Chapter

Wear Life of Bonded MoS_2 Film Lubricant

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Abstract

Bonded MoS_2 film lubricants are widely used in industry as solid lubricants. It has excellent lubrication properties, but it also has characteristics that require careful consideration. As is well known, its friction and wear are greatly affected by the environmental atmosphere and its wear life depends on the pre-treatment of the substrate. It was found that in many cases the wear life could not be correctly estimated by a specific wear rate and could be explained by the fatigue life, especially under high loading conditions. The atmosphere dependent wear life can also be explained by the fatigue life.

Keywords: solid lubricant, coating, friction, wear, atmosphere, fatigue, space use

1. Introduction

Molybdenum disulfide (MoS_2), along with graphite or PTFE, is a commonly used solid lubricant. One of the most commonly used forms of MoS_2 is a bonded film lubricant. Its application process is relatively simple and stable performance can be obtained, compared to other coatings such as sputtering. They are often used in automobiles and OA equipment, especially in aerospace applications.

Lubrication properties of MoS_2 are known to be greatly affected by environmental atmosphere, and the same is true for bonded MoS_2 film lubricants. They generally perform well in dry air, inert gas environments and in vacuum, compared to moist air environment. Because of this, they often used in space applications.

However, the performance in the atmosphere is often important even for space applications, which may be used in the atmosphere before the launching for the tests etc., and for devices that moves in and out of vacuum and the atmosphere.

The lubrication properties of bonded MoS_2 film lubricant in vacuum and in air were investigated, and it was found that specific wear rate is often not effective in estimating the wear life. Fatigue at the interface between the film and the substrate is found to be the main factor that determines wear life of bonded MoS_2 film lubricant, and short life in the atmosphere could be attributed to the fatigue.

2. Overview of bonded MoS_2 film lubricant

Figure 1 shows the typical application process of the bonded MoS_2 film lubricant. It can apply to various forms of products, including inner side of the holes.

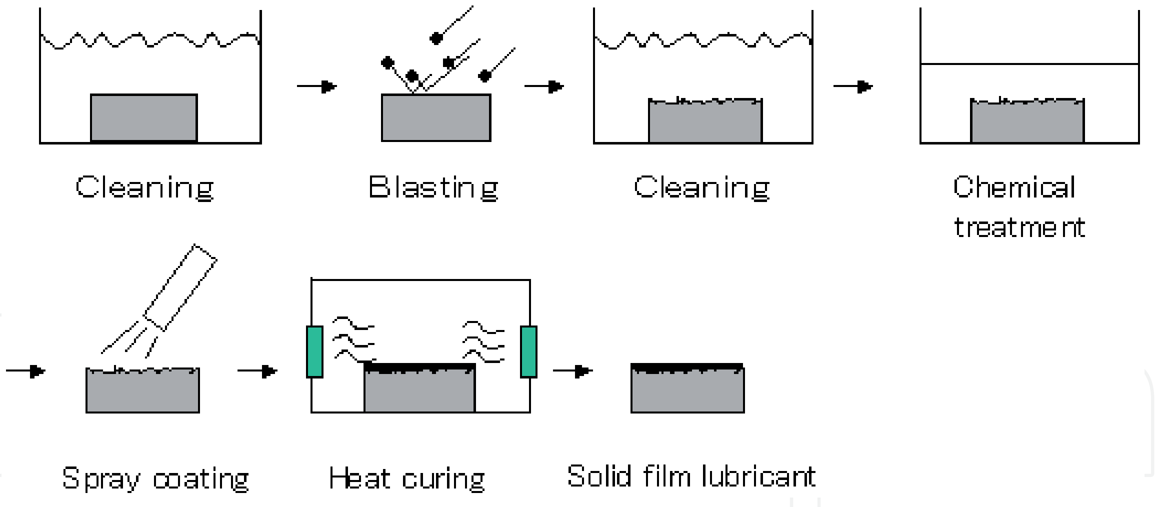

Figure 1.
Typical application process of bonded MoS_2 film lubricant.

The thickness of the film is typically about 10 micro-meters. Sometimes this is too large for some mechanical parts, e.g. precious ball bearings, but usually small enough to realize smooth engagement of the parts.

Figure 2 [1] shows the cross-section of the bonded MoS_2 film lubricant including substrate and film. The cross-section is enlarged vertically because it was cut diagonally. It can be seen that an intricately shaped substrate anchors the film. Such substrate surface morphology is produced by pretreatment of the substrate such as blasting. Chemical pretreatment passivates the surface of the substrate, some of which gives the surface a fine mesh-like structure. It has been reported that the final texture of the substrate surface is determined by blasting and that phosphate treatment, a type of chemical treatment, promotes significant changes in surface roughness [2]. Substrate pretreatment is an important process for providing a strong adhesion between the film and the substrate, resulting in a longer wear life of the bonded film lubricant [3].

As the lubrication performance in vacuum is excellent, the bonded MoS_2 film lubricants are often used in space applications [4–6]. **Figure 3** [4] shows the joint mechanism of the robot arm of the space station: ISS. Bonded MoS_2 film lubricant is applied to gears and sliding bearings in it. In general it seems to be often used for pure-sliding or rolling-sliding surfaces rather than pure-rolling surfaces.

Bonded MoS_2 film lubricants are used at a variety of sliding speeds and loading conditions, but naturally their limiting PV values are smaller than oil lubrication.

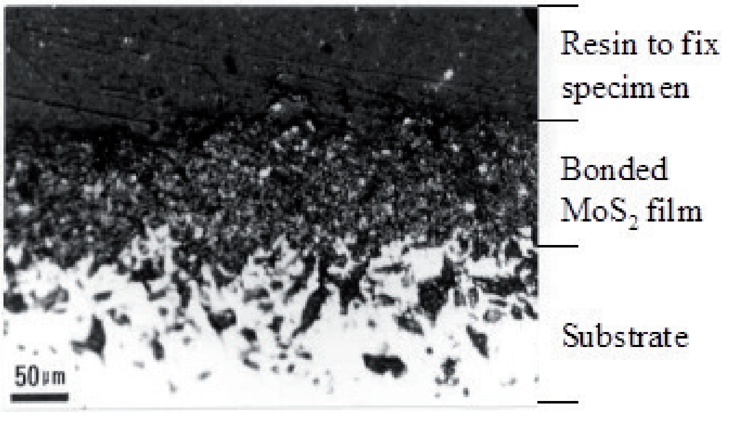

Figure 2.
Cross-section of bonded MoS_2 film lubricant [1].

