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Development of Solid-Lubricated Ball-Screws for Use in Space

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Abstract

The purpose of this study is to develop ball-screws lubricated by solid lubricant films containing molybdenum disulphide. The ball-screws (shaft diameter: ϕ 25mm, length: 667mm) were operated under a load of 40 to 120N at a speed of 1.5 to 200 rpm at 10^{-6} Pa. First, ball-screws made of stainless steel SUS 440C were studied using test equipment originally designed for this study. To reduce weight, the next step taken was to develop a ball-screw made of 6Al-4V-Titanium.

Long wear-life of more than 1×10^7 revolutions was achieved with solid lubricated ball-screws made of SUS440C and 6Al-4V-Titanium in a hard vacuum. According to the surface profile of the shaft measured after 1×10^7 revolutions, more solid lubricant remained on the surface of 6Al-4V-titanium than that of stainless-steel. Auger and EPMA analysis confirmed lubrication was maintained by solid lubricant on nuts and screws after the lubricant films on the balls were worn off.

Introduction

Rotating parts of space mechanisms are supported by sliding and rolling bearings. Among them a ball-screw provides a unique function: changing linear motion to rotation or vice versa with high energy efficiency. The need for a ball-screw for space use has been increasing, as space structures become larger and more complicated. For instance, a deployable test bed[1] will be realized only when a solid-lubricated ball-screw is employed. However, the friction and wear mechanism for a ball-screw for space use, when lubricated by a solid lubricant, remains unsolved. A limited number of papers referred to this unique machine element for space use[2,3].

Tribological behavior of a ball screw is of particular interest because it operates under a rolling-sliding frictional condition which is somewhat different from rolling or sliding friction.

This paper describes research and development of ball-screws

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lubricated by inorganic-bonded molybdenum disulphide films.

Experimental Procedures

1) Test Equipment

Fig. 1 shows the schematic diagram of the apparatus originally designed for this experiment. A shaft is set up vertically in the vacuum chamber and load is put on a nut by a dead weight. Lubrication characteristics of a ball-screw were studied by measuring frictional torque variation using strain-gages bonded on a plate spring which was set between a magnetic feedthrough and a ball-screw rotating shaft. Accordingly, the measured friction torque represents that of a ball screw and supporting bearings.

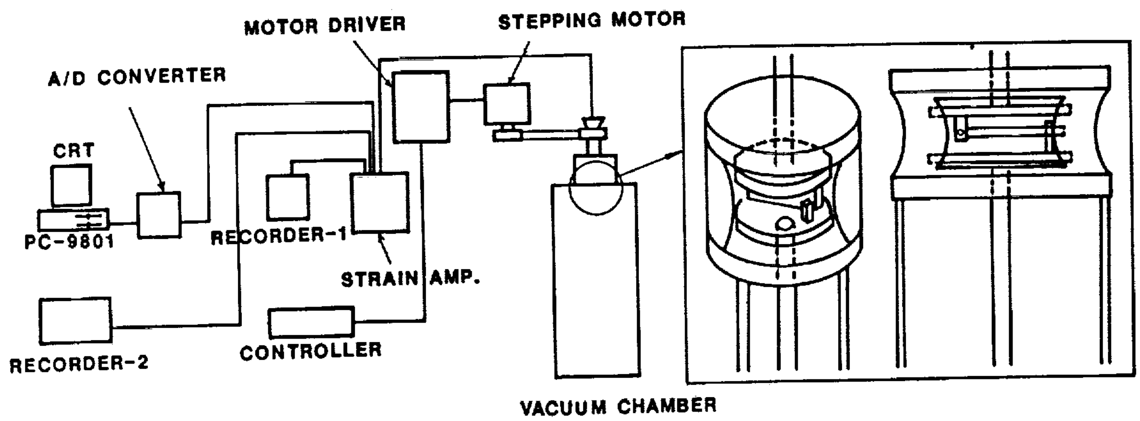

Figure 1 Schematic diagram of Apparatus

2) Test Specimens

The shape and size of ball-screw specimens used in this study are presented in Table 1 and Fig. 2. A ball-screw consists of three components: a screw shaft, 25mm in diameter and 667mm length with 6mm pitch, balls, and a nut with circulation parts. We selected two materials for a shaft and a nut. One is stainless steel, the other is 6Al-4V-titanium. Balls were made of stainless steel SUS 440C (equivalent to AISI 440C) and have diameter of ϕ 5/32"(ϕ 3.969mm). All parts were coated with an inorganic-bonded molybdenum disulphide film.

