WEAR CHARACTERISTICS OF BONDED SOLID FILM LUBRICANT UNDER HIGH LOAD CONDITION

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ABSTRACT

Wear properties of phenolic resin bonded molybdenum disulfide film lubricant were studied. In-vacuo journal bearing tests were carried out to evaluate the wear-life of this film lubricant. The wear-life depends on substrate materials and on sliding velocity. Pretreated substrate surfaces were examined to reveal the reasons for these results. Additionally, investigations on film wear mechanism were made.

INTRODUCTION

Bonded solid film lubricants are favorable candidates for lubricating gears, cams, sliding bearings or other sliding elements in mechanisms used in outer space(1)(2)(3). They are, in general, useful in high load and low speed conditions(4). They have a lower coefficient of friction, compared to soft metal films, higher allowable contact pressures, compared to bulk plastics, longer lives in pure sliding conditions, compared to sputter-deposited molybdenum disulfide films(5) and they are less sensitive to temperature change, compared to oils or greases.

Resin bonded molybdenum disulfide films probably have been the most widely examined of these kinds of lubricants. The authors have studied these films, especially from the viewpoint of application to the gears(6) and the journal bearings for the use of manipulator mechanisms for the Japanese Experiment Module (JEM) in space station "FREEDOM". Experimental results of durability tests, which were carried out for the application of the film lubricant to journal bearings, are described in this paper. In addition, a discussion on film wear mechanism is also included.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

In order to evaluate the friction and wear-life for plain journal bearings lubricated by the bonded solid film lubricant, an in-vacuo journal bearing tester was used. Figure 1 shows the tester configuration. The bearings used for the tests had a 10 mm bore and 7 mm width. The lubricant used in the tests was commercially available phenolic resin bonded molybdenum disulfide film. The films were spray-coated on both mating surfaces of bearings and shafts, then they were heat-cured. The film thickness was controlled between 7 to 13 microns. Material and pretreatments of shaft and bearing substrates are shown in Table 1.

Pretreatment is a very important factor to determine the film performance(7)(8). The sand-blasting is made mainly in order to roughen the surface to strengthen the mechanical bonding of the film to the substrate. Passivating is made mainly to give chemical stability to the surface.

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Substrate material combinations and bearing clearances with films applied are shown in Table 2. Only the 304 stainless steel bearings took the form of a bushing press-fitted into aluminum alloy holders. Other bearings were made directly on the holders.

The tester was set in a laboratory air environment and specimen temperature was not controlled. In all cases, the tester chamber was evacuated by a rotary and turbo-molecular pump system up to the 10^{-5}Pa mark first, then the test started. As soon as the test started, the vacuum went down to the 10^{-4}Pa mark, because of released gases from the lubricant. After a few minutes, the vacuum got back to the 10^{-5}Pa mark, which continued to the end of the test.

The shaft was oscillated by an AC servo motor through a reduction gear and feedthrough with an oscillational angle of 50 deg. The standard angular velocity examined was 10 deg./s, which was 0.87 mm/s in sliding velocity. Also some other velocities were examined. The loads were 1470 N (150 kg) and 1960 N (200 kg), which yielded 21 MPa and 28 MPa in projected area contact pressure, respectively.

EXPERIMENTAL RESULTS

Figure 2 shows a typical measured frictional torque trend for the bearings. The torque was large in the beginning and decreased to a steady level (Fig. 2-a). At the end of the test duration, the torque increased suddenly. This point was regarded as the wear-life for the bearing (Fig. 2-b). All the life-ended bearings had scoring damages and the damages positioned on the motor side end of the bearings, as shown in Fig. 3. That was probably caused by a peculiar misalignment of the tester.

Figure 4 shows the wear-life and coefficient of friction (steady state torque / bearing radius / load) for three kinds of shaft and bearing-substrate materials combinations. The coefficient of friction values were similar, but wear-life was very different between combinations, and there was considerable scatter in life for a given combination. The wear-life decreased in the order of SET 3, SET 2, SET 1 in Table 2.

Figure 5 shows the film wear-life and the coefficient of friction at several angular velocities. Although the wear-life seems to decrease at lower angular velocity, more experiments are required to confirm this trend because of the large data scatter. The coefficient of friction increases with the decrease in angular velocity.