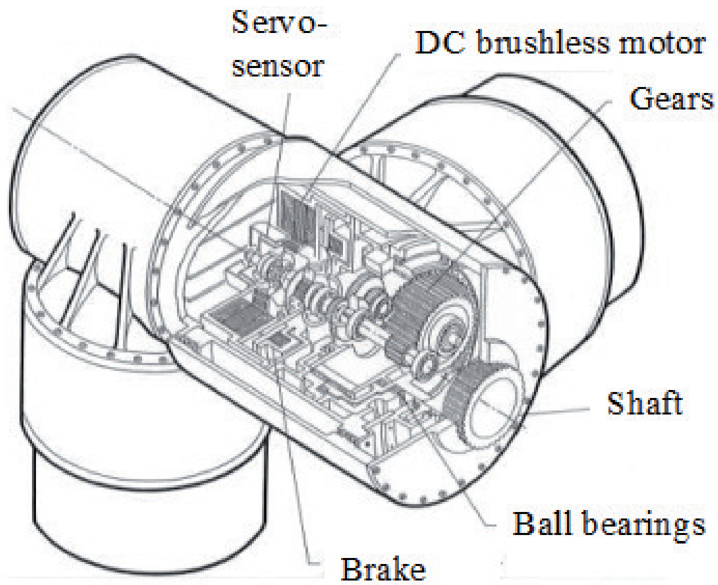

Figure 3.
Joint mechanism of robot arm of space station: ISS [3].

The working conditions under which they perform well seem to be high load and low speed conditions [7] where oil lubrication does not perform well. In this chapter, we will mainly discuss the friction and wear of bonded MoS_2 film lubricants under relatively high load and low speed conditions.

3. Wear life of bonded MoS_2 film lubricant

3.1 Effect of substrate

3.1.1 Experiment

The friction and wear life of journal bearings with bonded MoS_2 film lubricant applied to some substrates were investigated in vacuum using the test equipment shown in **Figure 4** [8]. **Figure 5** illustrates the friction measurement part of the equipment set in the vacuum chamber. The shaft was oscillated by AC servo motor through reduction gear and feedthrough. The radial load was applied by an air cylinder outside the vacuum chamber through a bellows. The bore and width of the bearing were 10 mm and 7 mm, respectively. The lubricant was applied both to the bearing and the shaft. The frictional torque was measured by the load cell above the test bearing.

The commercially available bonded MoS_2 film lubricant, including about 25 wt. % MoS_2 and phenolic resin binder, was spray coated and heat cured at 150°C for 1 h. The film thickness was about 10 micro-meters and the diameter clearance between the bearing and the shaft with lubricant film was 10-20 micrometers.

Table 1 [1] shows the substrate materials and pretreatment for the bearings and the shafts. **Table 2** [1] indicates the bearing and the shaft combinations. The circled numbers in the table correspond to those in **Table 1**. **Table 3** [1] shows the test conditions.

3.1.2 Experimental results

Figure 6 [1] illustrated the typical measured friction evolution. The measured friction drew the rectangular wave due to the oscillation motion and half of the total

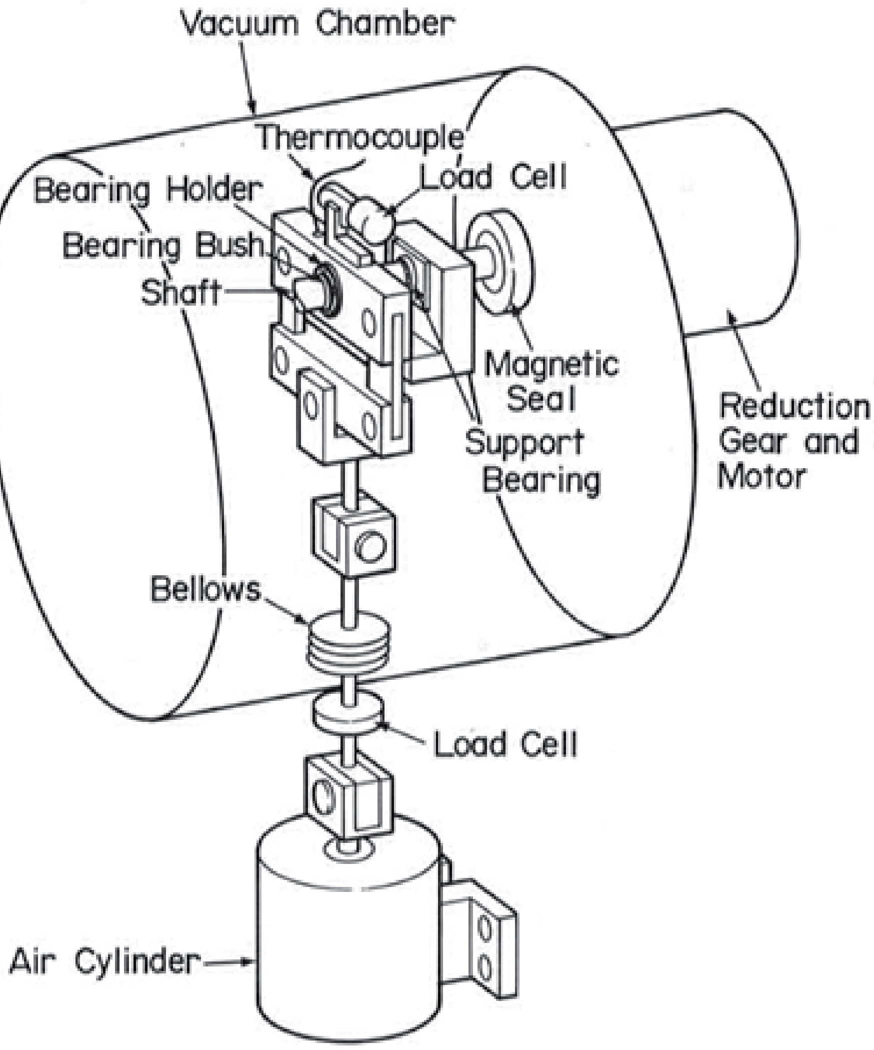

Figure 4.
In-vacuum journal bearing test equipment [7].

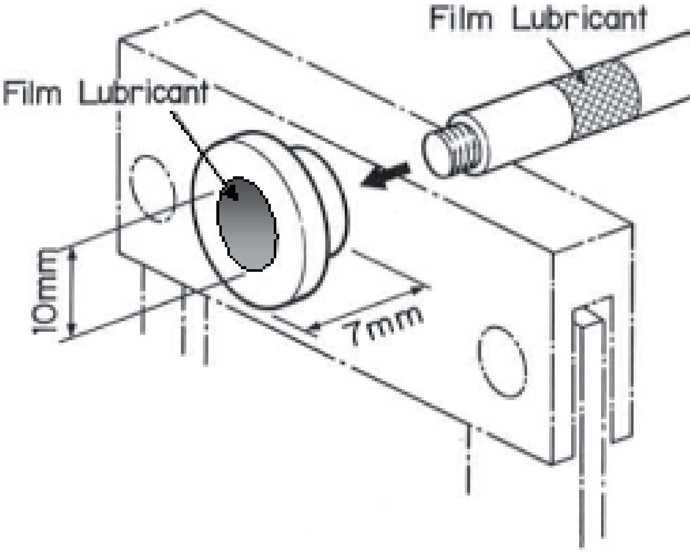

Figure 5.
Friction measurement part of the in-vacuum journal bearing test equipment.