Table 1 Specification of Testpiece

Shaft Diameter	Φ25
Lead	6mm
Ball Diameter	5/32"(3.969mm)
Material	Stainless Steel Ti alloy
Lubricant	MoS_2 Solid Lubricant

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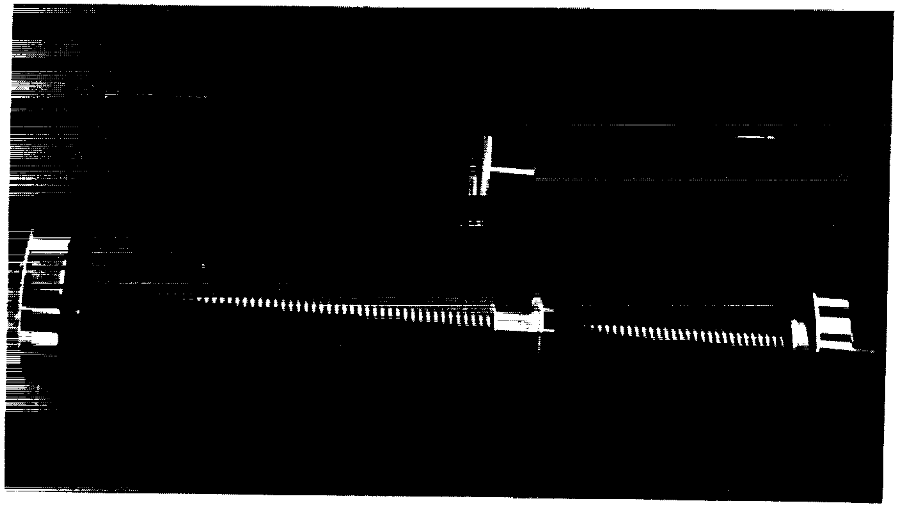


Figure 2 Ball Screw and Dead Weight

3) Test Condition

Test conditions are given in Table 2. Pressure in the test chamber was kept less than 10^{-6} Pa during testing. Tests were carried out at room temperature under an axial load of 40(Hertzian Contact Pressure: 95.6 MPa) to 120 N(157.7 MPa). The rotational speed of a shaft was typically 200 rpm but in some cases it was varied from 1.5 to 200 rpm in order to know the effect of rotational speed. Tests were terminated either when the frictional torque exceeded 2.5 N·m, or when the total number of rotations was over 1×10^7 revolutions.

Table 2 Test Conditions

Pressure	10^{-6} Pa
Load	40N~120N
Temperature	Room Temperature
Rotational Speed	1.5~200rpm

Results and Discussion

Stainless Steel Ball-Screws

Table 3 summarizes all test results obtained with stainless steel ball-screws. Three specimens used were designated as 001, 002 and 003.

Testpiece 001 was run under a load of 95.6, 109.3, 137.7, and 157.7 MPa(Hertzian contact pressure). The operating stroke of the nut was shortened whenever the load was increased. This made the comparison of shaft surfaces under different load conditions possible. Changes of friction torque with increase of load are presented in Fig. 3. Surface roughness and surface profiles of the shaft after the test are given in Table 3 and Fig. 4, respectively.

Table 3 Test Results of 440C Ball Screws

T/P No.	Hertzian Contact Pressure (MPa)	Total Number of Spins (rev.)	Surface Roughness (μm)		Film Thickness (μm)
			R a	Pk. to Valley	
001	(a) 95.6	6.74×10^{6}	1.36	10.28	1.0
	(b) 109.3	1.34×10^{6}	1.40	14.51	1.0
	(c) 137.7	0.79×10^{6}	2.13	17.89	1.0
	(d) 157.7	0.70×10^{6}	3.37	25.76	1.0
002	157.7	1.00×10^{6}	1.42	12.78	1.0
003	157.7	1.40×10^{7}	0.08	1.51	3.0

Friction torque exceeded the upper limit of 2.5 N·m when the specimen performed 6.74×10^{6} revolutions. The specimen was disassembled and inspected with the naked eye. No damage was found except accumulation of wear debris. Therefore, debris was taken away and the operation was restarted under a higher load of 109.3 MPa for 1.34×10^{6} revolutions. Since the friction torque remained stable, the load was increased to 137.7 MPa for 0.79×10^{6} revolutions and then to 157.7 MPa for 0.7×10^{6} revolutions when the friction torque finally reached the limit of 2.5 N·m.