DISCUSSION

Substrate Materials for Shafts and Bearings

It was reported that the wear-life generally increases with the increase in hardness for the substrate (7). However, such was not the case with these tests, i.e., the SET 3 wear-life exceeded that for SET 2. In order to reveal the reasons for these results, pretreated surfaces of materials used in the tests were investigated. Specimens with a flat surface of these materials were prepared for this investigation. Figure 6 shows the shape of the specimen. These flat surfaces were partially pretreated, and film was bonded to half of the pretreated area.

Figure 7 shows surface profiles for the specimens measured with TALYSURF. Corresponding numerical data are shown in Table 3. The aluminum alloy pretreated surface (Fig. 7-a) indicates a large degree of roughness, owing to sand-blasting. Heights of some peaks are comparable to lubricant film thickness, which means that films on such peaks had only a slight thickness, or even that there was no film on them. This is probably the most important reason for the short wear-life for the aluminum substrate bearing, besides low mechanical toughness of

aluminum alloy. The sand-blasting of the aluminum was the same as that for stainless steel, but this observation suggests that lower pressure or finer particles would be recommendable for sand-blasting aluminum alloy.

The pretreated surface of 440C stainless steel (martensitic stainless steel) in Fig. 7-b exhibits lower roughness height, on the average, than non-pretreated surface. This is because material was removed from the surface by sand-blasting. On the other hand, the pretreated surface of 304 stainless steel (austenitic stainless steel) in Fig. 7-c retained about the same height, on the average, as that for a non-pretreated surface. This is because plastic deformation was predominant, compared to material removal in sand-blasting on 440C stainless steel.

Table 3 indicates that 304 stainless steel had a greater roughness and wavelength than 440C stainless steel had, but the differences were small. Figure 8 shows cross sections of the pretreated area of the specimens. The difference in surface topography is more easily discernible. Finer irregularities are found on the surface of 304 stainless steel, which were never detected by TALYSURF, because of its poor resolution in the horizontal direction, compared to that in the vertical direction. These fine irregularities are assumed to be more helpful for mechanical bonding of the film to the substrate than the greater scale of roughness mentioned above. Consequently the 304 stainless steel bearing had longer wear-life.

Another possible reason for the longer wear-life for the 304 stainless steel bearing is that the 304 steel bushing, which was press-fitted into soft aluminum alloy holder moderated contact pressure, because it more easily deforms than the bulk steel. This is now under examination, using a 304 stainless steel holder as a bearing.

Angular Velocity

The decrease in wear-life, with the decrease in velocity, could be accounted for by film fatigue, which will be discussed again in the next section. The reason for the increase in the friction with the decrease in velocity is not clear, but it is assumed that the decrease in the release of absorbed gases in the film by the frictional heat, with decrease in velocity, would increase the friction(9).

The temperature measured at the outside wall of the holder (see Fig. 1) increased by only five or less at under 50 deg./s in angular velocity at the beginning of the tests, when the friction was higher than in the test when the friction was steady. Later in the test, temperature change by frictional heating was insignificant compared to room temperature changes. The frictional heat, generated under 50 deg./s angular velocity, was small and would not significantly affect the film wear-life (but would affect the friction). At 100 deg./s angular velocity, temperature increased more than 15 degrees. The decrease in the wear-life at 100 deg./s was therefore attributed to the frictional heat increase. In a larger velocity range, the decrease in the wear-life with the increase in the sliding velocity was previously reported(10). This would also be due to the frictional heat increase.

Wear Mechanism

Figures 9 and 10 show the worn film surface on a 304 stainless steel shaft and its profile. Figure 9 indicates many pits around flat surface. The width scale for these pits is on the order of a hundred microns and corresponds to that for profile's valleys of the corresponding area shown in Fig. 10a. Pits several microns in depth appear in the figure. In pertinent literature(10)(11)(12), 'blisters' were observed under much larger velocity conditions, but it is not clear whether the pits have anything in common with the blisters mentioned in the literature or not.

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The pits are not considered to originate from the inherently existing voids in the film, according to the observation of the film cross section, which is shown in Fig. 11. They were also not considered to be the blisters produced by frictional heat, because higher angular velocity did not decrease the wear-life under 50 deg./s, as mentioned above. This means frictional heat did not increase the film damage, such as the pits, in this sliding velocity range. Thus, the pits were estimated to be traces of partial debonding of the film materials from the film caused by fatigue entailed during the sliding process.

