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Comparison of Several Different Sputtered Molybdenum Disulfide Coatings for Use in Space Applications

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Abstract

Tribology experiments on different types of sputtered molybdenum disulfide (MoS_2) coatings (obtained from different vendors) using accelerated testing techniques were conducted. The purpose was to determine which would be the best coating for use with auxiliary journal bearings for spacecraft energy storage flywheels. Experiments were conducted in moist air (50% relative humidity) and in dry air (<100 PPM water vapor content) on a Pin-on-Disk Tribometer to determine how well the coatings would perform in air. Experiments were also conducted on a Block-on-Ring Tribometer in dry nitrogen (<100 PPM water vapor) to simulate how well the coatings would perform in vacuum. Friction, counterface wear, coating wear, endurance life and surface morphology were investigated.

Introduction

NASA Glenn is currently developing magnetic bearings to be used for levitating energy storage flywheels for the International Space Station and for satellites. To insure safety (if magnetic bearings should fail) and to prevent damage from "bumps," mechanical auxiliary bearings must also be developed for this application. Several different types of mechanical bearings are being considered as well as several different lubrication systems. If solid lubricants are selected, the one with the longest endurance life with reasonable friction and wear properties in a vacuum environment is the most desirable. However, many of the MoS_2 based lubricants being considered do not work well in ambient air. It is possible that exposure or mishandling in air might reduce the life or performance solid lubricant used for an auxiliary bearing. Thus it is desirable to choose a solid lubricant that works well under all environmental conditions.

Sputtered MoS_2 coatings were chosen for this study because they have been shown in many previous studies to be excellent lubricants in a vacuum environment [1-7]. The problem is that MoS_2 oxidizes in air [8-15] and can lead to damage to the coatings before they even get into space. Recently, new sputtered MoS_2 coatings have become available and have been tested [16-20] that are co-sputtered with various materials that improve their performance in air.

In order to help determine which of these coatings might be the best for this application, an accelerated testing program was developed to evaluate their tribological properties of these coatings under different environmental conditions. This paper deals with tribological accelerated tests on several different sputtered molybdenum disulfide (MoS_2) coatings in a 50 percent relative humidity (~10,000 PPM moisture content) air atmosphere and in a very dry air atmosphere (<100 PPM moisture content) using a Pin-on-Disk Tribometer. In addition, the same coatings were also evaluated in a dry nitrogen atmosphere (<100 PPM moisture content) using a Block-on-Ring Tribometer to simulate a vacuum condition.

Materials

Six different sputtered MoS_2 coatings were evaluated that were supplied from 5 different vendors. Table 1 lists the vendors and the additives in the films. The coatings were applied to the disks of the Pin-on-Disk Tribometer and to the rings of the Block-on-Ring Tribometer. A few Block-on-Rings tests were also conducted with blocks that were coated with the CSEM-Ti or CSEM-Al coating. The disks, blocks and rings used in this study were made of 440C stainless steel with a Rockwell hardness of C-57 to C-59. The disks were lapped and polished to a surface finish of 0.040 ± 0.015 µm centerline average (CLA). Instead of using pins in the Pin-on-Disk Tribometer, the pin holder was modified to hold and constrain from rolling

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a 0.476 cm radius (3/8 inch diameter) commercial grade 10, 440C ball that had the same surface roughness as the disks. The hardness of the balls was Rockwell C-60.

Table 1. Types of MoS_2 Coatings Evaluated in this Study.

Vendor's Name	Designation	Major Additive	Coating Thickness(μm)
Movic	Movic	None	0.6
Surftech	Surftech	None	0.3
Hohman Plating	Hohman	Antimony Trioxide	1.2
Teer	Teer-Ti	Titanium	1.2
CSEM	CSEM-Ti	Titanium	2.4
CSEM	CSEM-Al	Aluminum	3.5

Testing Apparatus

Pin-on-Disk Tribometer

The pin-on-disk Tribometer used in this study (Figure 1) has been described in detail in Reference 21. The specimens consisted of a flat rotating disk (6.3-cm diameter) in sliding contact with a stationary ball (0.476-cm radius) that was securely fastened in a holder. The ball slid on disk tracks that ranged from 6.0 cm to 4.4 cm in diameter. The rotational speed of the disk was controlled at 200 rpm giving linear sliding speeds of 0.63 to 0.46 m/s. The test specimens were encased in a plastic box to control the atmospheric moisture content. The load of 9.8 N (1 kg) was applied to the ball by a dead weight using a lever arm system. A strain gage was used to monitor and measure the frictional force.