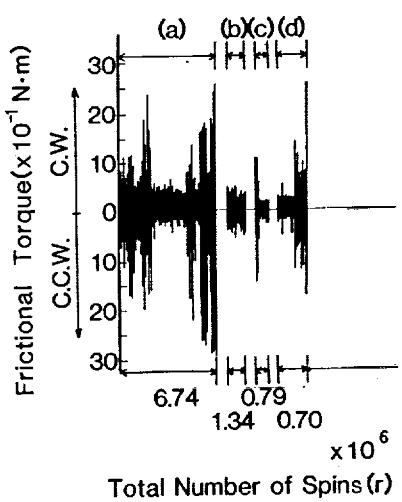
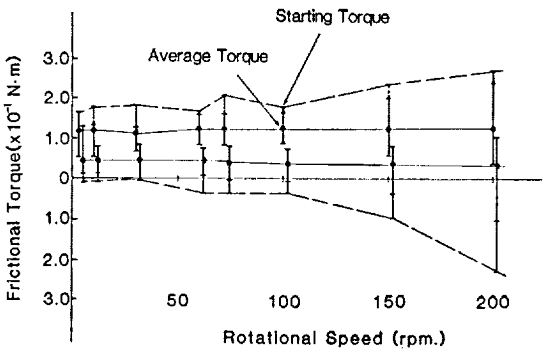


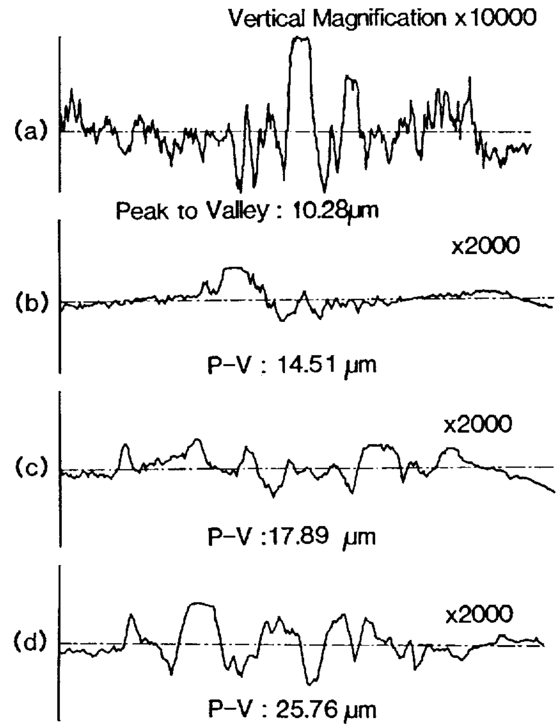
Figure 3 Variation of friction torque

Figure 5 illustrates variations of maximum and average friction torque at different speeds; these variations were measured



↑ Figure 5 Effect of rotational speed on friction torque of specimen 001

→ Figure 4 Surface profile of specimen 001



under a load of 95.6 MPa after the ball-screw was run about 4 x 10^6 revolutions.

At 100 rpm, both maximum and average torque are independent of rotational speed. They increased gradually as rotational speed exceeded 100 rpm.

When the frictional torque was stable, the calculated mechanical efficiency of the ball-screw was 0.95. This efficiency is almost as high as that of a conventional grease-lubricated ball-screw.

To know the wear life under the heaviest load(157.7 MPa), the specimen 002 was operated successively until the film was worn off. Variation of friction torque is presented in Fig. 6. Friction torque exceeded 2.5 N·m at 1 x 10^6 revolutions.