Figure 10-b shows the worn film surface profile for the shaft at approximately a half of the number of oscillations for the life-ended bearings. A wide, deep groove is observed on the motor side end of the worn surface. Figure 12 shows a microscopic image of this groove. The groove appears not to be the trace of abrasion, but to be an aggregation of pits or a trace of flaking in Fig. 12. Thus, the pitting or flaking wear is considered to dominate the film decrement.

If it is true that the film wear-life decreases with the decrease of sliding velocity, one reason is the increase in friction with the decrease in velocity, as mentioned above, and another is the increase in time in contacting area with the decrease in sliding velocity, both of which are the cause of the decrease in fatigue life.

Film-debonding, which is the direct cause of bearing failure, occurs at the interface between the lubricant film and substrate. Film-debonding from the substrate surface would strongly depend on the pretreated surface topography of the substrate, as compared with that from film itself. When the film-debonded points on the shaft and the bearing meet, the bearing life ends. However, even if film on one side, probably on the shaft, remains, failure could occur.

The debonded particles from the film consisted of molybdenum disulfide, bonding resin, additives and impurities. They, including molybdenum disulfide, could be abrasives to the metal substrate(12), but probably not so abrasive to the film itself, because of its embeddability. Once the film debonded from the substrate, it would act as an abrasive on the metal substrate.

Figure 13 shows a cross section of the film coated ring specimen, which was used in the block-on-ring wear test in nitrogen gas in another study(13). A deep wear groove was observed, including ring material between thick remaining films. This could be considered the trace of abrasion of the film wear particles to the ring material, as stated above.

Although friction still indicated a low value (coefficient of friction was 0.03) in the block-on-ring test, the metal wear particles from metal substrate, produced by the abrasion of the film wear particles, could cause a sudden increase in friction in the journal bearing, where it is much more difficult to exclude the particles from between the contacting surfaces than in the case of the block-on-ring test.

From the mechanism mentioned above, it is reasonable that a harder substrate has a longer film wear-life, because the harder substrate generally has greater resistance against abrasives. However, this is not always true, because the film wear-life also depends on the film bonding capacity for the pretreated substrate surface.

CONCLUSIONS

Wear properties for bonded molybdenum disulfide film were studied especially from the viewpoint of the application to journal bearings used in outer space. The following results were obtained.

1.   The longest film wear-life ranked in the order of 304 stainless steel, 440C stainless steel and aluminum alloy material substrate.

2.   The film wear-life seems to decrease with a decrease in sliding velocity in the low velocity range, though more experiments are needed to confirm this concept.

3.   440C and 304 stainless steel, which were processed with the same pretreatment, had different surface topographies. Probably, this difference gave longer life to the 304 stainless steel bearing.

4.   The film lost its thickness mainly by pitting wear. Once the film debonded from the substrate, the dedonding particles could abrade the metal substrate, and the bearing life ended, even if the film on either the shaft or the bearing remained.

In this study, 304 stainless steel bearing, lubricated by this film, was proved to have a life over a hundred times as long as that required for the JEM remote manipulator system mission, though the film's resistance to radiation and atomic oxygen must be investigated in the future. Suggestions for producing tougher bearings were also found from this study.

