off at a steady-state value of 0.20±0.02. On restart, after the tests had been stopped to measure wear, the friction coefficient was usually lower than it had been at the end of the previous interval. A continuous increase in friction coefficient (from the steady-state value) signified that the films were approaching failure (fig. 2).

Figure 2 shows that as film thickness increased, so did wear life. The 10-micrometer-thick film gave a wear life of 980 kilocycles, the 18-micrometer-thick film gave a wear life of 1845 kilocycles, the 45-micrometer-thick film gave a wear life of 4400 kilocycles, and the 62-micrometer-thick film gave a wear life of 6300 kilocycles. Wear life is shown to be directly proportional to film thickness in figure 3. This result agreed with results of previous experiments conducted on polyimide-bonded molybdenum disulfide films (ref. 6). The wear life of the polyimide-bonded graphite fluoride film was found to be about 100 kilocycles per micrometer of film thickness.

A friction trace for a 0.95-mm-diameter flat sliding against the 45 μm-thick polyimide-bonded graphite fluoride film is shown in figure 4. As found for the hemispherically tipped rider sliding on the same film (fig. 2), the friction coefficient started at a low value of 0.08 to 0.09, then rose gradually with sliding distance, and eventually leveled off at 0.24±0.02. This was slightly higher than the friction coefficient found for the hemisphere on film experiments (0.20±0.02). For the 0.95-mm-diameter flat sliding on the 45 μm-thick film, failure did not occur after 8500 kilocycles of sliding (which was arbitrarily chosen as the time duration of this test).

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Film Wear

Film wear was studied by taking surface profiles of the film wear track after each sliding interval. Figure 5 compares surface profiles of the wear traces on 45 μm-thick polyimide-bonded graphite fluoride films for (a) a hemisphere and for (b) a 0.95-mm-diameter flat after various intervals of sliding. Superimposed on each trace in figure 5 is a surface profile of the 440C HT stainless-steel substrate to show the topography and the location of the coating-substrate interface.

Because the vertical magnification of the surface profiles is about 50 times the horizontal magnification, the view of the surface is distorted. The surface profiles show that after 1 kilocycle of sliding very little wear had occurred on the film surfaces. But after only 5 kilocycles of sliding, the hemisphere had worn through the film and contact with the sandblasted metallic substrate had occurred. A similar result occurred with the three other film thicknesses. Thus, regardless of film thickness, the hemisphere had worn through the film to the metal after 5 kilocycles of sliding. From this point onward, wear was characterized by the gradual increase in wear track width.

The surface profiles of figure 5(b) indicate that the wear process for the flat sliding on the film was one of gradual wear through the film. It took approximately 3500 kilocycles of sliding for the rider to wear through the 45 μm-thick film and make contact with the metallic substrate. Once the metallic substrate was reached, the wear track gradually increased in width as was found for the hemisphere.

To quantify the wear process for the flat sliding on the film under a 1-kilogram load, film wear (for the first 3500 kilocycles of sliding) was calculated by measuring the cross-sectional area of the film wear tracks (from the surface profiles) after each sliding interval. At least four traces were taken at each interval. Figure 6 plots the average and the range of these values as a function of the number of sliding revolutions (expressed in kilocycles). The general

trend was that the film wear increased linearly (from zero) as a function of sliding revolutions. A linear regression fit (least squares) of the points gave an average film wear rate of $1.7\pm0.3\times10^{-7}$ cm^2/kc, or in terms of wear volume per unit sliding distance the wear rate was $1.7\pm0.3\times10^{-10}$ cm^3/cm. The wear rate for the hemisphere sliding on the film was $1.2\pm0.4\times10^{-7}$ cm^3/cm. Thus, wear was reduced about 700 times at the lower contact stress with a flat rider.

Film Wear Mechanisms

Wear of the film was also studied using an optical microscope to magnifications of 2000×. In general, for the hemisphere sliding on the film, the lubricating mechanisms and the appearances of the sliding surfaces were the same regardless of film thickness. Thus to avoid being repetitions, most of the photomicrographs shown are for the 45-μm-thick film. Figure 7 gives high magnification photomicrographs of the wear track on the 45 μm-thick polyimide-bonded graphite fluoride film after sliding intervals of $\frac{1}{4}$, 1, and 5 kilocycles.

The surface profiles of figure 5(a) show that on initial contact of the hemisphere on the film very little wear of the film occurred. However, figure 7 shows that the contact stress and the stresses induced by sliding caused cracking of the film to occur. At first, the cracks were very small (fig. 7(a)); but as sliding progressed, they propagated and enlarged (fig. 7(b)) and eventually led to crumbling and the complete breakup of the film on the wear track.

Once the original film was worn away, however, asperities on the 440C HT stainless-steel substrate interacted with the rider and helped support the load (fig. 7(d)). The polyimide-bonded graphite fluoride material tended to compact and sinter into a very smooth, continuous film in the regions between the asperities, and flat plateaus were worn on the tips of the metallic asperities (fig. 7(c)).

For the flat sliding on the film, the wear process was much different. Since the stresses were lower, no gross cracking or crumbling of the film was observed. Instead, the tips of the film asperities were able to support the load.

Figure 8 gives photomicrographs of the same area on the film wear track (for the flat sliding on the film) after sliding intervals of 1 and 60 kilocycles. The bright areas seen in the photomicrographs are flat plateaus worn on the film asperities. With repeated passes over the wear track, the ratio of bright areas to dark areas increased, indicating the gradual wear and truncation of the asperities. It took approximately 500 kilocycles of sliding to wear the film asperities down to the bulk film.

In order to quantify the contact stresses involved, the wear track was observed using an image analysis system. Table I shows how the estimated area of contact increased (in percent) as a function of sliding duration and the corresponding calculated values of stress. Figure 9 gives the estimated contact stress on the film asperities as a function of sliding duration. The stress was calculated by assuming that all bright areas were contacting the rider at any particular interval. However, this may not have been the case, and these values of contact stress may be low. Nevertheless, the data give an estimate of the contact stresses involved.

Assuming full contact on the film asperity tips, the rider contact after 1 kilocycle of sliding was estimated to be approximately 20%. Thus, the contact stress supported gy the film asperities was at least 69 000 kPa (10 000 psi). Because of film asperity wear, the contact stress decreased very rapidly during the first 15 kilocycles of sliding (fig. 9) to a value of 42 000 kPa (6100 psi). After 15 kilocycles of sliding, the rate of decrease slowed and it took approximately 500 kilocycles of sliding to reach a ''steady'' value of approximately 17 000 kPa (2500 psi). This represents a contact area of ap-

proximately 80 percent of full contact. Due to the mechanisms by which the film wore, full contact was never achieved. The wear mechanisms will be discussed next.

The wear progression of an individual film asperity is shown in figure 10 after intervals of 1, 5, and 60 kilocycles of sliding. The high-magnification photomicrographs show the truncation of a film asperity and its merging together with other asperities as wear occurred. The plateau on the film asperity was very smooth and reflective; however, there were some very fine cracks present and areas where a film fragment has spalled from the plateau. High magnification optical observation of the film wear track suggested that spalling of very thin layers on the plateaus was the primary wear mechanism while sliding was on the film asperities.

After 500 kilocycles of sliding, the film asperities were worn away. As figure 5 shows, the rider continued to wear gradually through the film until the metallic asperities on the substrate were reached at approximately 3500 kilocycles of sliding. The film wear mechanism (after the film asperities had been worn away), was very similar to the mechanism when sliding was only on the film asperity plateaus. Figure 11 shows an area of the film wear track after 1500 kilocycles of sliding. In general, the track was smooth and lustrous, but there were blistered areas and areas where a very thin layer of the film had spalled from the surface (fig. 11) and exposed unrubbed polyimide-bonded graphite fluoride. The area exposed after the film fragment had spalled (fig. 11) was not lustrous and appeared rough. The thickness of layers that spalled varied somewhat; usually they were less than 1 to 2 μm thick but occasionally they were as thick as 6 μm.

One mechanism by which spalling occurred, appeared to be due to texturing of the wear track. Texturing means that the individual constituents (polyimide and graphite fluoride) plastically flowed and coalesced on the wear track

into a very thin smooth layer at the surface of the film. After repeated passes were made over this layer, it tended to disengage from the bulk film by blistering and spalling. Another wear mechanism (not shown in the figures) appeared to originate in the bulk of the film, since the textured layers were up to 1 to 2 μm thick and some spalled areas were as much as 6 μm thick. These spalled areas were most likely caused by crack propagation due to defects in the bulk, while the thinner spalled layers were caused by scaling of the textured layer.

LUBRICATION MECHANISMS

Two stages (or regimes) or lubrication were found to occur for the polyimide-bonded graphite fluoride films. The first stage occurred during the gradual wear through the film. The lubricating mechanism during this stage appeared to be the shear (plastic flow) of a thin surface layer of the film between the rider and the bulk of the film.