In general, torque behavior is divided into three stages as seen

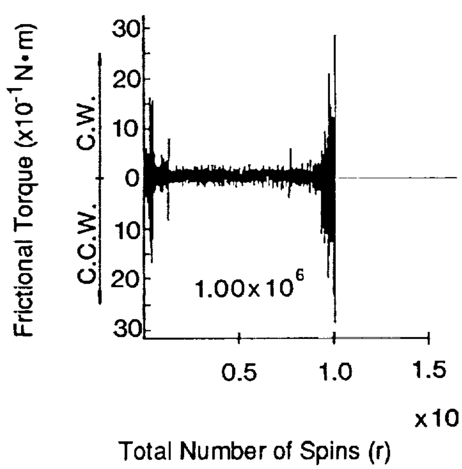


Figure 6 Variation of friction torque of specimen 002

in the Figure. The first stage represents an initial running-in process and is characterized by relatively high and unstable friction torque. In the second stage, friction torque becomes stable and good lubrication is maintained. In the third stage, friction becomes irregular.

Under a load of 157.7 MPa, the film lost lubricating ability after only 1x10^6 revolutions. Therefore, thicker film(thickness:3 μ m) was tested with the specimen 003. To avoid blocking of operation caused by wear particles, which was observed in the specimen 001, wear particle reservoirs were prepared in the nut. The result is seen in Fig. 7. Though the test was interrupted at 1.4 x 10^7 revolutions, no sign of film rupture was found.

Figure 7 Variation of friction torque of specimen 003

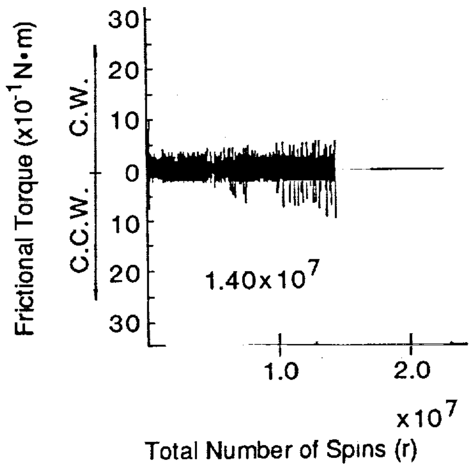


Fig. 8 indicates surface profiles of the shaft. As shown in Fig. 9, measurements were made at four points: virgin area(point A), near end point of operating region(point B), loaded side(point C) and unloaded side(point D) of operating region. By comparing to virgin area where Ra is 0.59 μ m and P-V(peak to valley) is 4.54, we find the loaded side of operating area

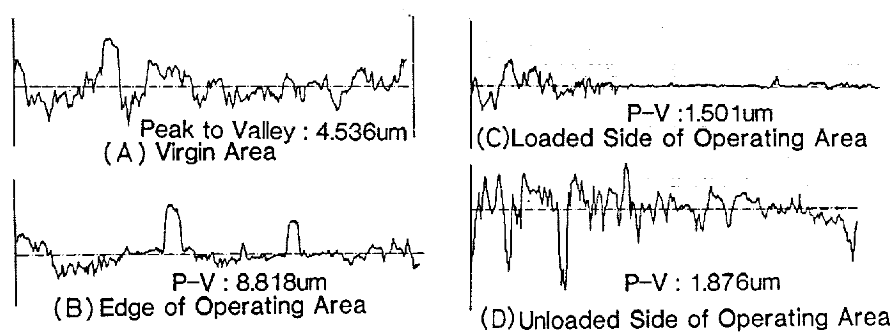
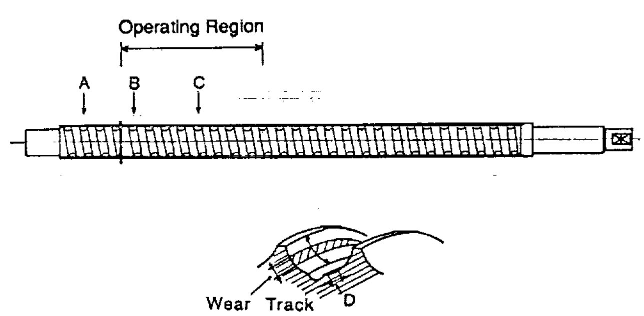


Figure 8 Surface profile of specimen 003 after test

Figure 9 Surface profile test points



(point C) has the surface roughness Ra of 0.08 and P-V of 1.5. This shows the solid lubricant film is worn away almost to the substrate surface. However, EPMA analysis indicated the existence of solid lubricants.