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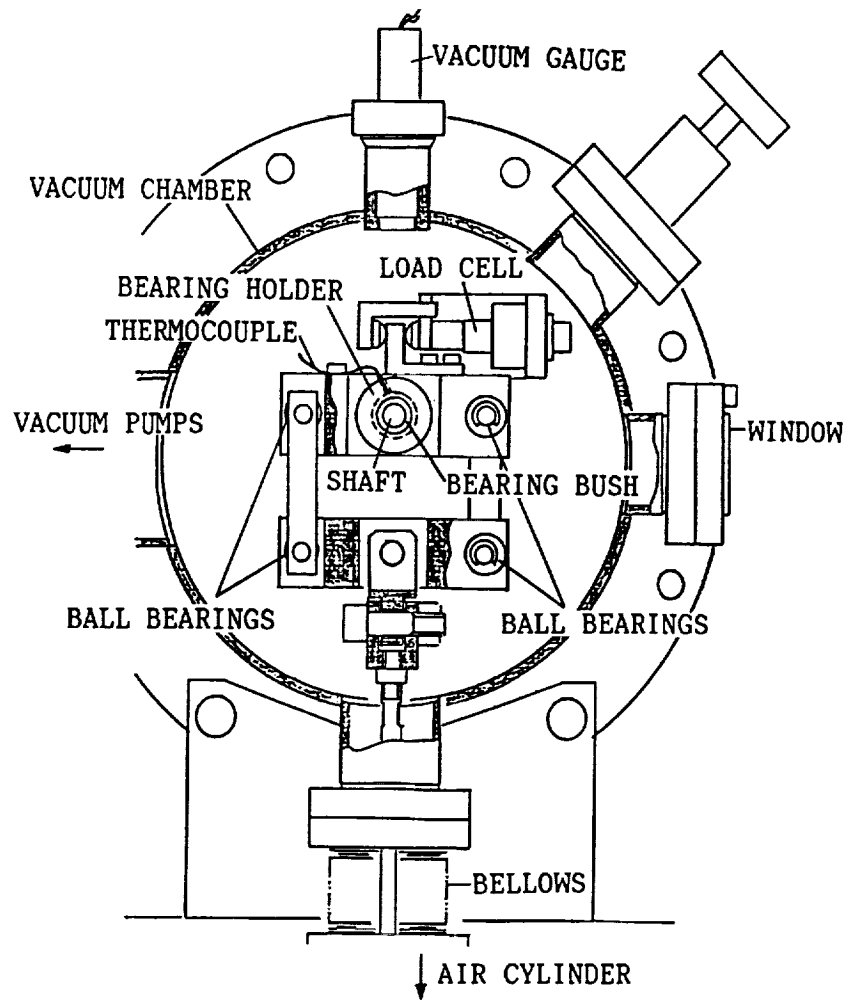
Figure 1. In-vacuo Journal Bearing Tester

Table 1. Substrate Materials

No.	MATERIAL	HEAT-TREATMENT	HARDNESS Hv.	PRETREATMENT
①	2017 ALUMINUM ALLOY	T4	120~130	SAND-BLASTING
②	440C STAINLESS STEEL	QUENCH HARDENING AND TEMPERING	570~590	SAND-BLASTING AND PASSIVATING
③	304 STAINLESS STEEL	-	220~250	SAND-BLASTING AND PASSIVATING

Table 2. Substrate Material Combinations

SET No.	SUBSTRATE MATERIAL		DESIGNED BEARING CLEARANCE (μm)
	BEARING	SHAFT	
1	①	②	40
2	②	②	10
3	③	③	20

*①, ② and ③ are Corresponding to Those in Tab. 1

10s. **30min.**

2N·m

(a) (b)
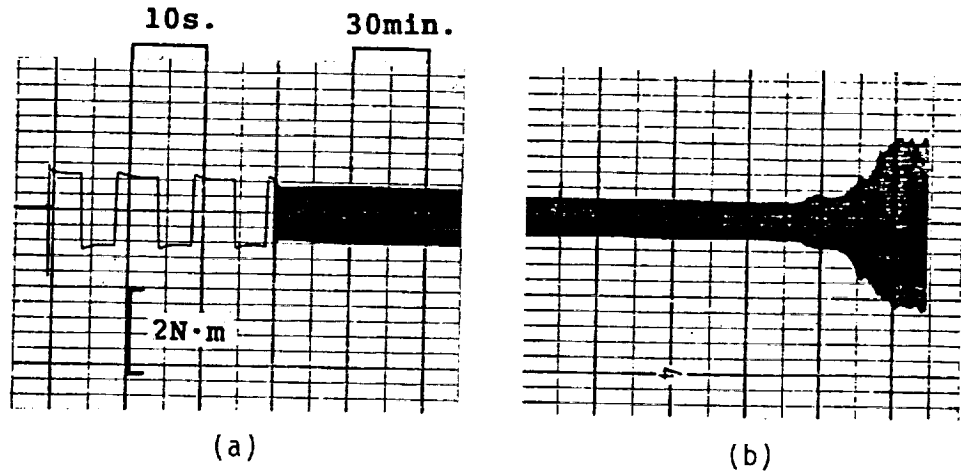
Figure 2.   Typical Frictional Torque Trend