Wear volume of the ball was determined by measuring the change in diameter of a wear scar on the ball and then calculating the volume of material removed. Wear volume of the disk was determined by measuring the wear track cross-sectional area using a surface profilometer and then calculating the volume of material removed. A discussion on how to evaluate solid lubricants in a pin-on-disk tester is given in the next section and in the reference by Fusaro [21].

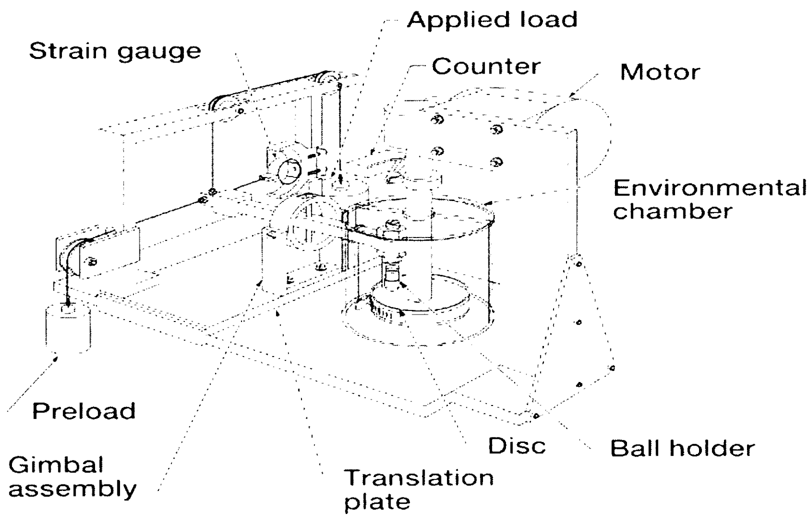


Figure 1. Schematic of Pin-on-Disk Tribometer

Block-on-Ring Tribometer

A schematic of the block-on-ring test elements is shown in Figure 2. As shown in the figure, the device consists of a rectangular block (0.6 cm wide x 2 cm long x 1 cm high) pressed against the periphery of a ring (1 cm wide x 5 cm diameter). The block can be flat (line contact) or it can be conforming (area contact). In this study only line contact was used.

The block and the ring used in this study were made from 440C stainless steel. The block was stationary and loaded with a dead weight against the ring. The ring was attached to a rotating shaft that can rotate in one direction. A probe attached to the block holder contacts a load transducer and measures frictional force between the block and the rotating ring. A thermocouple is imbedded near the contact area of the block to measure temperature.

The coating was applied to the contact area around the outside diameter of the ring and to the (0.6 x 1.5 cm) face of the block. In all cases, the surface roughness of the block is very important and can influence the results. To most closely reproduce the end-use application, the roughness should closely match that value. In this case, the surfaces were very smooth (0.05 to 0.10 X 10^{-6} m R_a). The sliding conditions for the block-on-ring test were as follows: sliding speed, 500 rpm, load, 225 newtons, temperature, 25°C.

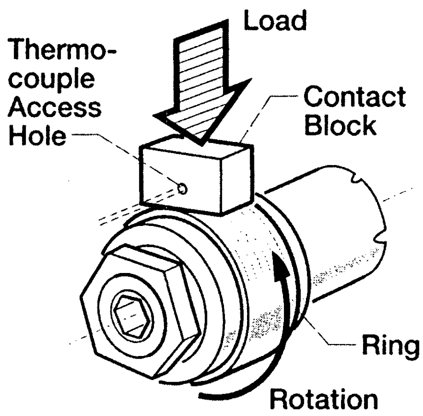


Figure 2. Schematic of Block-on-Ring Tribometer Specimens

Procedure

<u>Surface Preparation and Cleaning Procedure</u>
The cleaning procedure for the specimens before they were sent to the vendor was as follows:
1) Scrub surface under running water with a bottle-brush to remove abrasive particles.
2) Clean surfaces with pure ethyl alcohol using a lint-free cloth.
3) Scrub surface with a water paste of levigated alumina. Clean until water wets the surface readily.
4) Rinse the surface under running water to remove the levigated alumina (using the brush to facilitate removal).
5) Rinse the surface in distilled water.
6) Dry surfaces using dry compressed air. (Surfaces not dried quickly have a tendency to oxidize.)

<u>Pin-on-Disk Testing Procedure</u>
The procedure for conducting the pin-on-disk experiments was as follows: a pin (ball) and a disk (with applied sputtered MoS_2 coating) were inserted into the Tribometer test chamber (Figure 1). The test chamber was sealed, and dry air (<100-ppm H_2O), or moist air (~10,000-ppm H_2O) was purged through the chamber for 10 minutes before starting the test and then continuously throughout the test. When the purge was completed, the disk was set into rotation at 200 rpm. A 1-kilogram (9.8 N load was then applied to the disk as it rotated.