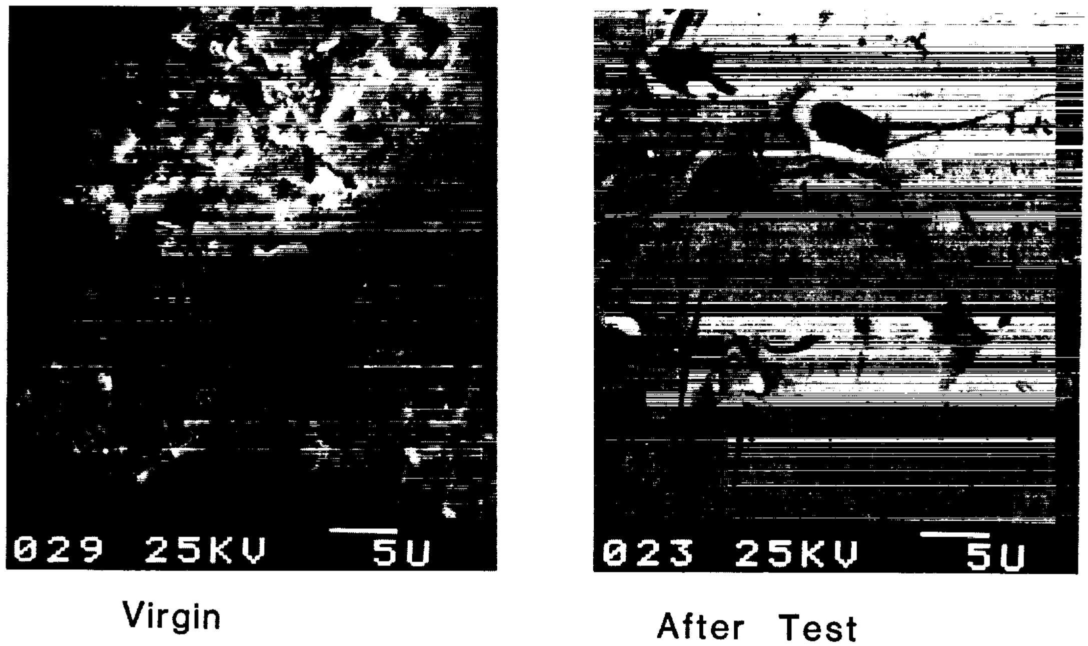


Figure 10 SEM picture of ball surface before and after test

Solid lubricants were found on loaded areas of the shaft but not on balls. Figure 10 compares a SEM picture of a virgin ball and that of a tested ball. The ball surface after test seems to have no lubricant film. This was confirmed by analysis using a Scanning Auger Microprobe Analyzer (Fig. 11 in the next page). Elements of solid lubricant films found on the ball before test(Mo, S, Ag and Sb) were lost on the tested ball. Operation of the ball-screw was not affected, as seen in Fig. 7. Thus, lubrication was maintained by films remaining on the shaft and nut after solid lubricants on balls were exhausted.

Ti-6Al-4V Ball-Screw

To reduce weight, a ball screw made of 6Al-4V-Ti alloy was developed. 40 % reduction in weight was achieved by changing material from stainless steel to titanium alloy.