The second stage occurred after the film had been worn through to the metal surface. The rider interacted with the asperities on the sandblasted metallic substrate and caused flats to be worn on the tips of those asperities (fig. 7(c)). The lubricating mechanism then became the shear of very thin lubricant films (<0.8 μm) between the rider flat and flat plateaus on the metallic asperities. The polyimide-bonded graphite fluoride could be discerned on the plateaus by color changes and interference fringes.

Figure 12 gives high magnification photomicrographs of the same area of the film wear track (for the hemisphere sliding on the 45 μm thick film) after sliding intervals of 120, 500, 1800, and 2800 kilocycles. The bright areas of figure 12 are flat metallic plateaus. The figure illustrates that the interaction of the rider with the sandblasted asperities was a gradual process. As sliding duration increased, the number of and the area of the individual asperity plateaus increased. Figure 12 also shows a number of voids (or depleted areas) in

the wear track. The dynamic nature of the lubrication process is evidenced by observing the movement of voids with sliding duration. Figure 13 gives an idealized schematic drawing of the sliding surfaces, illustrating this lubricating mechanism. The lubricant was supplied to the plateaus from the valleys between the asperities, and thin films of the lubricant essentially flowed across the plateaus and were deposited in a following valley.

A similar phenomenon occurred on the rider. The lubricant was supplied to the contact area from the buildup of worn polyimide-bonded graphite fluoride particles in the entrance region. The polyimide-bonded graphite fluoride was compacted and compressed (by the converging hemisphere-on-flat geometry) as it moved toward the contact zone and eventually coalesced into a very thin film that flowed across the flat rider scar and was eventually deposited in the exit region.

<center>Rider Transfer and Wear</center>

For the hemisphere sliding on the film very little interaction of the rider and the metallic asperities of the disk substrate occurred during the first 15 kilocycles of sliding. Thus, no m asurable wear was found, and only a thin transfer film of polyimide-bonded graphite fluoride was present on the rider. After 1/4 kilocycle of sliding, the tranfer film looked milky colored, suggesting that it was thinner than the wavelength of light (0.4 μm). On continued sliding, the transfer got thicker, and after 1 kilocycle of sliding, broad, multicolored interference bands covered the surface. Because the predominant colors of the bands were red, orange, yellow, and green, the thicknesses were from 0.8 to 0.5 μm.

After 15 kilocycles of sliding, the hemisphere had worn through the film and made contact with the sandblasted metallic asperities of the substrate, and wear of the rider occurred. Wear was determined by measuring the diameter of the wear scar on the rider and calculating the volume of material removed.

Table II gives rider wear rates for each interval in terms of wear volume per unit distance of sliding. In general, the thicker the film, the lower the rider wear rates that were obtained. This most likely was caused by the sides of the wear track partially supporting the load and thus lessening the load on the metallic asperities.

A transient high wear rate occurred for the 10 μm thick film between 5 and 15 kilocycles of sliding and for the 18 μm thick film between 60 and 120 kilocycles of sliding. This was believed to be caused by a large number of sharp, virgin metallic asperities contacting the rider and attenuating the wear. With the 18 μm thick film the sides of the film wear track helped support the load, and the transient high rider wear was not as severe and occurred later. The 45 and 62 μm thick films did not show this transient high wear since the asperities gradually made contact with the rider, due to the large thicknesses of the films and increased contact area.

When metallic asperity contact occurred with the rider, the transfer film to the rider became much thinner and less continuous than when sliding was completely on the film. This is seen in figure 14 which shows high magnifi-- cation photomicrographs of the (a) rider inlet area and the (b) rider exit area after 2800 kilocycles of sliding for the hemispherically-typed rider sliding on the 45 μm thick film.

The polyimide-bonded graphite fluoride tended to build up in the entrance region and was sheared thinner as it entered the contact zone. Interference fringes were observed in the entrance region and suggested that the polyimide-bonded graphite fluoride wear debris had coalesced into a very smooth, continuous film in the inlet area.

As the polyimide-bonded graphite fluoride material moved into the contact zone on the rider (flat area), it was sheared thinner and thinner until it was too thin or not continuous enough for interference fringes to be seen. The lubricant

flowed through the contact zone, and as figure 14(b) illustrates, tended to coalesce into a thicker film in the exit area.

A photomicrograph of the 0.95 mm-diameter flat on the rider before sliding is shown in figure 15. Also shown in figure 15 is the same rider flat after sliding intervals of 1/4, 250, and 8500 kilocycles. Figure 15(b) shows that initially very thin transfer occurred on the rider flat. Figure 16(a) gives a high magnification photomicrograph of that transfer. Broad, colorful interference bands are visible. On continued sliding, the amount of transfer to the rider gradually increased (figs. 15(b) and (c) and 16(a) to (c)). Comparing the friction trace of figure 4 with the amount of transfer, suggests the friction was lowest when the transfer was thinnest.

Transfer may not have been the only reason for the increase in friction coefficient between 0 to 250 kilocycles of sliding. Figure 9 and Table I indicate that the contact area was increasing and the contact pressure was decreasing during the sliding interval of 0 to 250 kilocycles. This may have also affected the friction coefficient and the resultant amount of transfer.

After approximately 3500 kilocycles of sliding, the bonded film was worn down to the metallic asperities. When this occurred the transfer film began to thin from the scouring action of the metallic asperities. Since the metallic asperity tips were gradually exposed to the rider, the transfer film thinned very slowly. For the same reason, the rider did not show any measurable wear until after 4500 kilocycles of sliding.

Figure 15(d) shows the wear scar after 8500 kilocycles of sliding. The transfer and the wear results were found to be identical to those experiments in which the hemisphere slid on the film.

The rider wear rates for the duration of this experiment were calculated and compared to those experiments in which the hemisphere slid on the films. The wear rate found for the flat sliding on the film from 4500 to 6000 kilocycles

$(0.0032 \times 10^{-15} \ m^3/m)$ was much less than found for the hemisphere sliding on the film; however, the flat-rider wear rate from 6000 to 8500 kilocycles $(0.021 \times 10^{-15} \ m^3/m)$ correlated very well with the steady-state hemispherical-rider wear rates (Table II).

Very little wear occurred to the rider for sliding intervals up to 6000 kilocycles, most likely, because enough lubricant was present to negate the scouring effect of the metallic asperities. Only when sufficient lubricant depletion occurred did the metallic asperities scour the rider flat and increase wear.

Failure Mechanisms

In previous investigations on polyimide-bonded graphite fluoride films 1 to 3, failure was arbitrarily defined to occur when the friction coefficient reached a value of 0.30. Observation of the surfaces in this study by optical microscopy revealed that this was a good choice since, when the friction coefficient reached 0.30, the sliding surfaces were no longer covered with very thin flowing films of lubricant as previously described. Instead a sizable portion of the surfaces were covered with dark powdery material.

Figure 17 shows photomicrographs of the rider contact area from the test on the 45 μm thick film after failure occurred. The photomicrographs typify what happened with the films of other thicknesses. A powdery band was found to extend from the rider inlet region to the exit region (fig. 17(a)). A similar band was found on the disk wear track.

It is believed this band resulted from depletion of the lubricant. Figure 12(d) shows valleys in the wear track becoming depleted of lubricant. When too many of these valleys became depleted, an excessive quantity of metallic wear particles was produced (from both the rider and disk substrate). These particles mixed with the lubricant and a powdery mixture of the two constituents resulted. It is interesting to note that the surfaces underneath this powdery buildup were still very smooth and no galling wear had taken place

SUMMARY OF RESULTS

Friction, wear, surface profilometry, and optical microscopy studies of a polyimide-bonded graphite fluoride film subjected to sliding against a hemisphere and a flat 440C HT stainless-steel surface indicate that:

1. Two stages (or regimes) of lubrication were found to occur.
   (a) In the first, the film itself supported the load and the lubricating mechanism was the shear (plastic flow) of a thin surface layer of the lubricant between the rider and the bulk of the film.
   (b) In the second, the lubricating mechanism consisted of the shear of thin films of the lubricant between a flat area on the rider and flat plateaus generated on metallic asperities of the substrate. The second stage took place after the original film was worn away.

2. The wear mechanism of the film (that occurred during the first stage of lubrication) was found to be strongly dependent on contact stress. Two mechanisms were found operating.
   (a) The first was due to crack propagation in the bulk. The rate and depth appeared to be a function of contact stress.
   (b) The second was due to spalling of a thin, textured surface layer ($<2~\mu m$ thick). This mechanism only occurred with the lighter contact stresses.

3. No detectable rider wear occurred in the first lubrication stage; but after transition to the second stage, rider wear increased with sliding distance.