Some preliminary experiments were conducted to determine the friction characteristics of unlubricated 440C stainless steel sliding on itself. From those results, it was decided to make the criterion for failure for these tests to be a friction coefficient of 0.30, much less than the friction coefficient of unlubricated 440C stainless steel (>0.60). An automatic cutoff system was used to shut down the apparatus when the friction coefficient reached 0.30.

Two types of friction and wear testing procedures were followed: (1) the "continuous testing method" and (2) the "interval testing method." In the continuous testing method, the test was run continuously until a friction coefficient of 0.30 occurred. The specimens were removed from the Tribometer and the wear scars were measured using an optical microscope and the coating wear was measured using a surface profilometer. The visual microscope was also used to evaluate the morphology of the sliding surfaces at magnifications to 3000X. The number of revolutions to reach this value of friction coefficient was defined as the endurance life of the coating. In the "interval testing method," the specimens were removed from the test chamber at predetermined intervals of sliding and the specimen contact areas were evaluated as in the continuous testing method. The specimens were then placed back into the chamber and the previous test procedure is repeated. Sliding continued until a friction coefficient of 0.30 was obtained. The advantage of the interval method is that wear as a function of sliding distance can be determined and that the type of wear occurring on the surfaces before failure can be studied. In continuous testing, only wear at the end of a test can be determined and run-in wear cannot be separated from steady-state wear. One caveat on the "interval testing method" is that care must be taken to replace the specimens with the same orientation and alignment that they had before they were removed. Lives from both methods were nearly identical in air, although a slight friction "run-in" occurs at the start of each interval test.

Block-on-Ring Test Procedure

The specimens were inserted into the apparatus and the chamber sealed. The chamber was then purged with the nitrogen before starting the test for 10 minutes and then continuously throughout the test. This procedure was repeated each time a test was stopped until the test was completed. Both the continuous testing method and the interval testing method (as described above) were used for these experiments but they were not stopped as many times as for the pin-on-disk tests. This was done because of concern that the surfaces may have experienced oxidation degradation during the time they were removed.

Results and Discussion

Pin-on-Disk Friction Coefficient

Friction coefficient for each pin-on-disk experiment was constantly monitored though out the tests. Table 2 and Figure 3 present the steady-state friction coefficients for all coatings tested in both moist air and dry air. The lowest friction coefficient of 0.04 was obtained in dry air for 4 of the films, the Movic, the Surftech, the Hohman and the Teer-Ti coatings. The CSEM-Ti coating produced a friction coefficient of 0.06 and the CSEM-Al coating produced a friction coefficient of 0.08.

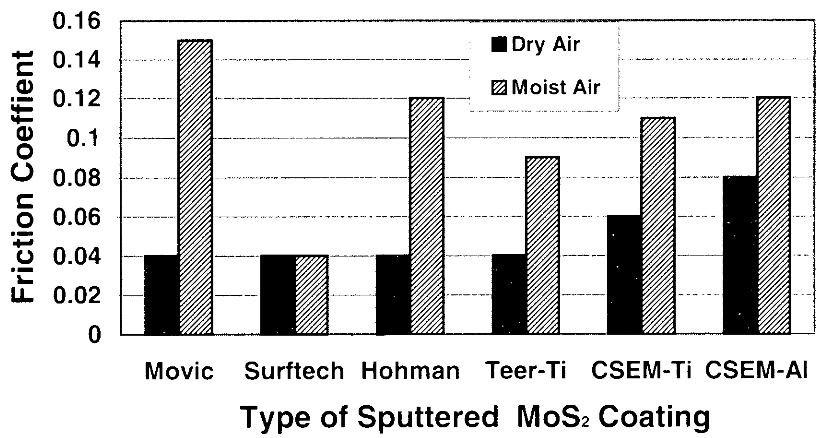


Figure 3. Average Steady State Friction Coefficient for different sputtered MoS_2 films (obtained from various vendors) and tested in moist air and dry air on a pin-on-disk Tribometer.

The Surftech coating also produced a steady-state friction coefficient of 0.04 in moist air, but all the other coatings produced much higher friction coefficients in moist air than dry air. In moist air, Movic produced the highest friction coefficient of 0.15, the value for the Hohman and the CSEM-Al coatings was 0.12, the

CSEM-Ti coating was 0.11 and the Teer-Ti coating was 0.09. For vacuum applications, the friction coefficients in dry or moist air are not really relevant except for the fact that higher friction coefficients usually mean higher wear and also shorter lives. It may also be useful information for designing components that might have to operate both in air and in vacuum. With MoS_2 coatings in general, friction coefficient is much more affected by water vapor than oxygen, thus friction in dry air more closely approximates the friction that would be obtained in vacuum.