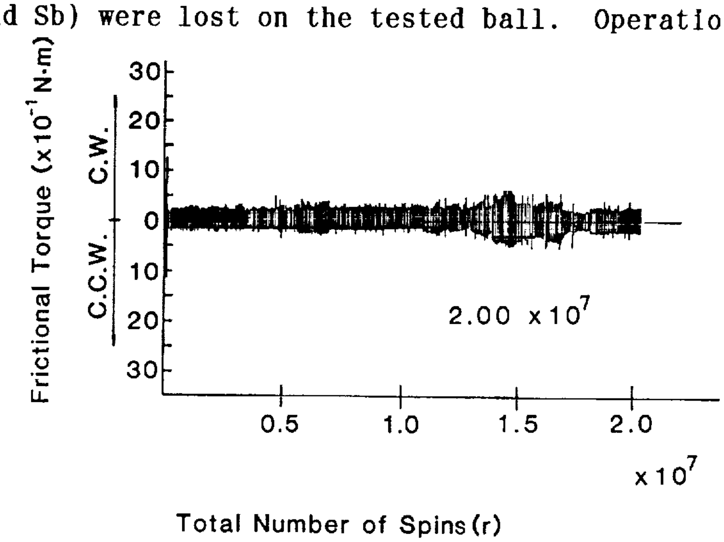
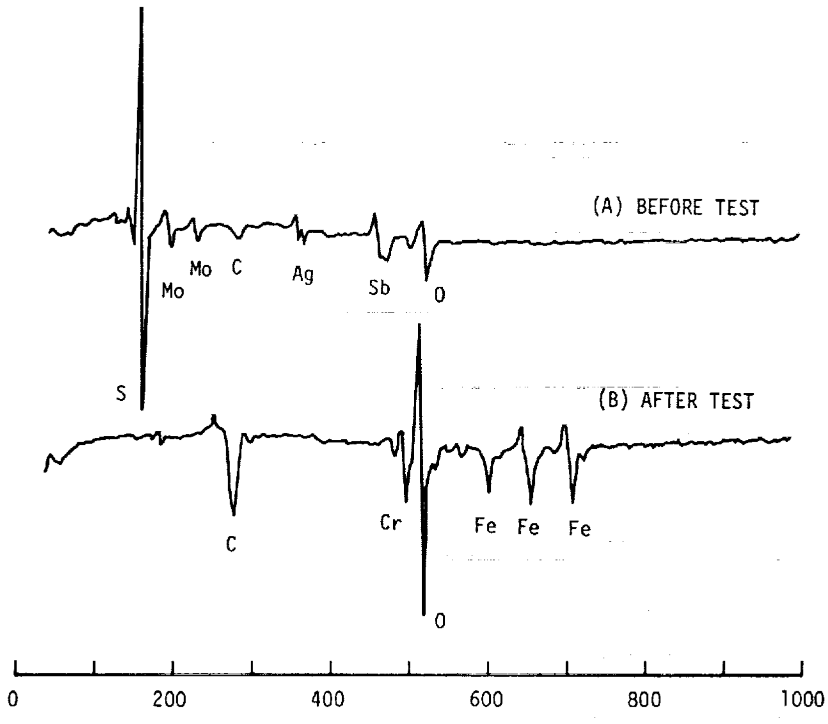


Figure 12 Variation of friction torque of 6Al-4V-Ti ball-screw

Figure 11 Auger spectrum of ball of specimen 003 before and after test



This Ti-6Al-4V ball screw was examined under the same conditions(157.7 MPa and 200 rpm) as the stainless-steel ball-screw 003. Variation of friction torque is given in Fig. 12. The specimen was successfully run to 2.0×10^7 revolutions. It exhibited low friction and a friction pattern similar to the stainless-steel ball-screw.

Surface profiles of the shaft are shown in Fig. 13. Figure 14 presents pictures of the shaft surfaces. EPMA analysis revealed that again, no component of the film was found on the ball surface.

However, more solid lubricant seems to be left on the titanium alloy shaft than on the stainless-steel shaft. Considering the fact that the Ti shaft was operated 6×10^6 revolutions more than the 440C shaft, we conclude that the newly-developed 6Al-4V-titanium ball-