Specimen: SET 1, Angular Velocity: 10 deg./s, Load: 1470N
(a): at the Beginning of the Test,
(b): at the End of the Test

FILM COATED AREA

SLIDING AREA

SCORING DAMAGE   MOTOR SIDE

1   2   3   4   5   6   STAINLESS 7 HARDENED
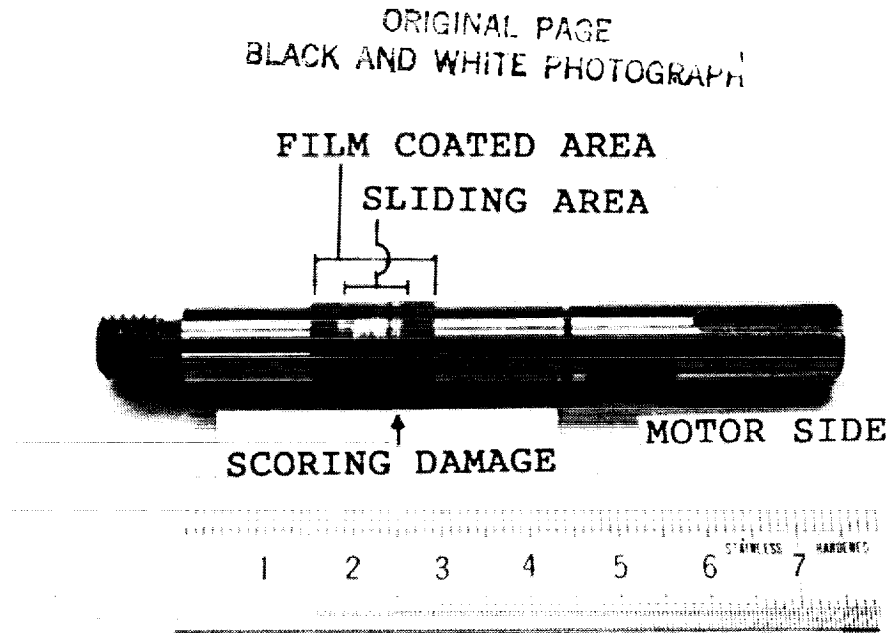
Figure 3.   No Longer Usable Bearing Shaft

Figure 5. Wear-life and Coefficient of Friction at Several Angular Velocities
Specimen: SET 3, Load: 1960N

○ : WEAR-LIFE, ● : COEFFICIENT OF FRICTION

Figure 4. Wear Life and Coefficient of Friction for Three Substrate Combinations
Angular Velocity: 10 deg./s
Load: 1470N

○ : WEAR-LIFE
● : COEFFICIENT OF FRICTION
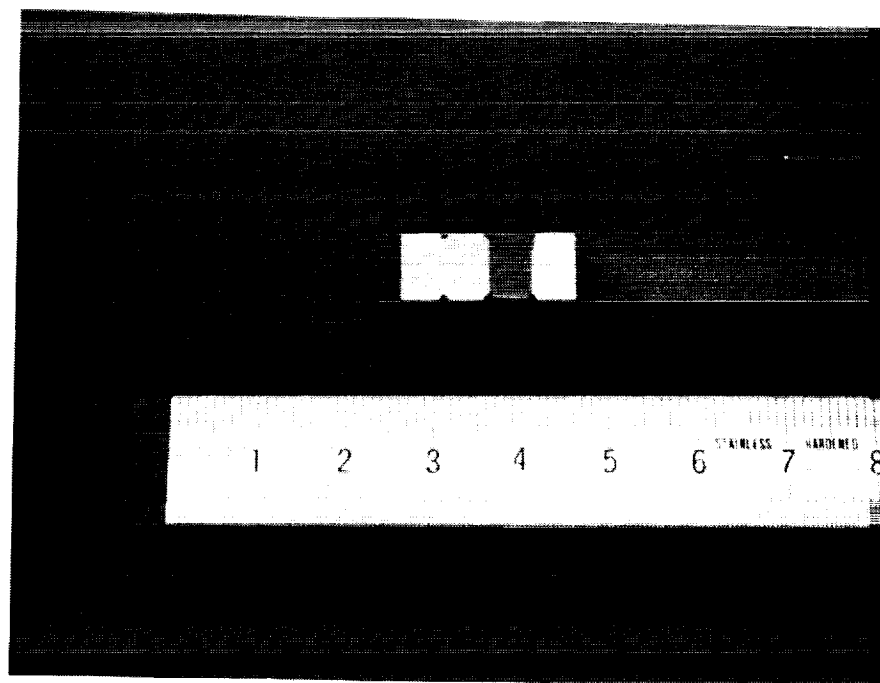
Figure 6. Pretreatment Surface Specimen