No.	Substrate material	Heat-treatment	Hardness Hv.	Pretreatment
①	JIS 2017 aluminum alloy	JIS T4	120-130	Sand-blasting
②	JIS 440C stainless steel (martensitic stainless steel)	Quench hardening and tempering	570-590	Sand-blasting and passivating
③	JIS 304 stainless steel (austenitic stainless steel)	—	220-250	Sand-blasting and passivating

Table 1.
Substrate materials and pretreatment for bearings and shafts [1].

Set No.	Substrate material	
	bearing	Shaft
1	①	②
2	②	②
3	③	③

Table 2.
Bearing and shaft combinations [1].

Motion	Oscillation
Atmosphere	10^{-5} Pa vacuum
Load	1470 N
Angular velocity	10 deg./s
Oscillational angle	50 deg

Table 3.
Test conditions [1].

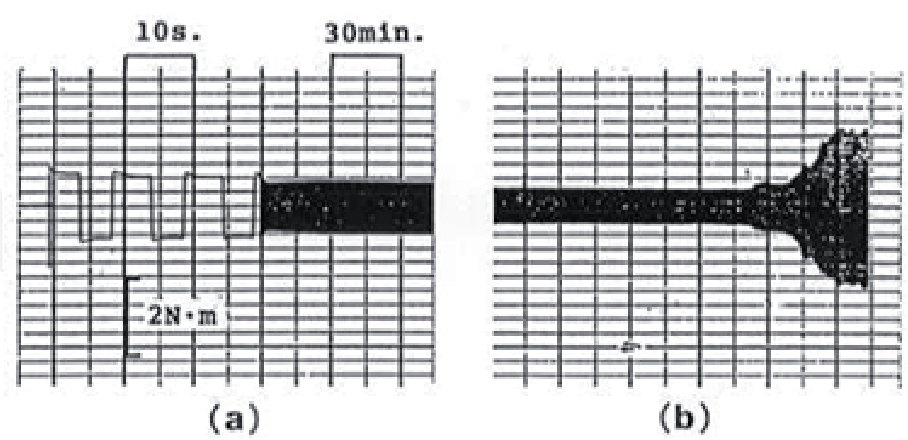

Figure 6.
Typical measured friction evolution [1].

amplitude was used as the frictional force. The friction gradually decreased with the number of oscillations and suddenly increased. This sudden increase point was used as the wear life of the lubricant.

Figure 7 [1] shows the appearance of the tested shaft. A part of the film lubricant was removed and the metal substrate was exposed and scratched. **Figure 8** [1] shows

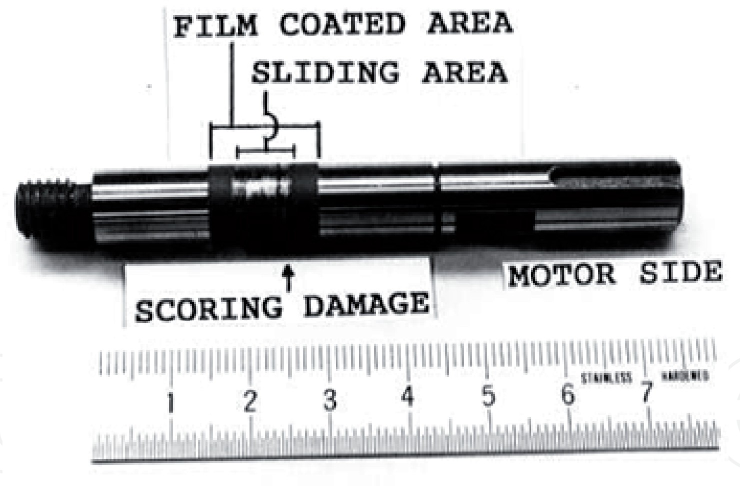

Figure 7.
Appearance of the tested shaft [1].

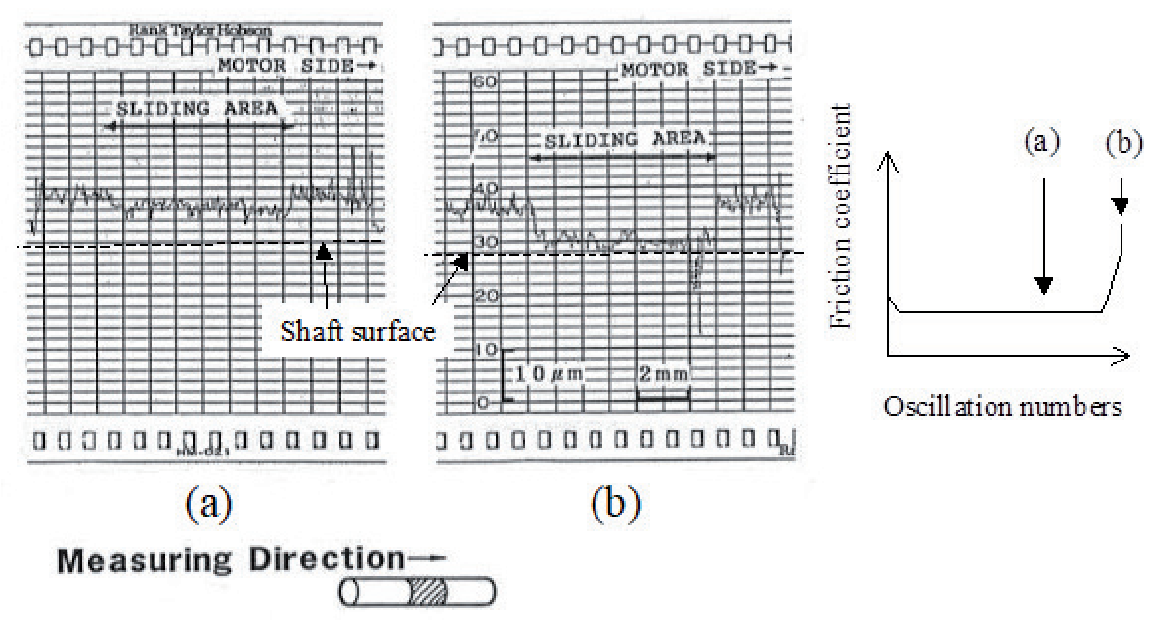

Figure 8.
Lubricant film profiles: (a) about 60% of wear life, (b) after the friction increase [1].

the lubricant film profiles of Set No.3 specimen in **Table 2** at the points (a) and (b) in the wear life shown in the right diagram. Most of the film thickness remained near the end of the wear life, and the scratched part was observed at the end of the test.