4. During the first stage of lubrication, a hemisphere wore through the film in 5 kilocycles of sliding, while it took the flat 3500 kilocycles to wear through the same thickness. Thus, reducing stress (for the same total load) markedly reduced film wear rate and extended wear life.

5. During the second stage of lubrication, lubricant was supplied to the metallic asperity plateaus from two sources: from the valleys between the asperities, and from the sides of the film wear track. Thus, as film thickness was increased, the wear life of this stage also increased since the sides helped support the load and increased the lubricant supply.

6. Failure (high friction and rider wear rates) was characterized by the depletion of the polyimide-bonded graphite fluoride from the valleys between the metallic asperities and by the production of very fine powdery metallic debris. No galling wear of the surfaces was observed.

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TABLE I. - EFFECT OF SLIDING DURATION ON THE

CONTACT AREA AND THE RESULTANT CONTACT

STRESS FOR A 0.95 MM-DIAMETER FLAT

SLIDING ON A POLYIMIDE-BONDED

GRAPHITE FLUORIDE FILM

UNDER A 1-KILOGRAM

LOAD

[Percent area of contact determined using an image
analysis system.]

Sliding duration, kc	Projected area of contact, %	Contact stress	
		psi	kPa
1	20	10 000	69 000
15	33	6 100	42 000
60	37	5 400	37 000
250	60	3 300	23 000
500	80	2 500	17 000
1500	80	2 500	17 000

TABLE II. -- EFFECT OF FILM THICKNESS ON RIDER WEAR RATE FOR 0.476 CM HEMISPHERICAL TIPPED RIDERS SLIDING ON POLYIMIDE-BONDED GRAPHITE FLUORIDE FILMS

Sliding interval, kc	Film thickness, μm			
	10	18	45	62
0 to 1	None	None	None	None
1 to 5	0.60×10^{-15}	None	None	None
5 to 15	1.19×10^{-15}	None	None	None
15 to 60	0.13×10^{-15}	0.083×10^{-15}	0.069×10^{-15}	0.062×10^{-15}
60 to 120	0.12×10^{-15}	0.15×10^{-15}	0.056×10^{-15}	0.039×10^{-15}
120 to 250	$0.14\times p0^{-15}$	0.043×10^{-15}	0.023×10^{-15}	0.008×10^{-15}
250 to 500	0.51×10^{-15}	0.034×10^{-15}	0.025×10^{-15}	0.018×10^{-15}
500 to 900	0.75×10^{-15}	0.19×10^{-15}	0.047×10^{-15}	0.030×10^{-15}
900 to 1800	2.7×10^{-15}	1.0×10^{-15}	0.15×10^{-15}	0.062×10^{-15}
1800 to 2800	(a)	2.0×10^{-15}	0.33×10^{-15}	0.14×10^{-15}
2800 to 3800	(a)	(b)	0.64×10^{-15}	0.24×10^{-15}
3800 to 5000	(a)	(b)	0.88×10^{-15}	0.49×10^{-15}
5000 to 6000	(a)	(b)	(c)	0.74×10^{-15}
6000 to 6250	(a)	(b)	(c)	1.3×10^{-15}

[a]Failure at 980 kilocycles.

[b]Failure at 1845 kilocycles.

[c]Failure at 4400 kilocycles.
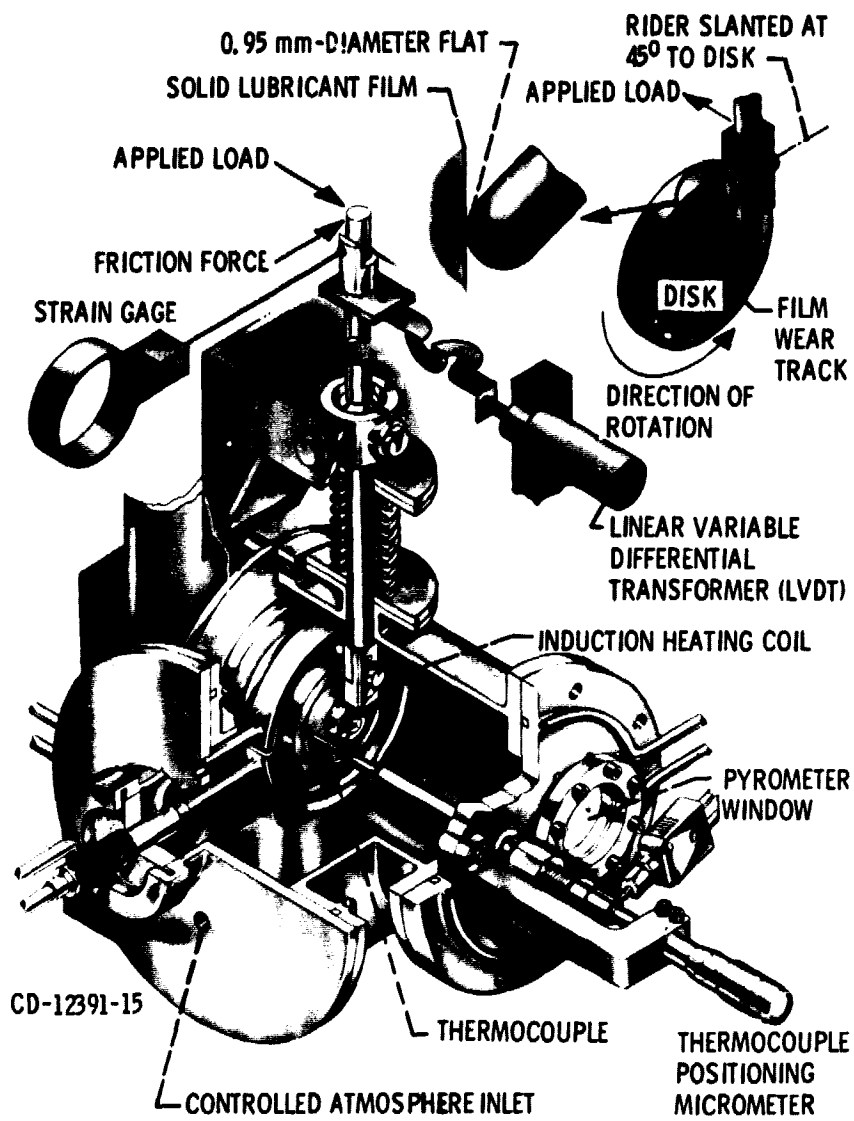
Figure 1. - Friction and wear apparatus.
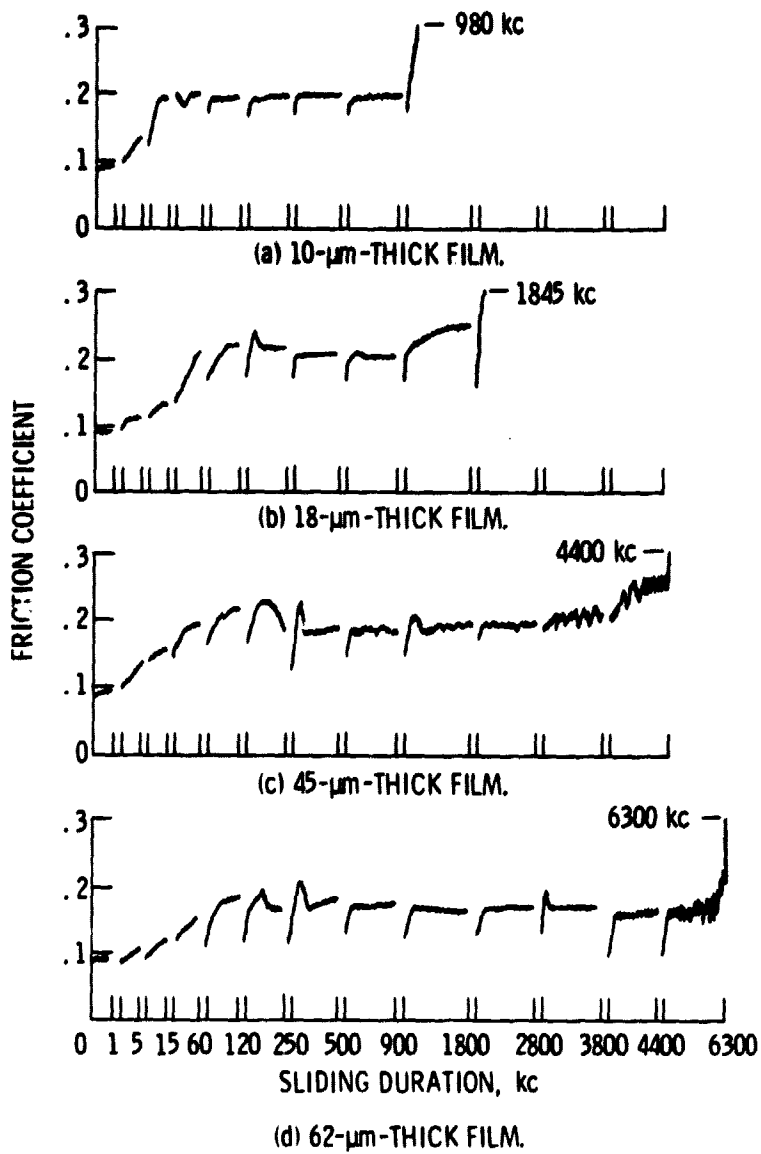
Figure 2. - Friction traces for 440C HT stainless-steel hemispherically tipped riders sliding on polyimide-bonded graphite fluoride films 10, 18, 45, and 62 μm thick.
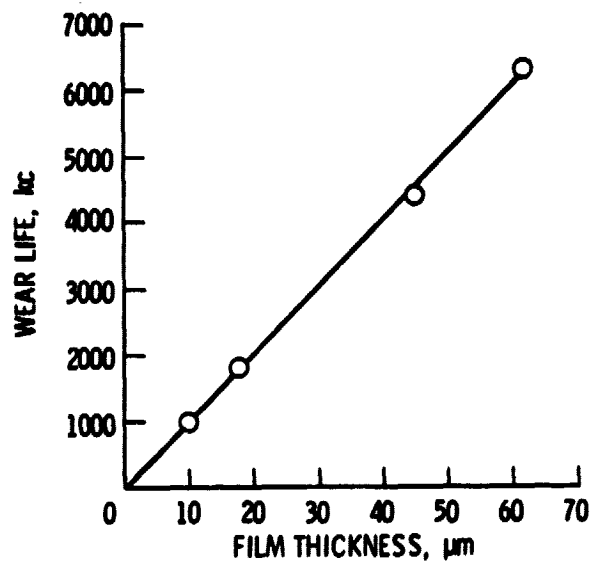
Figure 3. - Wear life as a function of
polyimide-bonded graphite fluoride
film thickness.
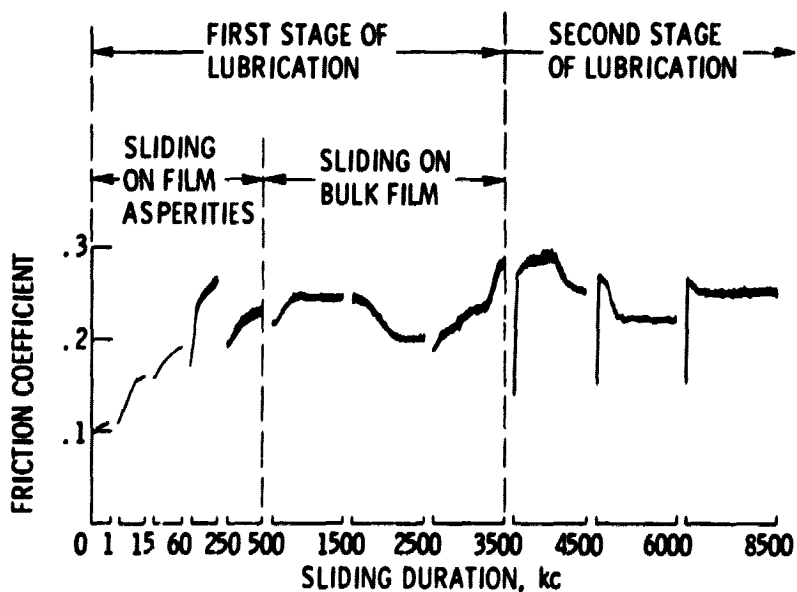
Figure 4. - Friction trace for a 440C HT stainless-steel
hemispherically tipped rider (with a 0.95 mm diameter
flat on it) sliding on polyimide-bonded graphite
fluoride film.