100μm

Figure 9. Typical Worn Film Surface

Table 3. Numerical Data for Pretreated Surface Topography

MATERIAL	Ra (µm)	R_{max} (µm)	SKEWNESS	WAVELENGTH (rms µm)
2017 ALUMINUM ALLOY	1.9	15.5	-0.20	40.1
440C STAINLESS STEEL	1.1	7.5	-0.42	23.8
304 STAINLESS STEEL	1.2	8.8	-0.42	27.9

(a)

(b)

(c)
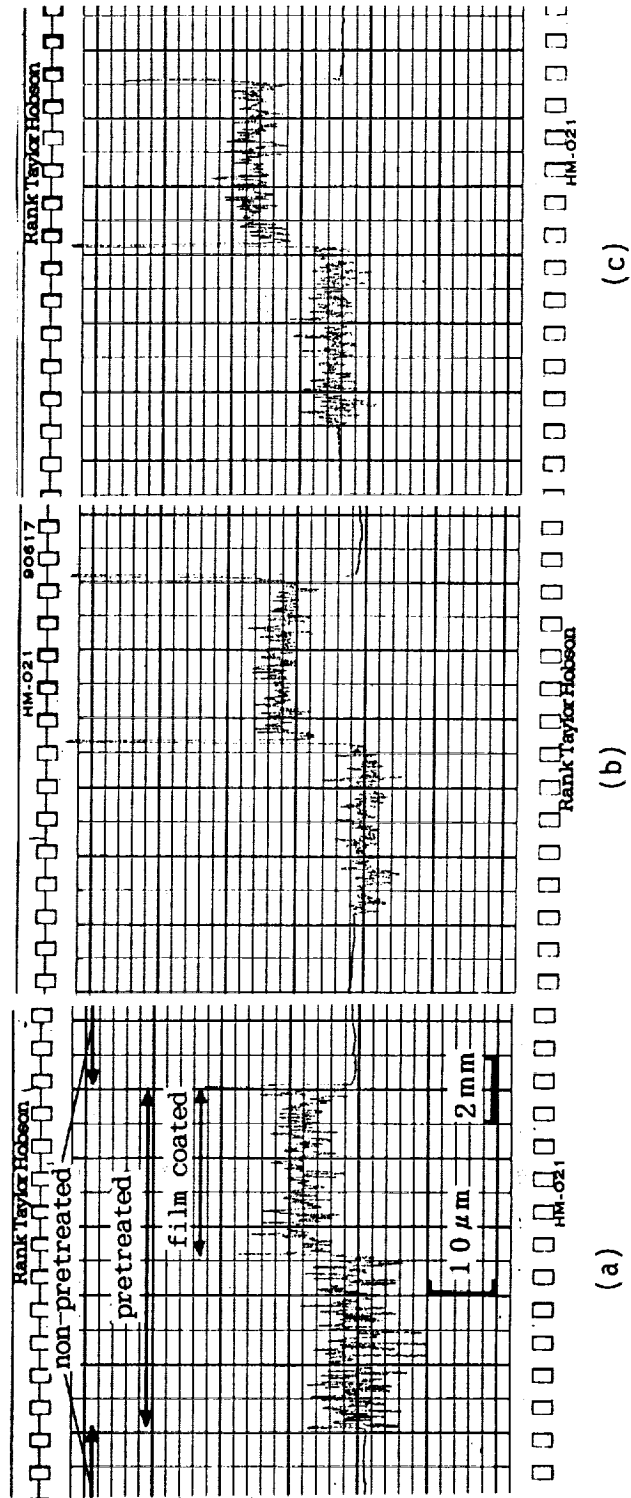
Figure 7. Surface Profiles for Pretreated Surface Specimens
(a): 2017 Aluminum Alloy, (b): 440C Stainless Steel, (c): 304 Stainless Steel