Figure 9 [1] indicated the wear life and friction coefficient of the tested combinations. There was no significant difference in the friction coefficients, but the wear life of the SUS304 was much longer than the others.

3.1.3 Discussion

It was observed that the film thickness of the lubricant gradually decreased, but it seems that the wear life suddenly came with most of the film thickness remaining. This form of wear has been observed in several previous studies [9, 10]. This means that specific wear rates cannot be used to predict wear life. In some studies, specific wear rates has been proposed for the wear life estimation of the bonded MoS_2 film lubricant [9, 11]. It may be used for relatively large sliding speed and low load conditions, but cannot be used for small sliding speed and high load conditions like this case.

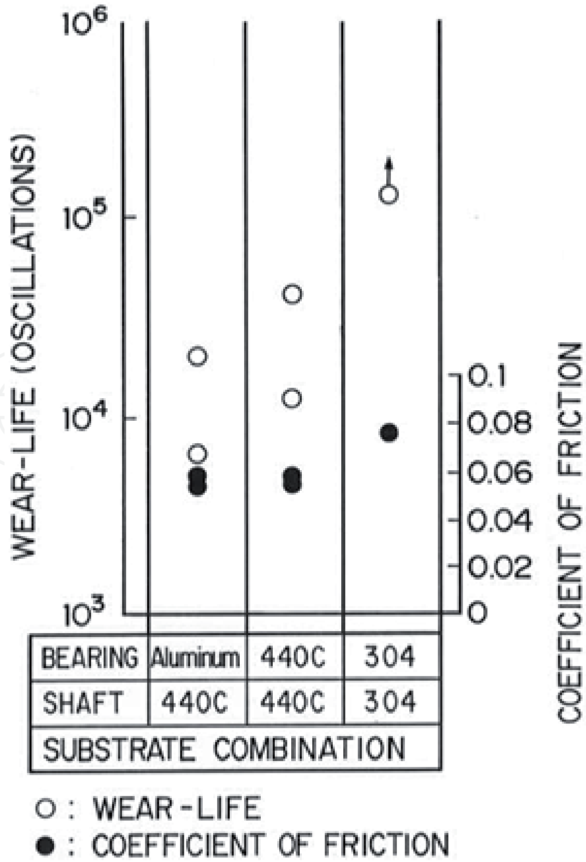

Figure 9.
Wear life and friction coefficient of the tested combinations [1].

The sudden decrease of the film is probably due to the de-bonding of the film from the substrate, possibly due to fatigue. The adhesion strength between the substrate and the film must affect the fatigue strength, that is, the wear life, and is strongly dependent on the anchoring effect by the surface morphology of the pretreated substrate.

The surface morphology of the pretreated substrate was investigated using "pretreated surface specimen" shown in **Figure 10** [1]. A portion of one side of a

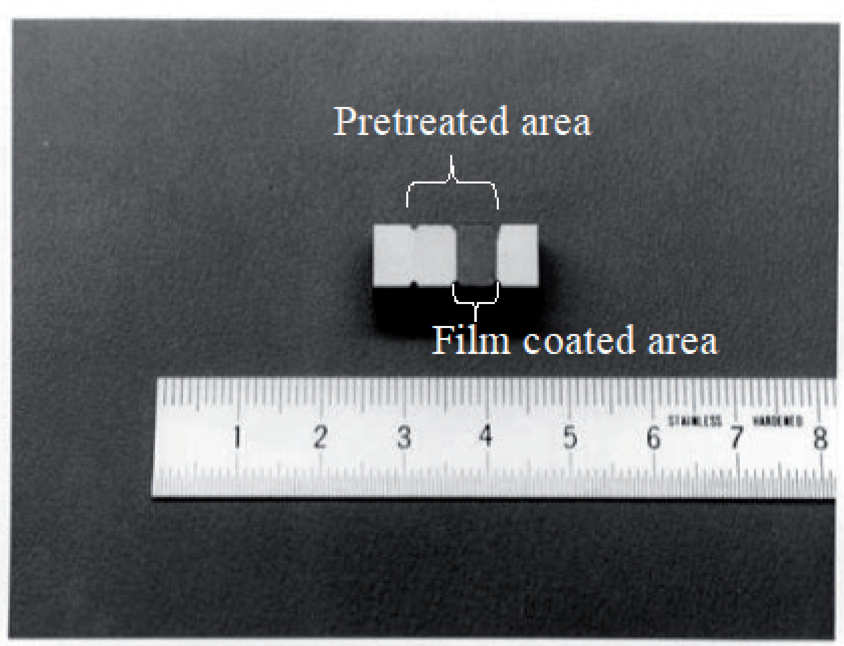

Figure 10.
Pretreated surface specimen [1].

rectangular metal specimen was pretreated and the bonded MoS_2 film lubricant was applied to half of the pretreated area. **Figure 11** [1] shows the surface profiles of the specimens. As shown in (a) and (c), the pretreated areas of the aluminum alloy substrate and the SUS304 stainless steel substrate had a roughness that went up and down across the original surface, while that of the SUS440C stainless steel substrate

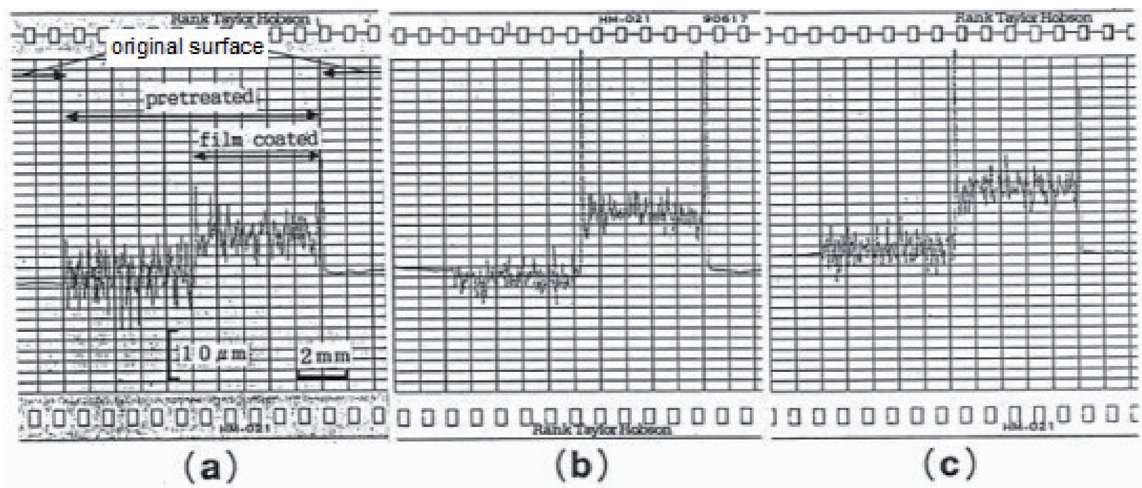

Figure 11.
Surface profiles of the pretreated surface specimens, (a) aluminum alloy, (b) SUS440C, (c) SUS 304 [1].