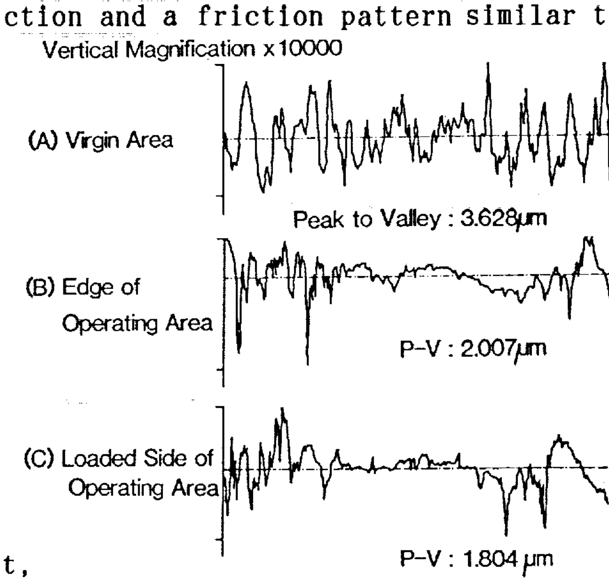
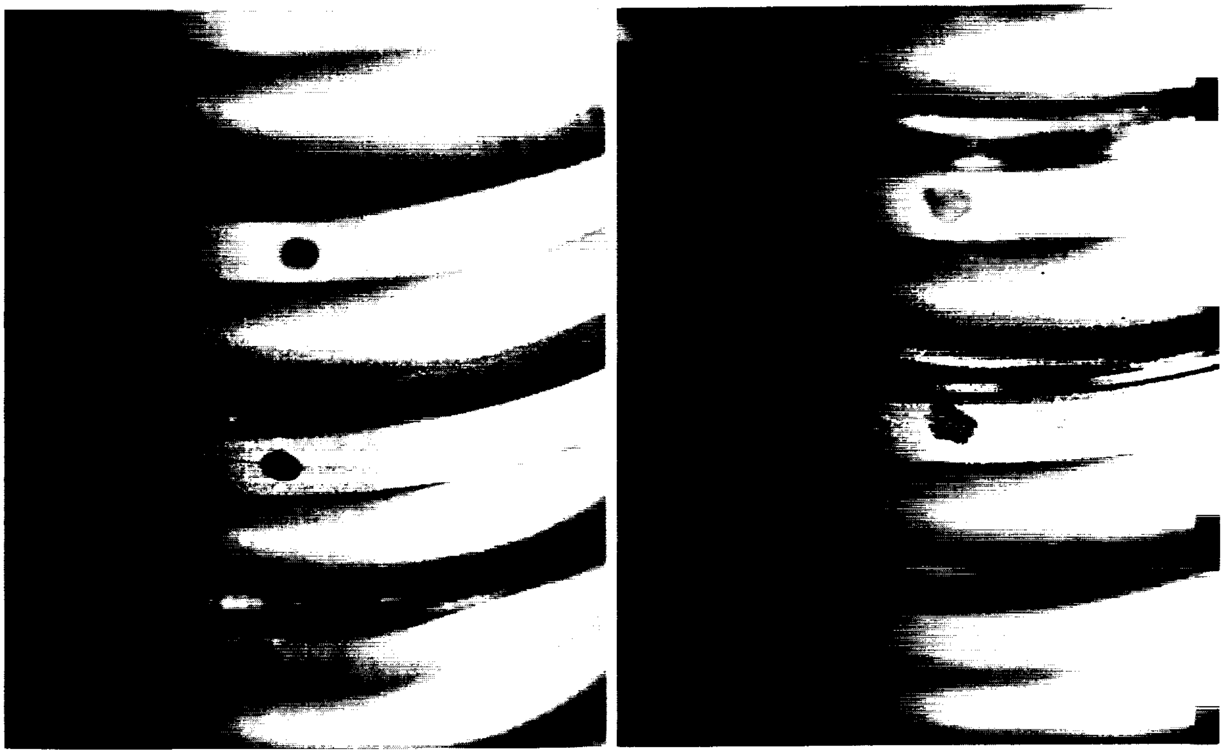


Figure 13 Surface profile of titanium alloy shaft

Figure 14 Surface of titanium shaft after test



(A)Virgin Area

(C)Loaded Side of Operating Area

screw possesses better performances than 440C ball-screw.

Conclusion

Solid lubricated ball-screws made of stainless steel and titanium alloy were tested in ultra-high vacuum and found to be applicable to space mechanisms. A 40 % reduction in weight was possible with a newly-developed 6Al-4V-Ti ball-screw compared to a stainless-steel one. The titanium alloy ball-screw demonstrated better lubricating ability than that of SUS 440C. Obtained results can be summarized as follows:

(1)Long wear-life of more than 1 x 10^7 revolutions was achieved with ball-screws lubricated by an inorganic-bonded film under a load of 157.7 MPa at 200 rpm at 10^{-6} Pa.
(2)A 6Al-4V-titanium ball-screw was developed and exhibited longer wear life than ones made of 440C.
(3)The mechanical efficiency of the tested solid lubricated ball-screw reaches 0.95 under good lubricating conditions.

References

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