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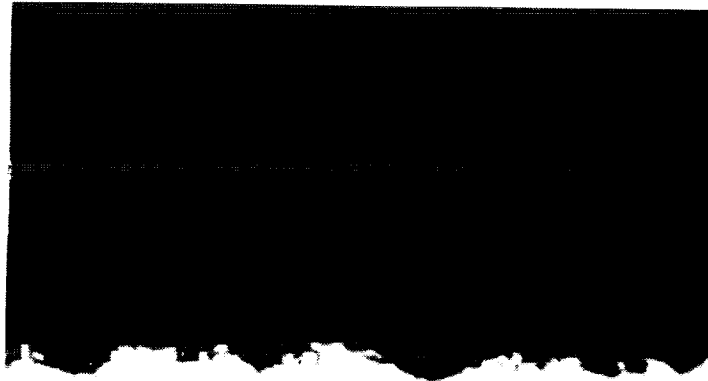
25μm ← SUBSTRATE

(a)
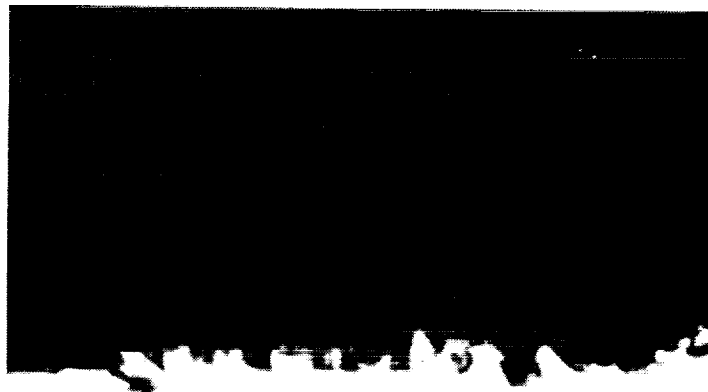
25μm ← SUBSTRATE

(b)

Figure 8. Cross Sections of Pretreated Surface Specimens
(a): 440C Stainless Steel (b): 304 Stainless Steel

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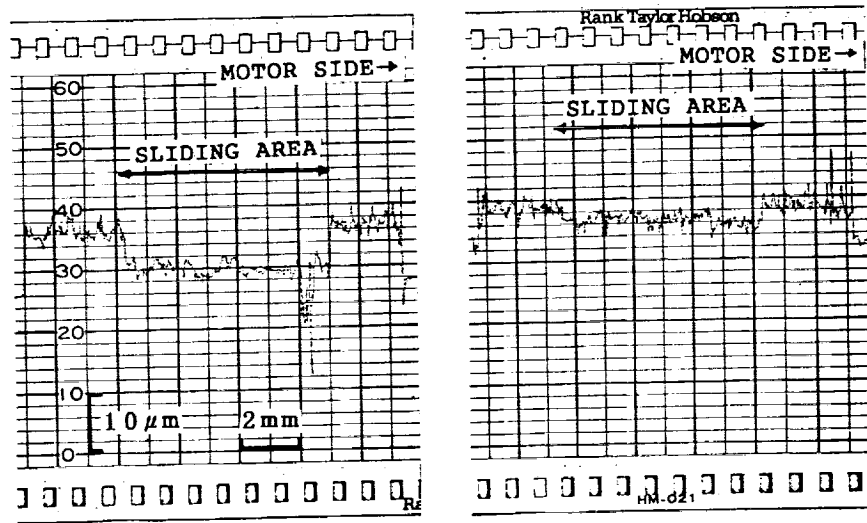
Figure 10. Surface Profiles for Worn Film on 304 Stainless Steel Shaft
(a): No Longer Usable (b): After 1.27 x 10⁵ Oscillations

Figure 11. Cross Section View, Film Coated Surface for 304 Stainless Steel
Pretreated Surface Specimen. Cut at 10° Inclination.