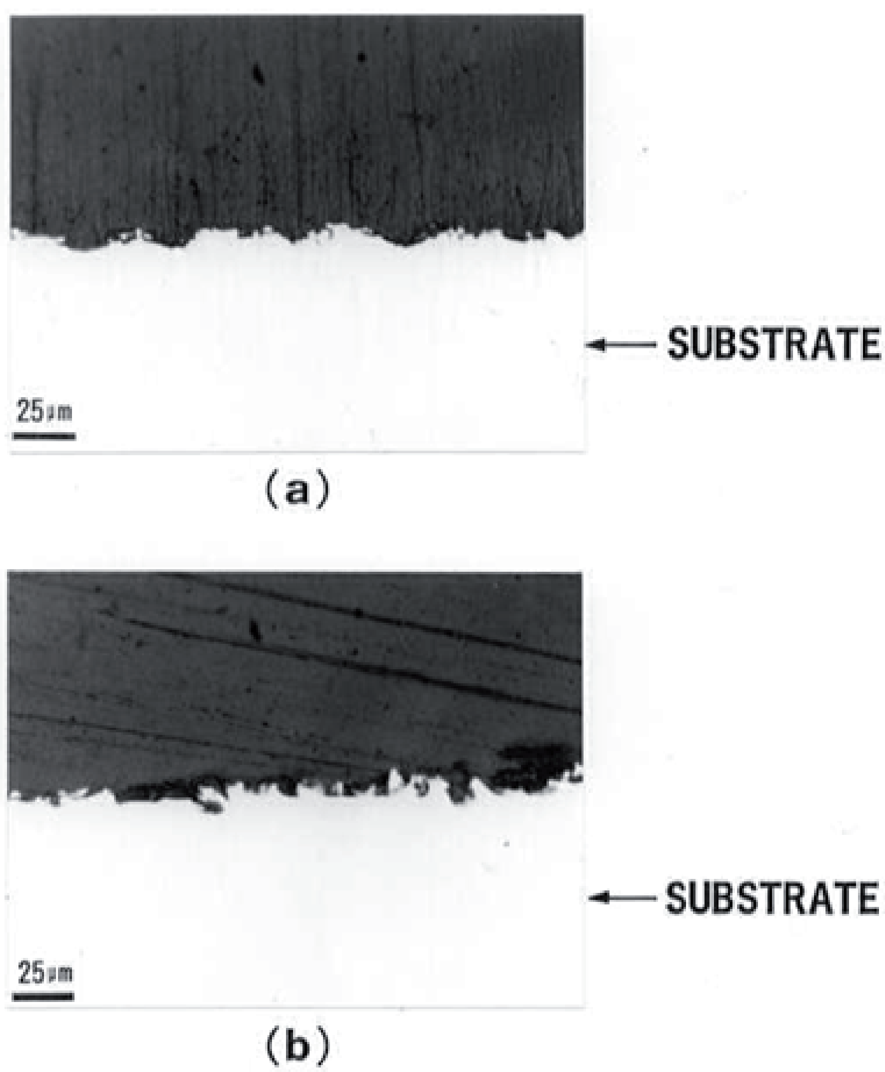

Figure 12.
Cross-sections of the pretreated surface specimens: (a) SUS440C substrate, (b) SUS304 substrate [1].

was below the original surface. This means that ductile metal surfaces such as aluminum alloy and SUS304 stainless steel (austenitic stainless steel) were deformed plastically by the blasting and that of brittle metal such as SUS440C (martensitic stainless steel) seems to have had its surface layer taken away by the blasting. This resulted in a characteristic surface morphology.

Figure 12 [1] shows the cross- sections of the pretreated surface specimens. The SUS304 specimen indicated the intricate surface morphology, while the SUS440C specimen had a monotonous wavy surface morphology. Probably these morphologies brought the strong adhesion between the substrate and the film, that is, the long wear life, to the SUS304 substrate and short wear life to the 440C substrate. The work hardening would also have contributed to the long wear life of the SUS304 substrate. The short wear life of aluminum alloy substrate could be attributable to the deformation of surface morphology by the load due to the lack of the hardness.

3.2 Effects of atmosphere

3.2.1 Experiment and results

Friction and wear life characteristics were investigated under various loads, sliding speeds in air and vacuum atmospheres using the test equipment used in Section 3.1. Test materials and test conditions are shown in **Table 4** [8] and **Table 5** [8], respectively. SUS630 is a precipitation hardened stainless steel with high strength, and was chosen for the shaft specimen in consideration of actual applications.

Figure 13 [8] shows a typical change in the friction coefficient with the number of oscillations in air and in vacuum. The friction coefficient was several times larger and the wear life was several ten times shorter in air than in vacuum. The relationship between the friction coefficient and the load is shown in **Figure 14** [8]. Friction coefficient used was in the steady state as shown in **Figure 13**. Friction coefficient was about 0.2 in air and about 0.05 in vacuum regardless of test conditions.

Figure 15 [8] shows the relationship between the bearing pressure and the wear life. The wear life refers to the number of oscillations when friction increased sharply. There are two groups, one in vacuum and one in air, with differences in wear life of hundreds of thousands of oscillations. It seems that there is no relationship between the groups.

3.2.2 Discussion

Figure 16 [8] shows the lubricant film profile at about 70% wear life in air, obtained under the same test conditions as No. 5 in **Table 5**. Most of the film thickness remained, as in the in-vacuum test shown in **Figure 8**. This suggests that the wear life in air, as well as in vacuum, is due to the de-bonding of the film from the substrate, and that the fatigue strength of the film-substrate interface may determine the wear life.

Fatigue strength of some metals are known to be affected by atmosphere and be larger in vacuum than in air (e.g. [12]). However, it has been shown that the propagation rate of fatigue cracks in epoxy resins is almost the same in both

Shaft material	JIS 630 stainless steel (precipitation hardened stainless steel)
Bearing bush material	JIS 304 stainless steel
Bearing bore, mm × length, mm	10 × 7, 5 × 7, 10 × 3.5
Bearing clearance, μm	~20

Table 4.
Test materials [7].

No.	Bearing bore × width (mm)	Load (N)	Bearing pressure (MPa)	Oscillational angle (deg.)	Angular velocity (deg. /s)	Atmosphere
1	10 × 7	5880	84	50	50	vacuum
2	10 × 7	1960	28	50	50	vacuum
3	10 × 7	980	14	50	50	vacuum
4	10 × 7	5880	84	50	50	air
5	10 × 7	1960	28	50	50	air
6	10 × 7	980	14	50	50	air
7	10 × 7	5880	84	50	5	vacuum
8	10 × 7	5880	84	50	5	air
9	10 × 7	1960	28	300	50	vacuum
10	10 × 7	1960	28	300	50	air
11	5 × 7	980	28	50	50	air
12	10 × 3.5	980	28	50	50	air

Table 5.
Test conditions [7].