Table 2. Pin-on-Disk Test Results

MoS_2 Coating	Steady-State Friction Coefficient		Endurance Life (Kilocycles)		Counterface Wear Rate ($m^3/m \times 10^{-18}$)		Coating Wear Rate ($m^3/m \times 10^{-16}$)	
	Moist Air	Dry Air	Moist Air	Dry Air	Moist Air	Dry Air	Moist Air	Dry Air
Movic	0.15	0.04	7 ± 3	120 ± 17	700 ± 300	4 ± 2	---	---
Surftech	0.04	0.04	39 ± 6	41 ± 7	15 ± 12	3 ± 1	---	---
Hohman	0.12	0.04	76 + 46	100 ± 26	145 ± 135	24 ± 6	---	---
Teer-Ti	0.09	0.04	55 ± 10	361 ± 15	60 ± 20	3 ± 1	107 ± 35	16 ± 8
CSEM-Ti	0.11	0.06	625 ± 100	1440 ± 440	30 ± 10	3 ± 1	44 ± 6	11 ± 5
CSEM-Al	0.12	0.08	400 ± 52	1248 ± 205	300 ± 120	3 ± 2	113 ± 55	22 ± 8

Pin-on-Disk Endurance Lives

The average endurance life and variation for each coating in dry air and in moist air is given in Table 2, and the average is shown in bar graph form in Figure 4.

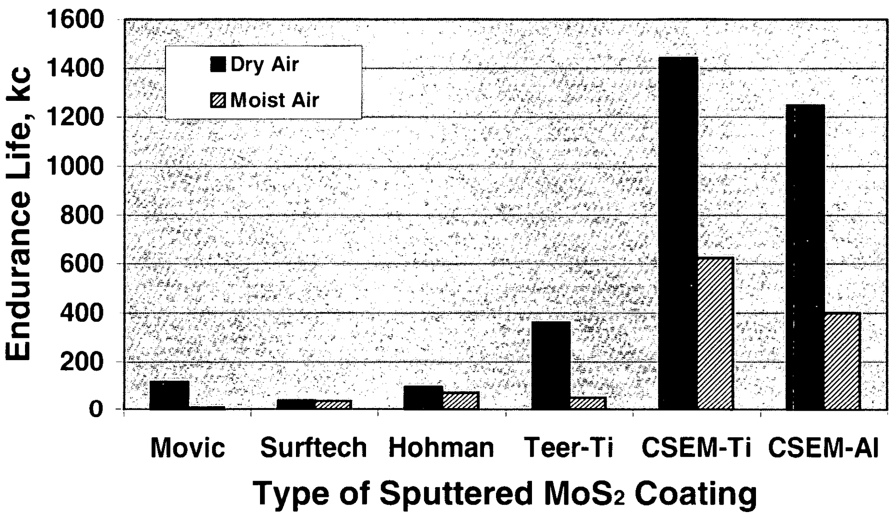


Figure 4. Average Endurance Life for different sputtered MoS_2 films (obtained from various vendors) and tested in moist air and dry air on a pin-on-disk Tribometer.

In general, most of the coatings had longer endurance lives in dry air than in moist air. The Surftech coating produced equivalent lives in both atmospheres, but the lives in both were very short (~40 kc). The Movic coating had the shortest life in moist air (7 kc) but a life of 120 kc in dry air. The Homan coating had an average life of 76 kc in moist air and 100 kc in dry air, which was equivalent to the Movic coating in dry air. The Teer-Ti coating had an average life of 55 kc in moist air but an average life of 361 kc in dry air. The CSEM-Ti and CSEM-AL coatings gave longer lives in moist air that any of the other coatings in dry air and were even longer in dry air. From an endurance point of view the CSEM-Ti and CSEM-Al coatings were far superior to the others in either moist or dry air, but they were also the thickest.

Some discussion of the Teer-Ti and CSEM-Ti coatings is appropriate at this point. The process for producing sputtered MoS_2 coatings that contain titanium was invented by Teer Coatings Limited and they have the patent rights to the coating. CSEM has obtained a license to also make the coating using the Teer process; therefore the two coatings are basically very similar. As far as could be ascertained by the authors, the basic difference between the two coatings is that the CSEM-Ti coating contains more titanium than the Teer-Ti coating. In addition, the CSEM-Ti coating is twice as thick.

Pin-on-Disk Counterface Wear

The variation of wear to the counterfaces (440C balls) sliding against the various coatings is given in Table 2 and the average in Figure 5. In general, much lower wear to the counterfaces occurred in dry air than in moist air. The exception was the Surftech coating that produced low wear in both atmospheres, but part of that was due to the fact that lives were very short and not much actual sliding occurred. Except for the Hohman coating, the counterface wear of all coatings was equivalent in dry air. The overall best combination of low counterface wear in both dry and moist air occurred with the CSEM-Ti coating.