100μm
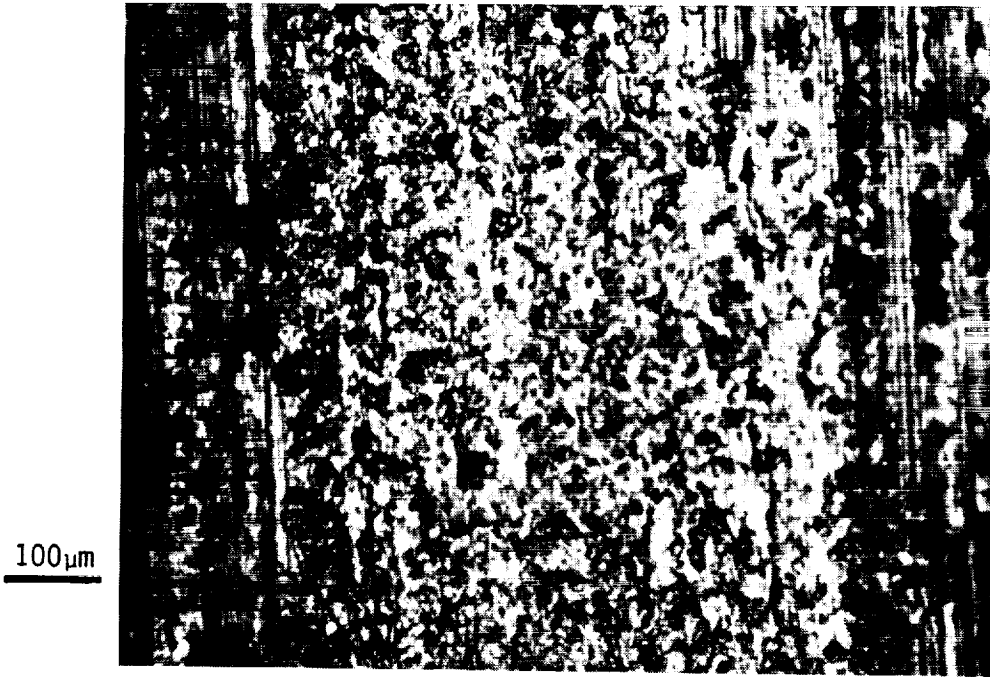
Figure 12.   Large Groove in Fig. 10(b)

100μm
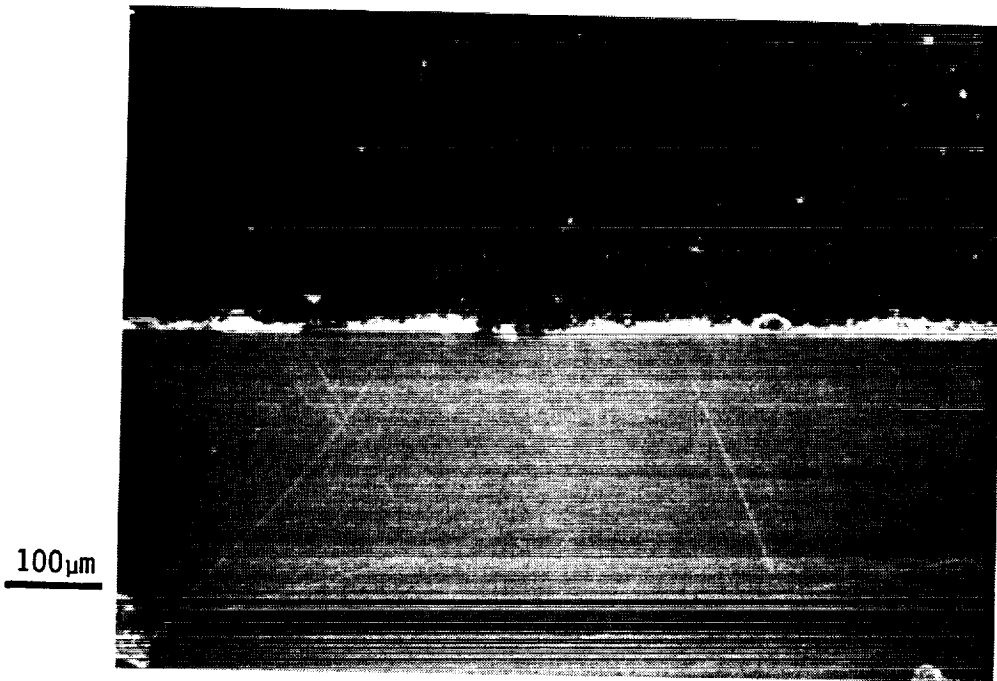
Figure 13.   Cross Section of Ring Specimen