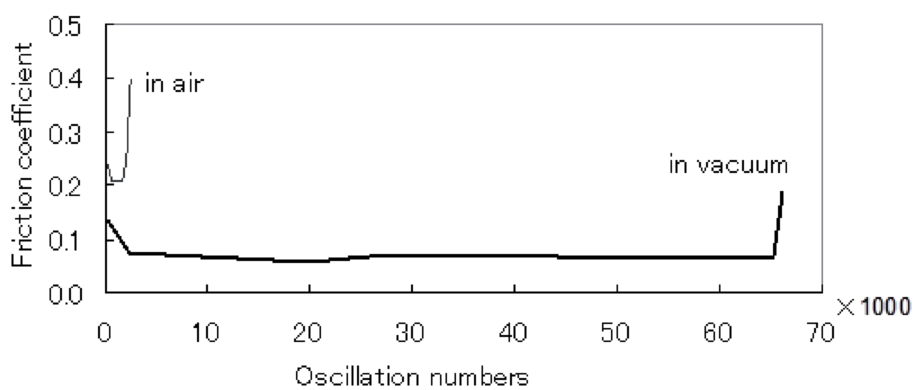

Figure 13.
Typical change in friction coefficient in air and in vacuum [7].

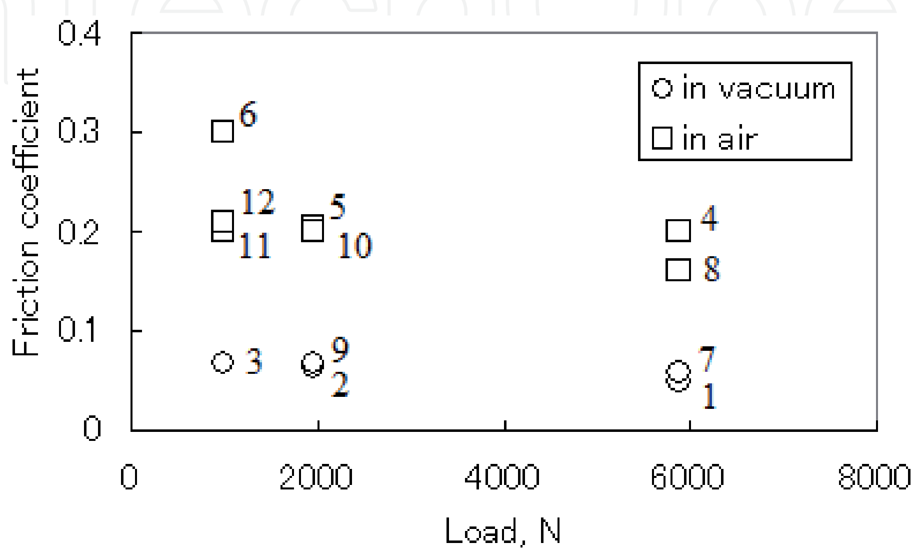

Figure 14.
Relationship between the friction coefficient and load [7]. The numbers correspond to those in ***Table*** *5.*

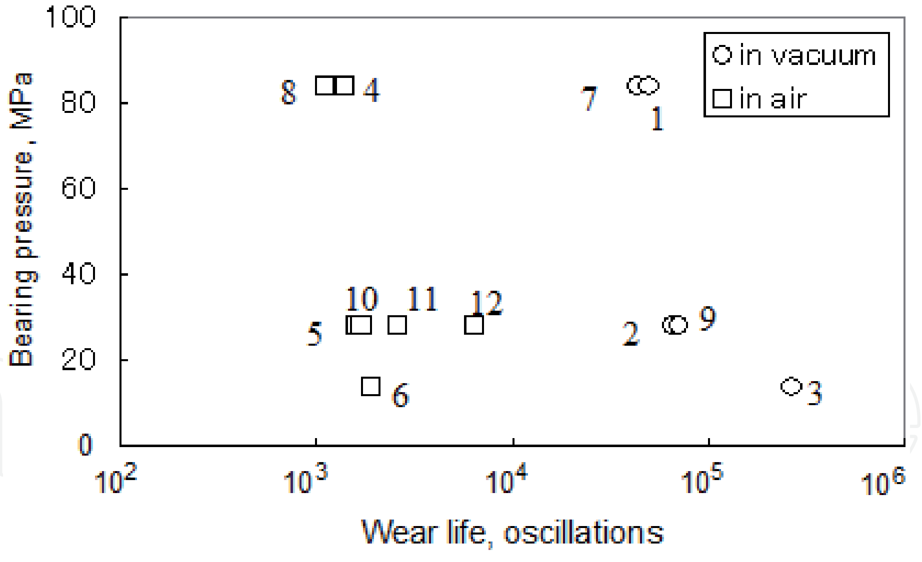

Figure 15.
Relationship between bearing pressure and wear life [7]. The numbers correspond to those in ***Table 5****.*

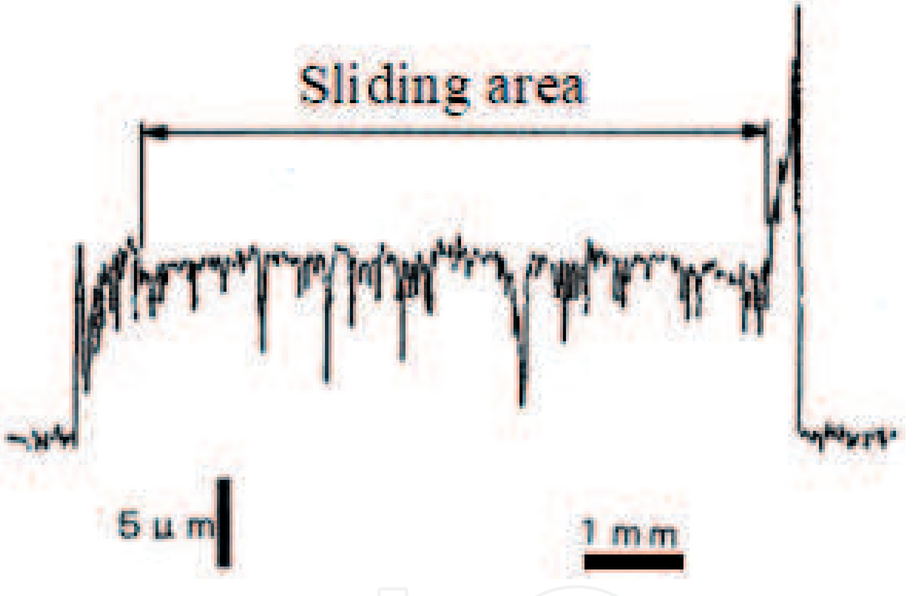

Figure 16.
Lubricant film profile at about 70% wear life in air [7].

vacuum and air [13], and in general, the fatigue of resins, which are the binders of the films, is considered to be less affected by the atmosphere. Therefore, the short wear life due to fatigue of film lubricants in air is not considered to be due to their reaction to the environmental atmosphere. The factor that differs between vacuum and air and is considered to affect fatigue is the friction coefficient.