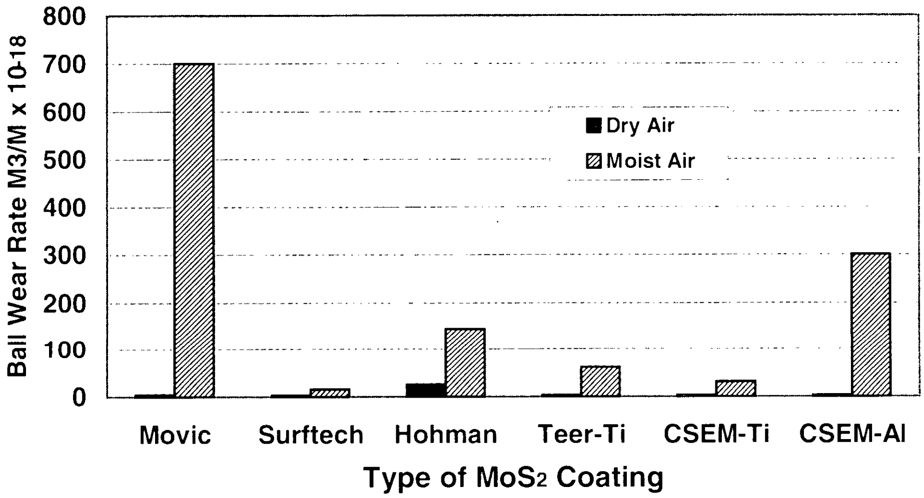


Figure 5. Average 440C steel counterface wear for different sputtered MoS_2 films (obtained from various vendors) and tested in moist air and dry air on a pin-on-disk Tribometer.

Pin-on-Disk Coating Wear

The Teer-Ti, CSEM-Ti and CSEM-Al coatings were strong enough to support the load and wore gradually away until the substrate was reached. Coating wear rate was not measurable for the Movic, Surftech and

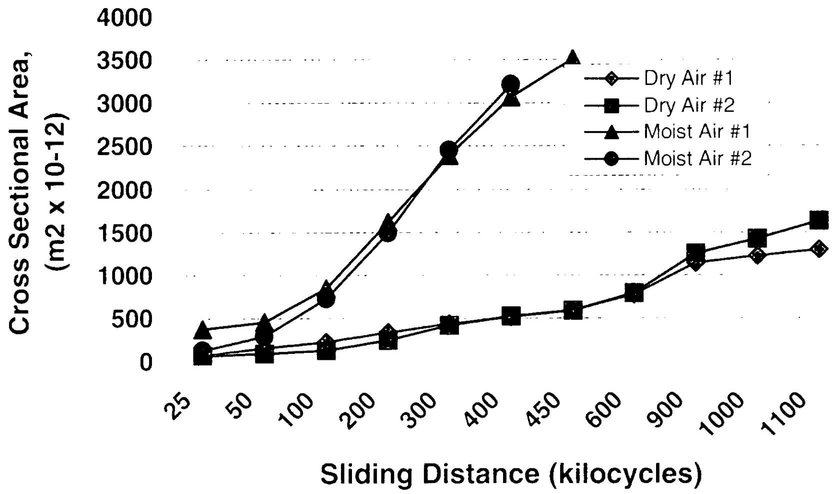


Figure 6. Coating Cross-Sectional-Area as a function of sliding distance for 440C steel sliding against sputtered CSEM-Al MoS_2 coatings in moist air and dry air on a pin-on-disk Tribometer.

Hohman coatings, since these coatings were either too soft or too thin to support the sliding 440C ball counterface. These coatings were worn away very quickly to a thin film that provided the lubrication. See Fusaro [21, 22] for a discussion on the mechanisms of solid coating lubrication. Figure 6 presents Cross Sectional Area of the coating wear as a function of sliding distance in kilocycles for 440C steel sliding against sputtered CSEM-Al MoS_2 coatings and tested in moist air and dry air. Two tests are shown for each condition. The figure shows that the wear rate is fairly reproducible and that the wear rate is nearly constant in dry air. In moist air, between 50 and 100 kc, the rate increased, but then was nearly constant.

The variation of the coating wear rates is given in Table 2 and the averages in Figure 7 for the three coatings that were able to support the load. Again the dry air atmosphere provided the lowest wear rates. The CSEM-Ti had the lowest average wear rate of 7×10^{-15} m^3/m, the next lowest was the Teer-Ti coating (10×10^{-15} m^3/m) followed by the CSEM-Al coating (14×10^{-15} m^3/m). It thus appears that the primary reason for the increased endurance life of the CSEM-Ti coating compared to the Teer-Ti coating was due to the fact that the CSEM coating was much thicker and it took longer to wear through.