10 µm
500 µm

POLYIMIDE-BONDED
GRAPHITE FLUORIDE FILM

SANDBLASTED
METALLIC
SUBSTRATE

1 kc OF SLIDING.

1 kc OF SLIDING

5 kc OF SLIDING

500 kc OF SLIDING

500 kc OF SLIDING

3500 kc OF SLIDING

WEAR TRACK

WEAR TRACK

4400 kc OF SLIDING

8500 kc OF SLIDING

(a) HEMISPHERE.

(b) 0.95 mm DIAMETER FLAT.
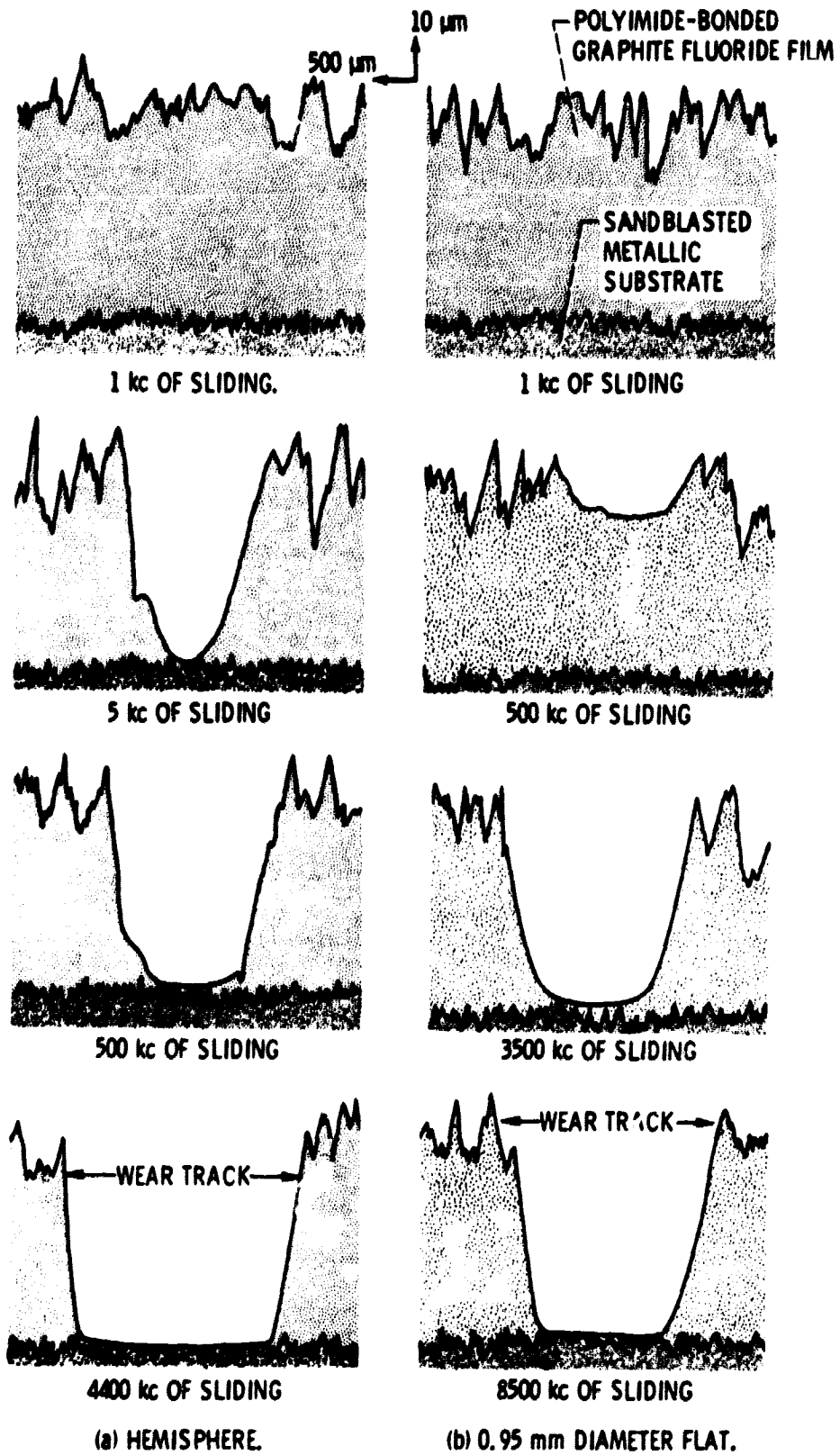
Figure 5. - Comparison of surface profiles of the wear tracks on polyimide-bonded graphite fluoride films for a hemisphere and for a 0.95 mm diameter flat after various intervals of sliding on the film.
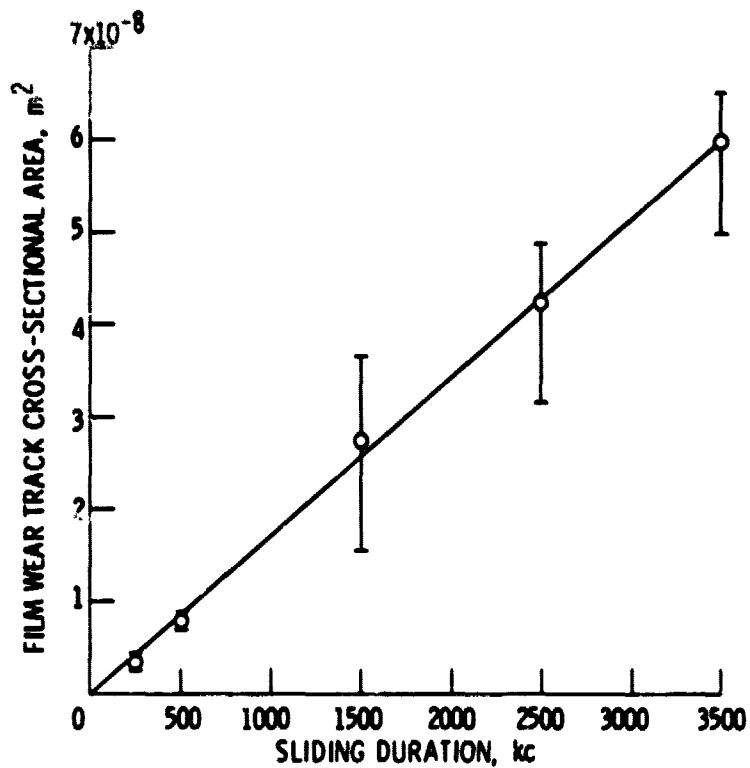
Figure 6. - Wear of polyimide-bonded graphite fluoride film as a function of sliding duration for a 0.95 mm diameter flat sliding on the film.