Stress analysis was performed to investigate the effects of the friction coefficient on the stress in the film [8]. The analysis was performed as a plane strain perfect elasticity problem. Young's modulus of the film was measured in dry air to be about 10 GPa. Calculation conditions are shown in **Table 6** [8].

Figure 17 [8] shows examples of the calculated stresses in the film. Since the film thickness is small compared to the contact length, the stress is almost constant in the depth direction of the film.

Figure 18 [8] shows the relationship between the maximum shear stress at the interface between the film and the substrate in the direction parallel to the interface and wear life. All points are on a straight line, whether they are in vacuum

	Film thickness (μm)	Young's modulus of film (GPa)	Poisson's ratio of film	Young's modulus of substrate (GPa)	Poisson's ratio of substrate
	10	**10**	**0.3**	**197**	**0.3**
No.	**Bearing bore (mm)**	**Shaft diameter (mm)**	**Line load (N/mm)**	**Friction coefficient**	**Corresponding test numbers**
1	10.02	10	840	0.05	1, 7
2	10.02	10	280	0.05	2, 9
3	10.02	10	140	0.05	3
4	10.02	10	840	0.2	4, 8
5	10.02	10	280	0.2	5, 10, 12
6	10.02	10	140	0.3	6
7	5.02	5	140	0.2	11

Table 6.
Calculation conditions [7].

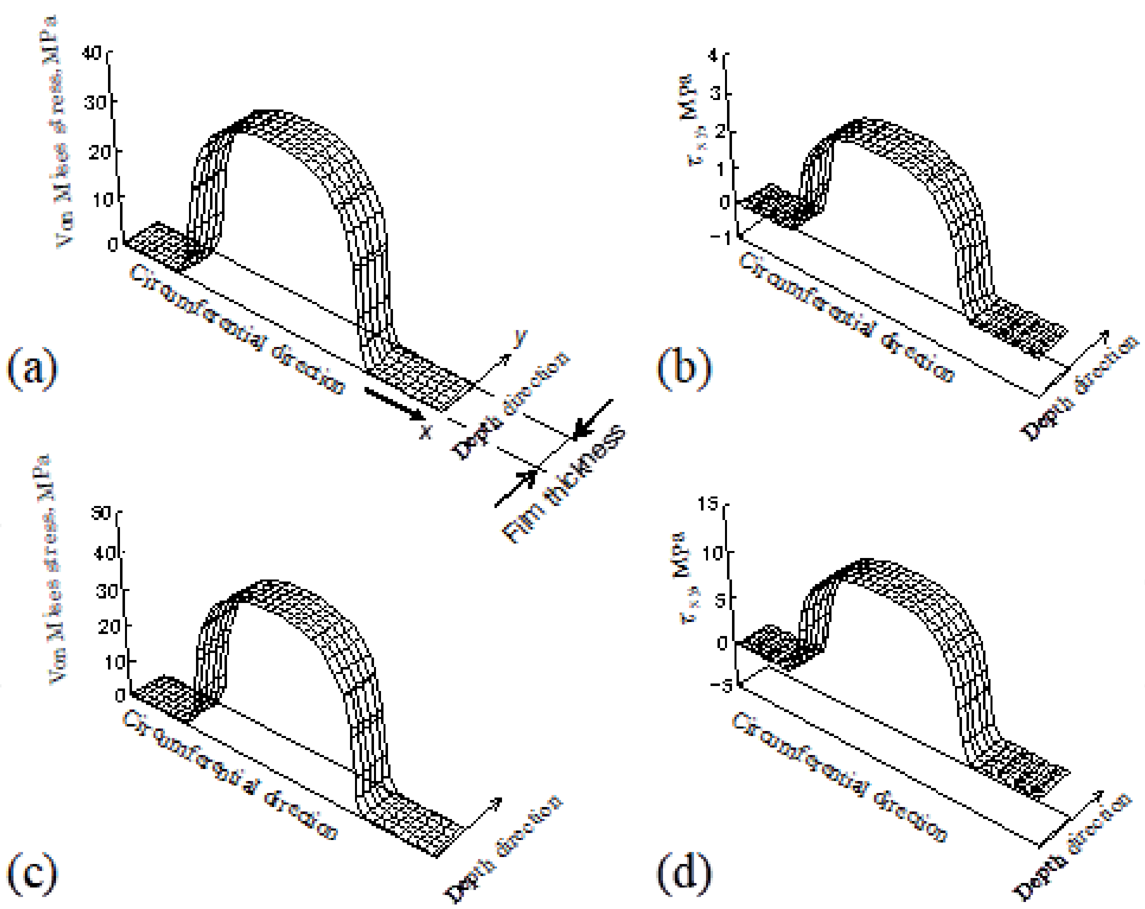

Figure 17.
Examples of calculated stresses in the film [7].

or in air. This is a typical S-N curve for fatigue phenomenon. Therefore, the wear life of the bonded MoS_2 film lubricant can be attributed to fatigue due to shear stress at the interface. Since the contact width is much larger than the film thickness, the shear stress at the interface is almost the same as the shear stress at the film surface, i.e., the product of the friction coefficient and the contact pressure,

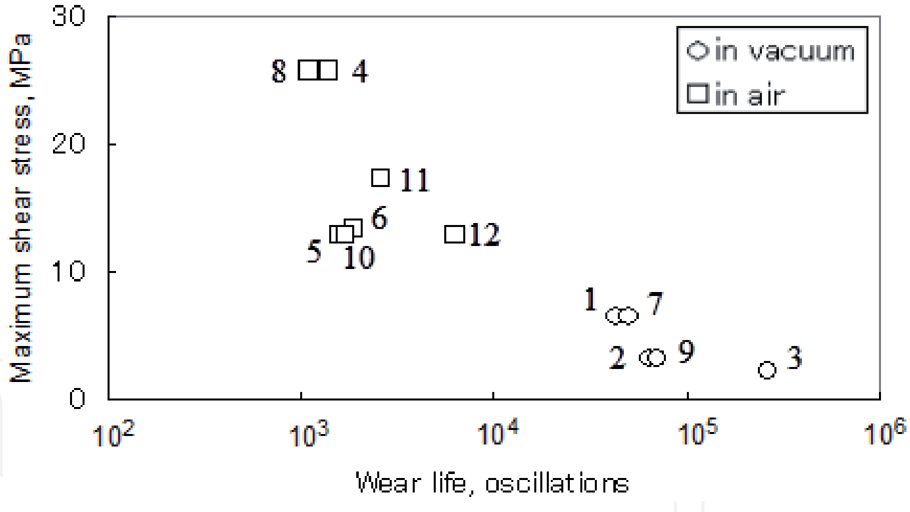

Figure 18.
Relationship between the maximum shear stress at the interface between the film and the substrate and wear life [7].