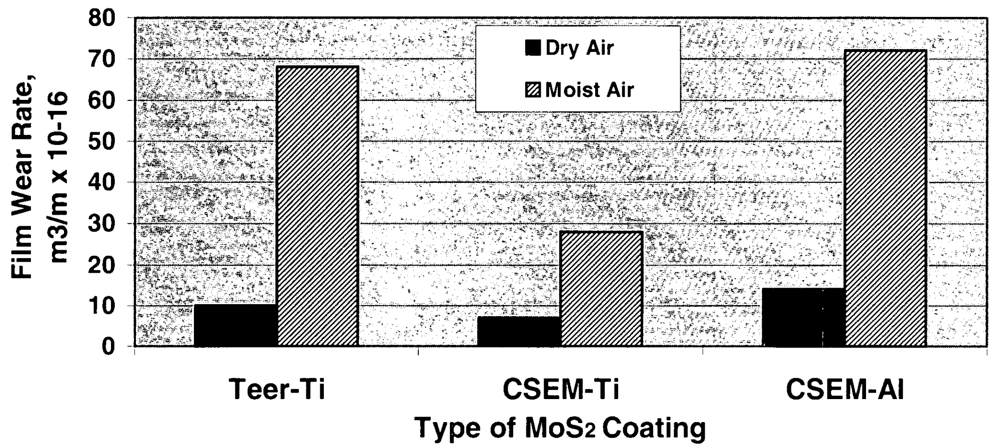


Figure 7. Average coating wear rate of different sputtered MoS_2 coatings (obtained from various vendors) and tested in moist air and dry air on a pin-on-disk Tribometer.

Like friction coefficient, endurance life and counterface wear, the coating wear rate was greater in moist air than in dry air. The lowest wear in moist air was the CSEM-Ti coating, which was 28×10^{-15} m^3/m, but was about 4-times higher than what was obtained in dry air. The other two coatings gave 2 to 3 times higher wear rates than the CSEM-Ti coating in moist air.

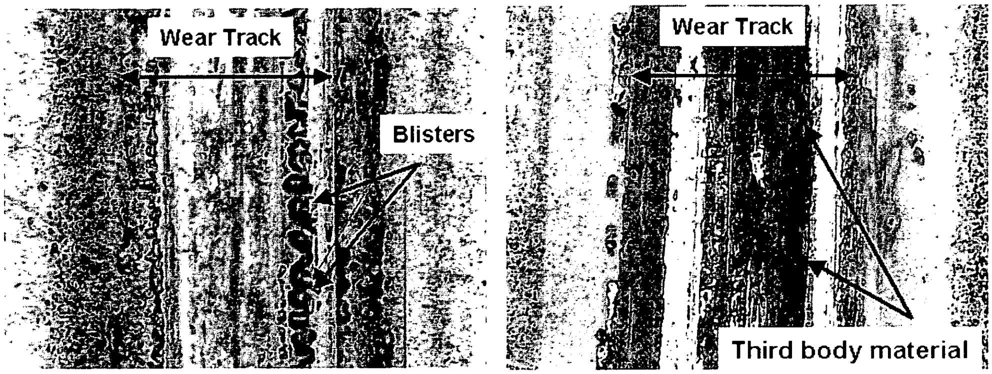
Pin-on-Disk Coating Morphology

In accelerated testing, statistical analysis of test data can provide numerical comparisons between coatings. But in order to obtain a more complete understanding of which coating would be best for your application, a simple technique like optical microscopy can be used to help in the evaluation. To do that, surfaces must be evaluated before failure. Therefore another reason for interval testing is to observe the rubbing surfaces with an optical microscope to magnifications as high as 3000X.

Figure 8 shows photomicrographs of the Movic coating wear tracks produced in dry air after 23 kc of sliding and in moist air after 2 kc of sliding. Dark blisters can be observed on the dry air wear track and dark powdery third body material (third body material is either wear material or decomposed wear material that remains on the wear surfaces) can be found in the center of the moist air track. Similar surfaces were found with the Surftech coating. These results are very similar to the results of previous studies that were conducted by Fusaro [13] on burnished MoS_2 films that showed that the MoS_2 burnished film oxidized to form MoO_3 in air and that the water vapor in the atmosphere accelerated this process.