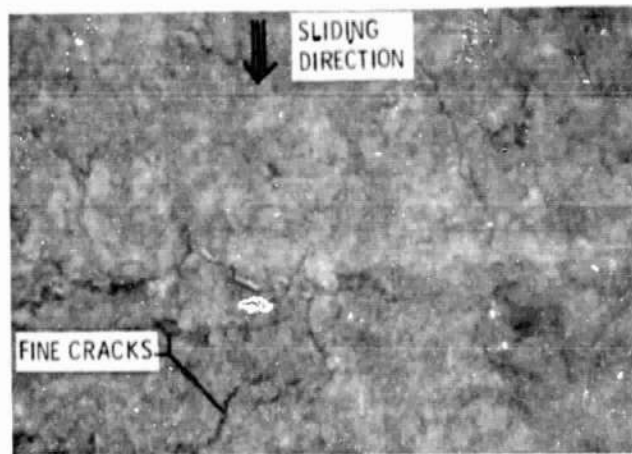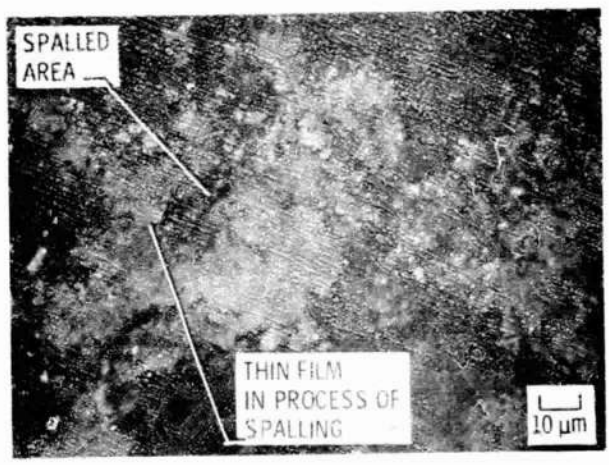
(a) 1/4 kc OF SLIDING.
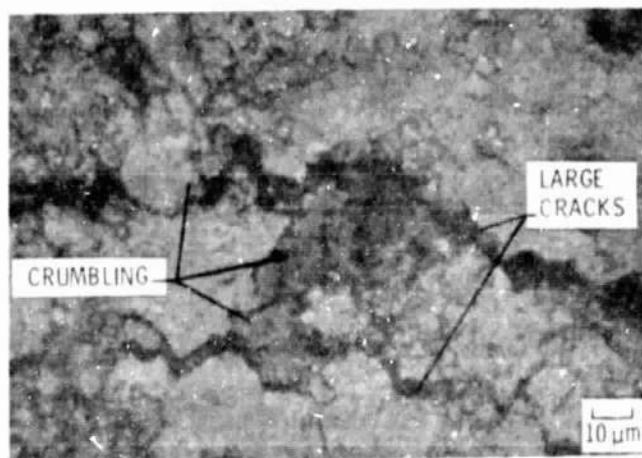
(b) 5 kc OF SLIDING.
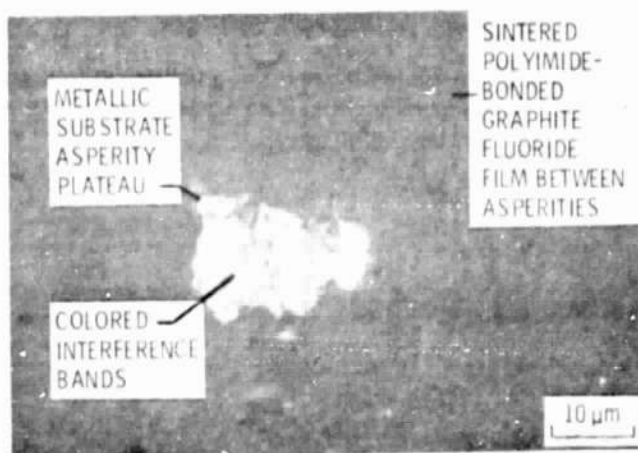
(c) 15 kc OF SLIDING

Figure 7. - High magnification photomicrographs of the central
area of the wear track (for the hemisphere sliding of the 45-
micrometer-thick polyimide-bonded graphite fluoride film)
after sliding intervals of 1/4, 5, and 15 kilocycles.

WEAR TRACK

POLYIMIDE-
BONDED
GRAPHITE
FLUORIDE
FILM

FLAT
PLATEAUS
ON FILM
ASPERITIES

(a) 1 kc OF SLIDING.

PLATEAU
AREAS
INCREASING

100 μm
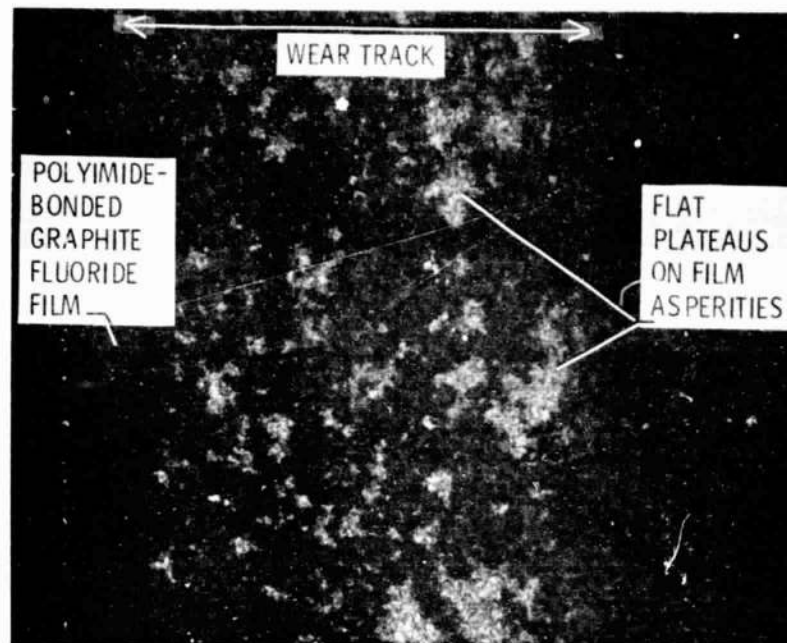
(b) 60 kc OF SLIDING.