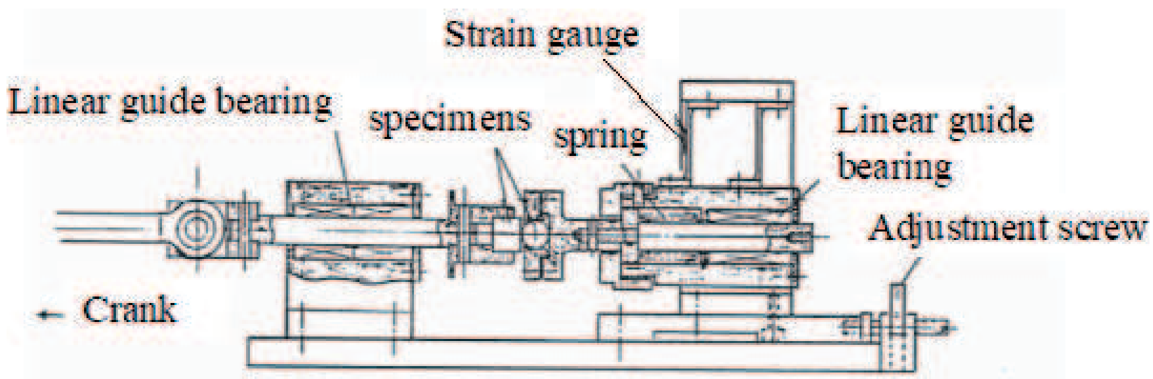

Figure 19.
Repeated vertical loading machine [13].

as shown in **Figure 17(b)** and **(d)**. Since the maximum von Mises stress, which contains a large component of vertical loading, did not show the same relationship as the shear stress, damage inside the film is not considered to be the cause of wear life in this case. Thus, the difference in wear life between vacuum and air is due to the friction coefficient between vacuum and air.

The effect of repeated vertical loading was investigated separately. **Figure 19** shows the "repeated vertical loading machine" [14], in which the bonded MoS_2 film lubricant on the flat surface was subjected to the repeated vertical pressure by a steel ball with 5/16 in. (~7.9 mm) diameter. A sinusoidal load of 0.98 N to 4.4 N was applied at a frequency of 1000 cpm.

Only dents with a few micrometer depth were observed on the tested lubricant films after more than 10^7 times loading, as shown in **Figure 20** [14], and no de-bonding was observed. Hence, the repeated shear stress, i.e. the friction, rather than the repeated vertical load causes the de-bonding of the film lubricant.

4. Conclusions

Wear life of bonded MoS_2 film lubricants was found to be caused by de-bonding of the film from the substrate due to fatigue under relatively high load and low speed condition. In order to improve wear life, it is important to select substrate materials with appropriate surface morphology through pretreatment to provide

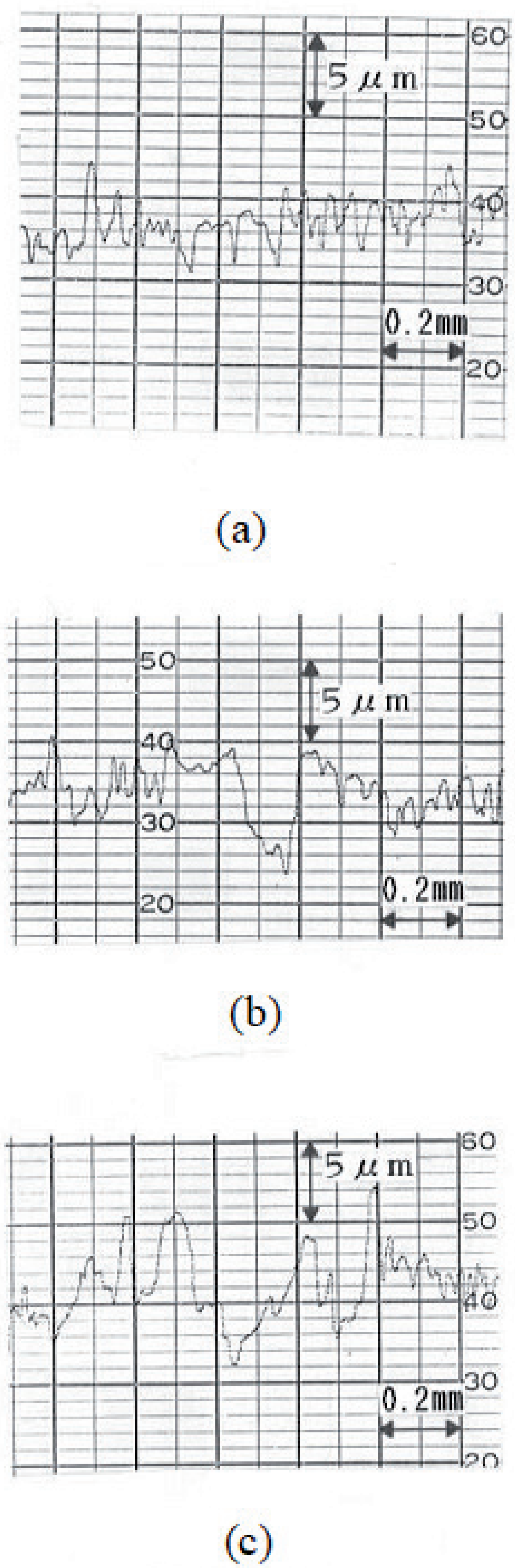

Figure 20.
Surface profiles of the film after the tests: (a) static loading, (b) 1 × 10^7 loadings, (c) 4.4 × 10^7 loadings [13].

strong adhesion to the film. The specific wear rate, which assumes that the amount of wear of the material is constant according to the load and sliding distance, is not suitable for estimating the wear life of bonded MoS_2 film lubricants under these conditions.

When the thickness of the film is much smaller than the contact length, as in the case treated here, the frictional force directly becomes the shear force at the interface, which determines the fatigue life of the film-substrate adhesion. In other words, the friction coefficient has a direct effect on the wear life of the film lubricants. It was shown that the wear life of bonded MoS_2 film lubricant in vacuum is much longer than in air. This is because the friction coefficient in vacuum is much smaller than in the air.

In order to improve the wear life in air, it is effective to reduce the friction coefficient in air. It is the moisture in air that increases the friction of MoS_2 in air. Attempts to reduce the friction in air, such as adsorbing a surfactant on MoS_2 to prevent the adsorption of water molecules and thus imparting hydrophobicity to MoS_2 [15], are expected to expand the application fields of bonded MoS_2 film lubricants.

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