Figure 9 gives photomicrographs of the wear tracks on CSEM-Ti sputtered MoS_2 coatings tested in dry air after 660 kc of sliding and in moist air after 160 kc of sliding. Both surfaces are very smooth with no indication of decomposition in either atmosphere unlike results from the Movic and Surftech tests. Fine

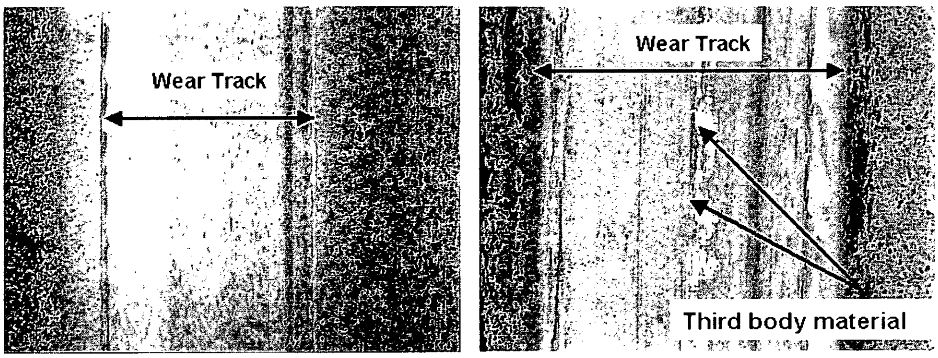
powdery debris can be seen outside of the wear track areas. In the moist air tests, there was some back-transferred third body material that may have been the cause of the higher wear in moist air.
Figure 10 shows a high magnification photomicrograph of the sputtered CSEM-TI MoS_2 coating after 900 kc of sliding showing an area that has been worn through to the substrate. A very thin secondary film has formed from third body material in this area that has prevented metal-to-metal contact.



200 µm 200 µm

Dry air, 23 kc **Moist Air, 2 kc**

Figure 8. Photomicrographs of Movic wear tracks after 23 kc of sliding in dry air and 2 Kc of sliding in moist air on a Pin-on-disk Tribometer.



200 µm 200 µm

Dry Air after 660 kc **Moist Air after 160 kc**

Figure 9. Photomicrographs of CSEM-Ti MoS_2 wear tracks after 660 kc of sliding in dry air and 160 kc of sliding in moist air on a Pin-on-Disk Tribometer.

Figure 11 shows photomicrographs after 650 kc of sliding in dry air and after 350 kc of sliding in moist air of the sputtered CSEM-Al MoS_2 coating wear tracks. In dry air, as shown in the figure, the track is very smooth; however there are areas where brittle fracture has occurred. In moist air, small surface pits can be seen on the track; and in addition, brittle fracture has also occurred but is not seen in the area shown on this figure.

Pin-on-Disk Counterface Morphology
Transfer films to the 440C ball counterfaces occurred for most of the sputtered MoS_2 coatings that were evaluated in this study. They were generally characterized by a buildup of material in the inlet area, thin flowing transfer across the scar flat and then powdery debris in the exit area. Figure 12 shows a photomicrographs of the transfer to a 440C stainless steel ball that slid against a CSEM-Al sputtered MoS_2 film. This type of transfer is typical of most of the tests in dry air and moist air on all the films. There was one exception and that was sputtered CSEM-Al in moist air. Figure 12 also shows a photomicrograph of the transfer to the 440C ball that slid

against the CSEM-Al MoS_2 coating in moist air after 50 kc of sliding. In this case, there is a small buildup of material in the inlet area but a minimal amount of transfer to the scar itself.

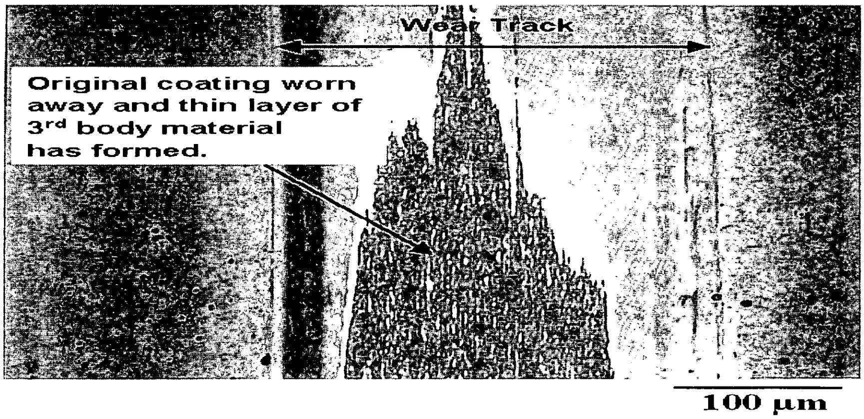


Figure 10. Photomicrograph of CSEM-Ti MoS_2 wear tracks after 900 kc of sliding in dry air on a Pin-on-Disk Tribometer showing a thin area where original coating has worn away.