Figure 8. - Photomicrographs of the same area of the wear track
after 1 and 60 kc of sliding for a 0.95 mm diameter flat sliding
on a polyimide-bonded graphite fluoride film.
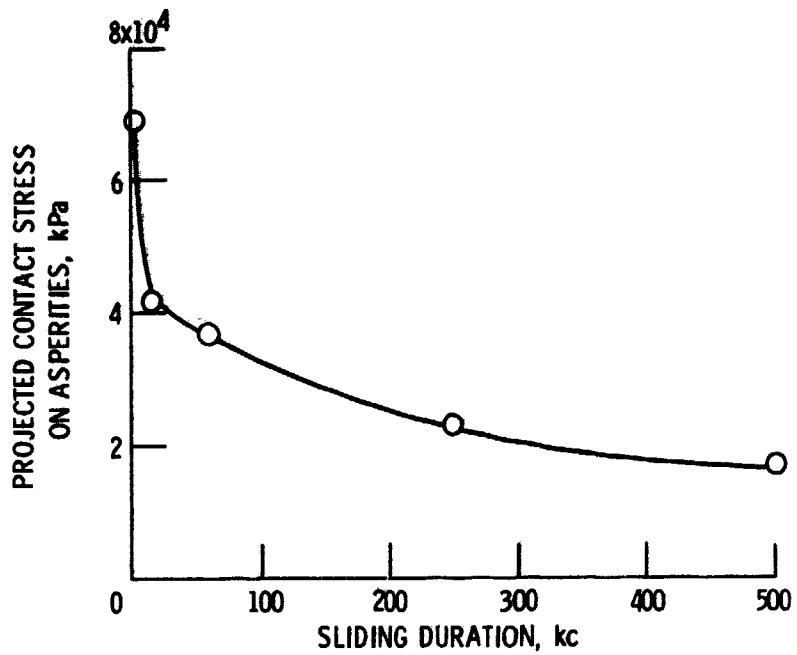
Figure 9. – Projected contact stress on the asperities of a
polyimide-bonded graphite fluoride film as a function of
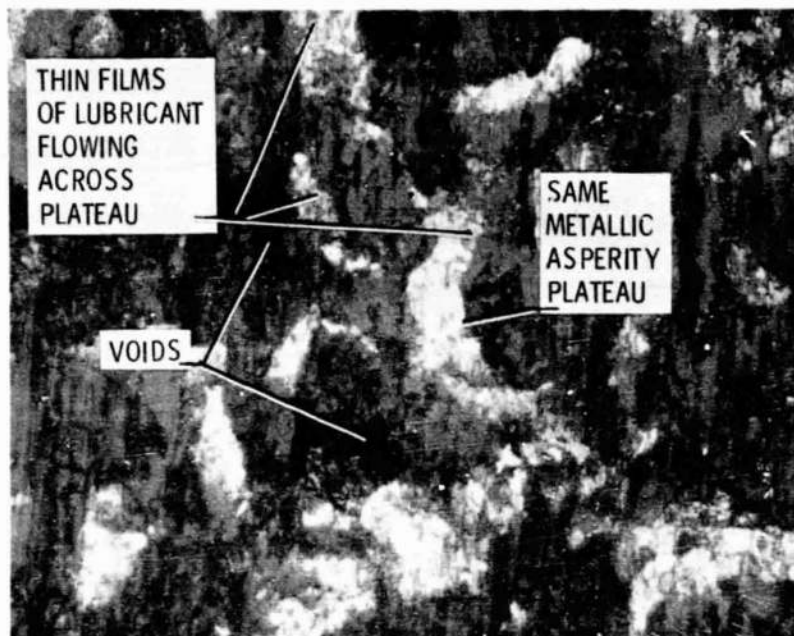sliding duration for a 0.95 mm diameter flat sliding on
the film.
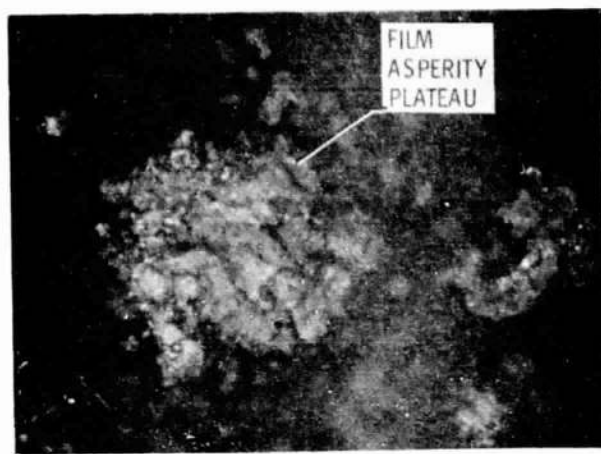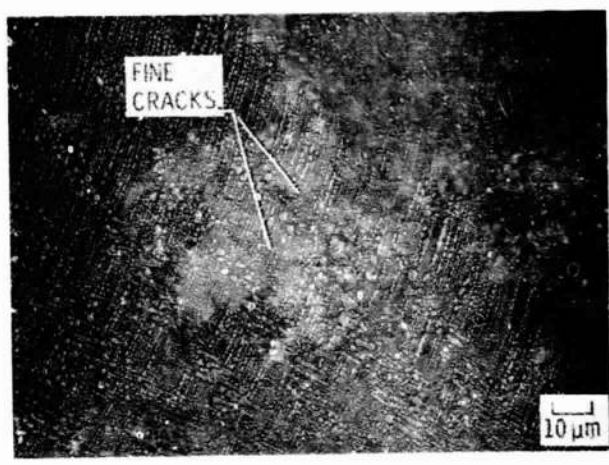
(a) 1 kc OF SLIDING.

(b) 5 kc OF SLIDING.

(c) 60 kc OF SLIDING.

Figure 10. - High magnification photomicrographs of the same polyimide-bonded graphite fluoride film asperity, showing the wear progression which occurred when a 0.95 mm-diam flat slid against the film.
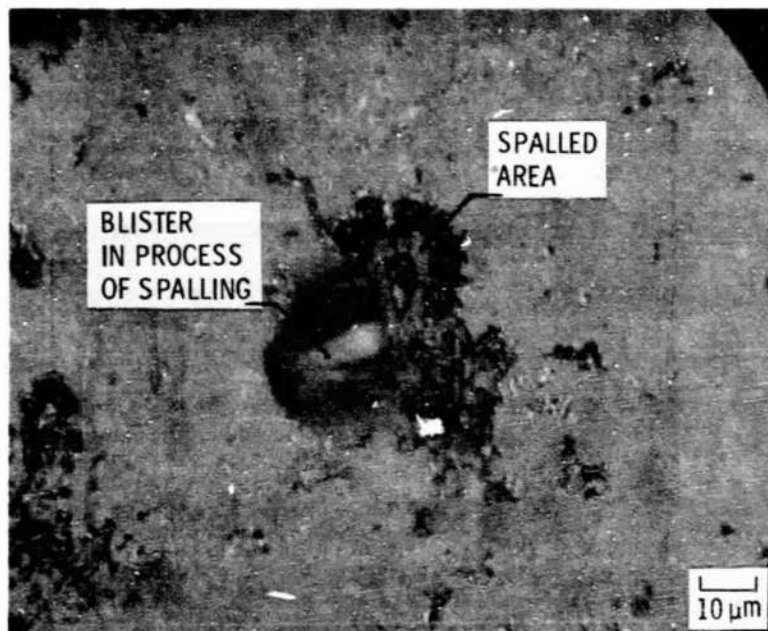
Figure 11. – High magnification photomicrograph of the wear track which was taken after the 0.95 mm diameter flat had slid for 1500 kc on the polyimide-bonded graphite fluoride film, showing blistering and spalling of a thin layer of the film.
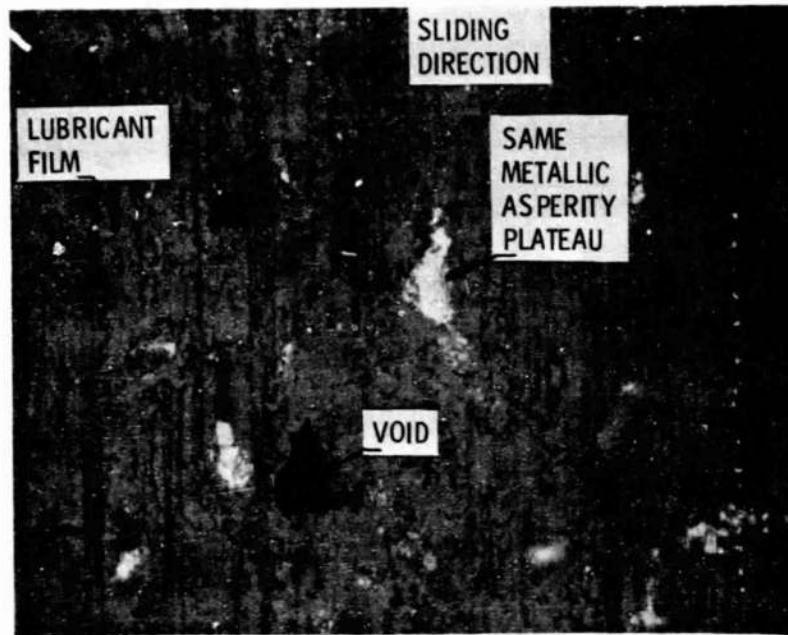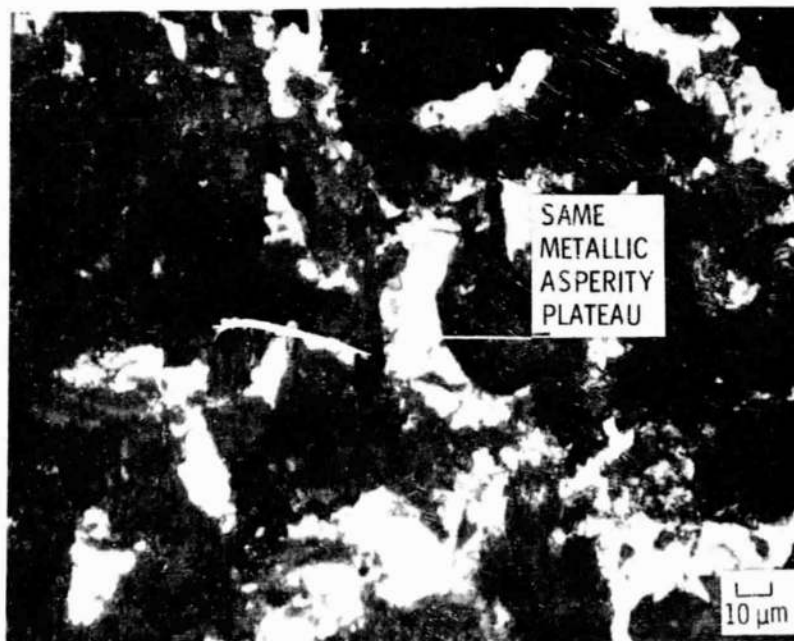
(a) 120 kc OF SLIDING.

(b) 500 kc OF SLIDING.

Figure 12. - High magnification photomicrographs of the same area on
the polyimide-bonded graphite fluoride film wear track (for the hemi-
sphere sliding on the 45 μm thick film) after sliding intervals of 120,
500, 1800, and 2800 kc.

(c) 1800 kc OF SLIDING.

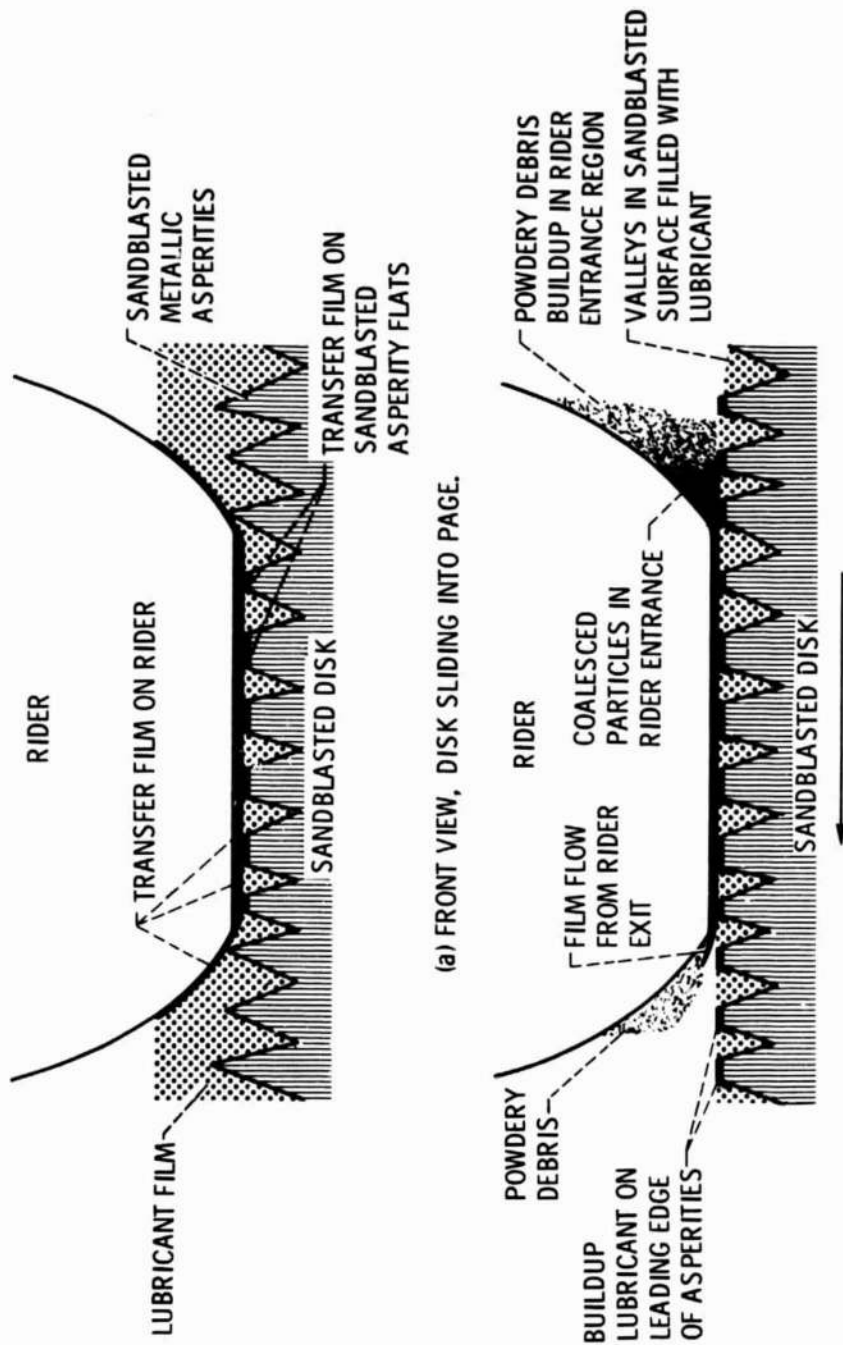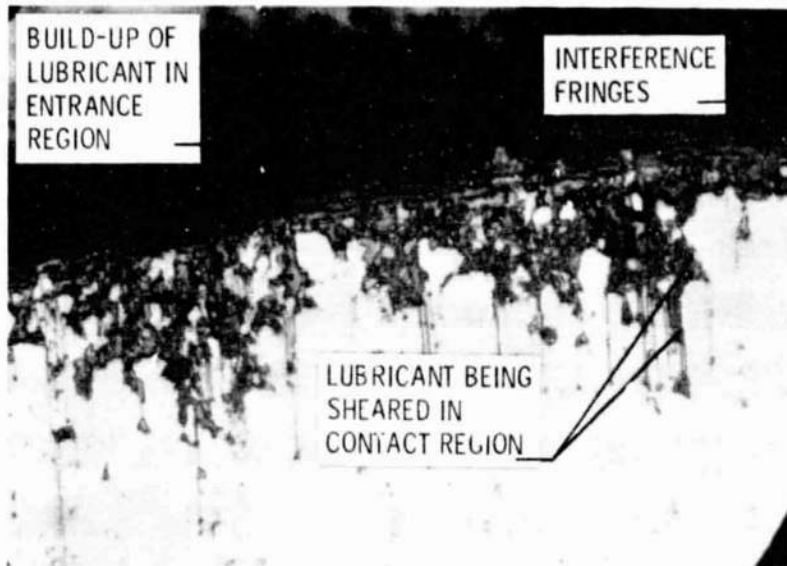(d) 2800 kc OF SLIDING.

Figure 12. - Concluded.

RIDER

SANDBLASTED
METALLIC
ASPERITIES

TRANSFER FILM ON
SANDBLASTED
ASPERITY FLATS

TRANSFER FILM ON RIDER

SANDBLASTED DISK

LUBRICANT FILM

(a) FRONT VIEW, DISK SLIDING INTO PAGE.

RIDER

POWDERY DEBRIS
BUILDUP IN RIDER
ENTRANCE REGION

VALLEYS IN SANDBLASTED
SURFACE FILLED WITH
LUBRICANT

COALESCED
PARTICLES IN
RIDER ENTRANCE

FILM FLOW
FROM RIDER
EXIT

POWDERY
DEBRIS

SANDBLASTED DISK

BUILDUP
LUBRICANT ON
LEADING EDGE
OF ASPERITIES

(b) SIDE VIEW, DISK SLIDING RIGHT TO LEFT.

Figure 13. - Idealized schematic drawing of sliding surfaces, illustrating lubricating mechanism in the second stage of lubrication.
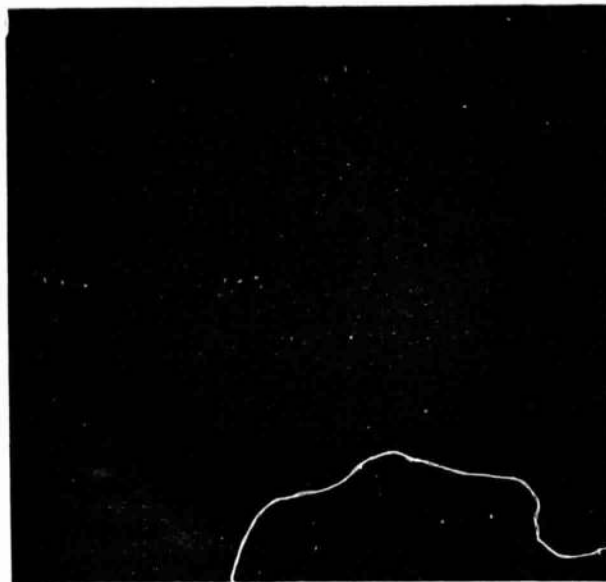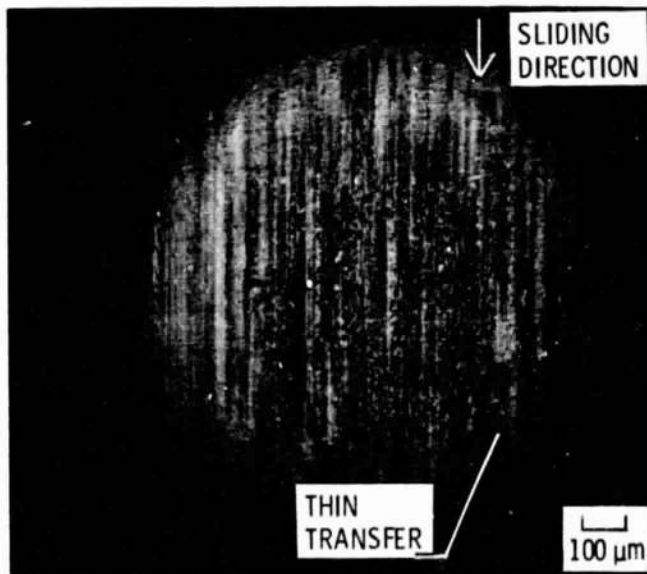
(a) RIDER INLET AREA.

(b) RIDER EXIT AREA.

Figure 14. - High magnification photomicrographs of the rider wear
scar inlet and exit areas of the 0.476 cm radius hemispherically-
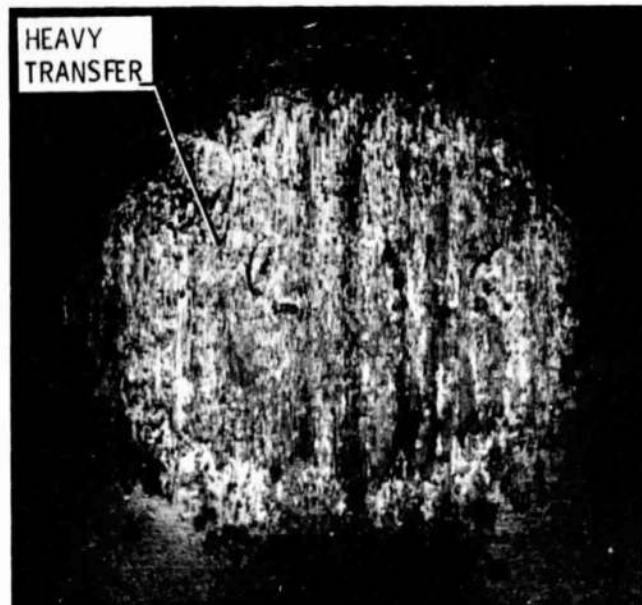tipped rider after 2800 kc of sliding on the 45 μm thick film.
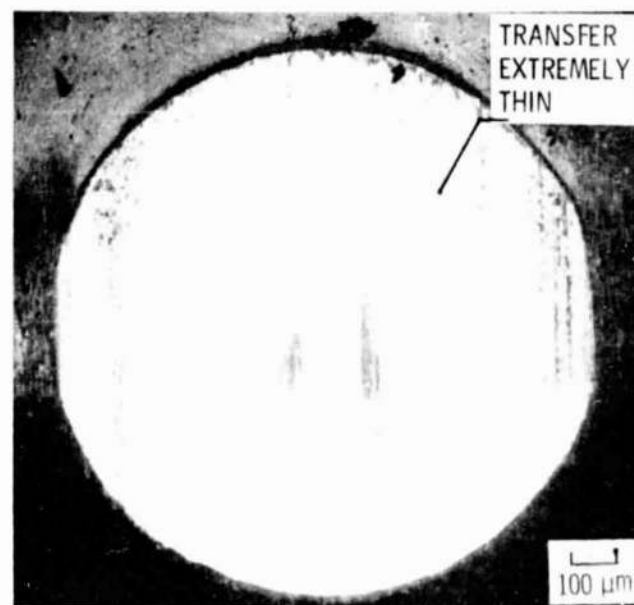
(a) FLAT AREA BEFORE SLIDING.

(b) 1/4 kc OF SLIDING.

Figure 15. - Photomicrographs of the 440C HT stainless
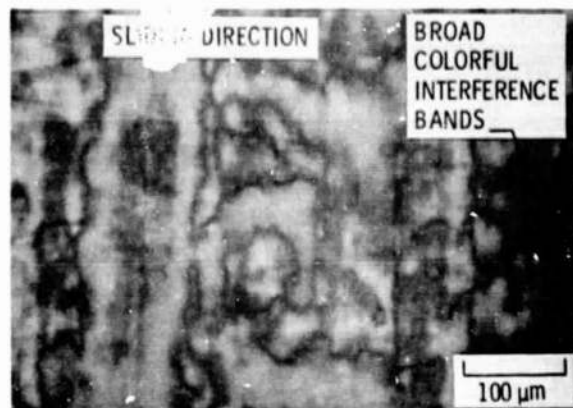steel rider (with the 0.95 mm diam flat) after various
sliding intervals.

(c) 250 kc OF SLIDING.

(d) 8500 kc OF SLIDING

Figure 15. – Concluded.

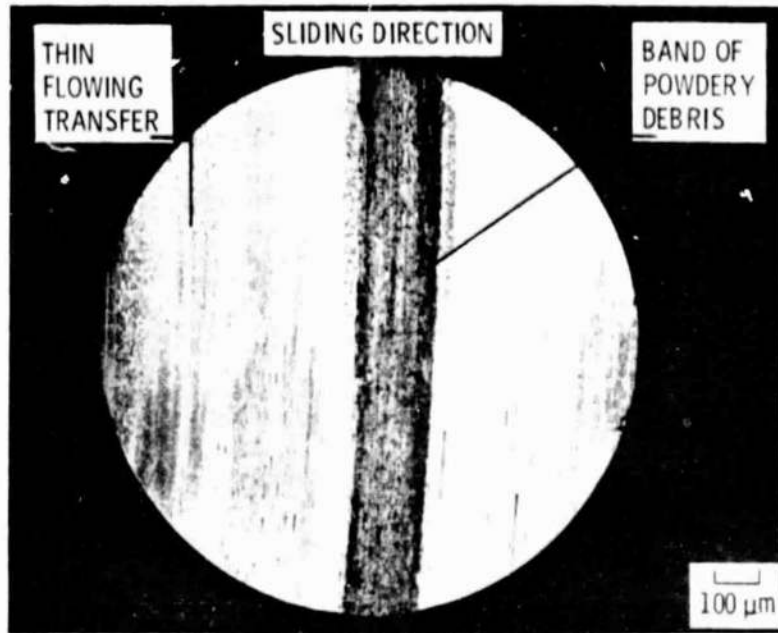(a) 1/4 kc OF SLIDING.

(b) 5 kc OF SLIDING.

(c) 120 kc OF SLIDING.

Figure 16. - High magnification photomicrographs of typical transfer to the 0.95 mm diameter flat on the rider after various sliding intervals.

THIN FLOWING TRANSFER

SLIDING DIRECTION

BAND OF POWDERY DEBRIS

100 μm

(a) OVERVIEW OF RIDER CONTACT AREA.

BAND OF POWDERY DEBRIS

POWDERY DEBRIS IN RIDER INLET

10 μm

(b) HIGH MAG. VIEW OF POWDERY DEBRIS IN THE RIDER INLET AREA.

Figure 17. - Photomicrographs of a typical rider contact area after failure had occurred.

1. Report No. NASA TM-81396	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MECHANISMS OF LUBRICATION AND WEAR OF A BONDED SOLID LUBRICANT FILM		5. Report Date
		6. Performing Organization Code
7. Author(s) Robert L. Fusaro		8. Performing Organization Report No. E-296
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

To obtain a better understanding of how bonded solid lubricant films lubricant and wear (in general), the tribological properties of polyimide-bonded graphite fluoride films were studied (in specific). A pin-on-disk type of testing apparatus was used; but in addition to sliding a hemispherically tipped rider, a rider with a 0.95-mm-diameter flat area was slid against the film. This was done so that a lower, less variable contact stress could be achieved. Two stages (regimes) of lubrication were found to occur. In the first, the film supported the load and the lubricating mechanisms consisted of the shear of a thin surface layer (of the film) between the rider and the bulk of the film. The second occurred after the bonded film had worn to the substrate, and consisted of the shear of very thin lubricant films between the rider and flat plateaus generated on the metallic substrate asperities. The film wear mechanism was found to be strongly dependent on contact stress.

17. Key Words (Suggested by Author(s)) Solid lubricant Graphite fluoride Wear mechanisms Polyimide Lubrication mechanisms Bonded film	18. Distribution Statement Unclassified - unlimited STAR Category 27		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*