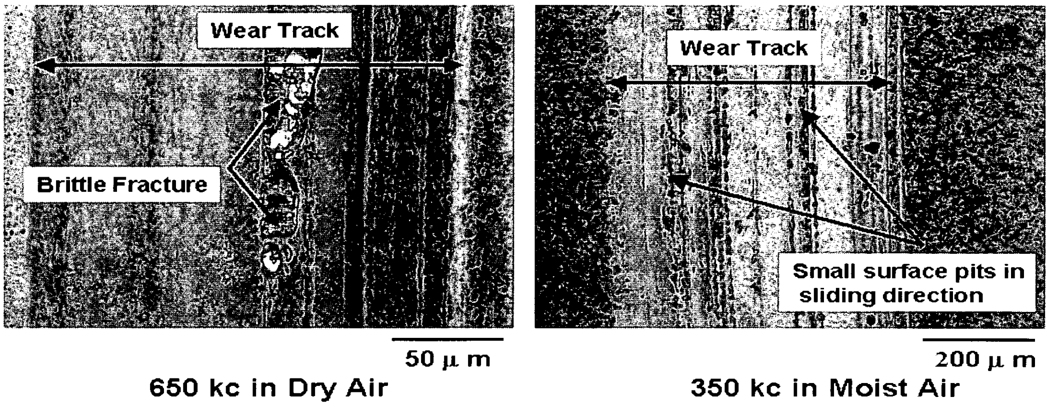


Figure 11. Photomicrographs of CSEM-Al MoS_2 wear tracks after 650 kc of sliding in dry air and 350 kc of sliding in moist air on a Pin-on-Disk Tribometer.

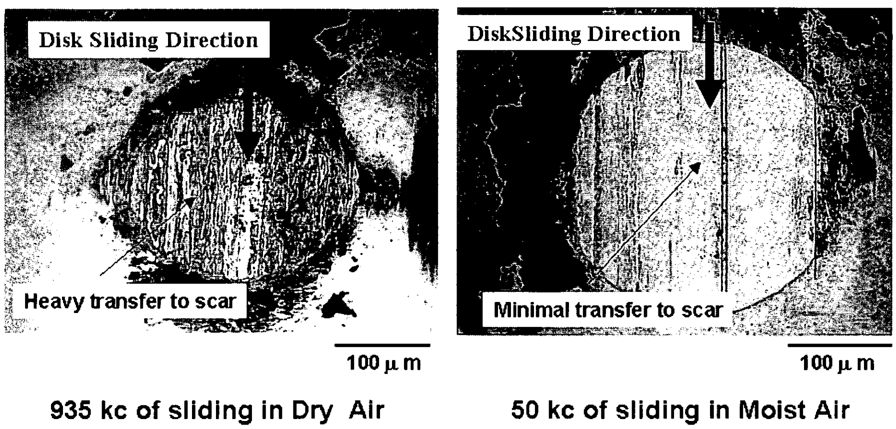


Figure 12. Photomicrographs of the wear scars on the 440C stainless steel ball counterfaces against CSEM-Al sputtered MoS_2 coatings on a Pin-on-Disk Tribometer.

Block on Ring Friction Coefficient

The average steady-state friction coefficients for the tests conducted in dry nitrogen on the Block-on-Ring Tribometer tests are given in Table 3 and also in Figure 13. In addition to non-coated blocks, a few tests were also conducted with coated blocks. In general friction coefficients were lower in dry nitrogen on the Block-on-Ring Tribometer than those obtained in dry or moist air with the Pin-on-Disk Tribometer. The Movic and Hohman coatings gave the lowest friction coefficients of 0.01. The values found for the other coatings were: CSEM-Ti, 0.02, Teer-Ti, 0.03, Surftech, 0.04 and CSEM-Al, 0.07. The coated blocks sliding on the coated rings did not change the steady-state value of the friction coefficients obtained as compared to the non-coated blocks.

Block-on Ring Endurance lives

The variation of coating endurance lives for the tests conducted on the Block-on-Ring Tribometer are given in Table 3 and the averages are given in Figure 14. The longest endurance life for the Block-on-Ring Tribometer tests were obtained with the Hohman MoS_2 coating, although there was considerable variation. The longest average life was obtained for the CSEM-Ti coating tested against a CSEM-Ti coated block. A coated block versus an uncoated block increased the average life of the CSEM-Ti coating from 323 kc to 6132 kc. The Teer-Ti sputtered MoS_2 coating gave an average life of 303 kc which was very similar to that found for the CSEM-Ti coating against the uncoated block. The Movic coating sliding against a non-coated block gave a life of 1165 kc, but the life sliding against a coated CSEM-Ti block decreased to 360 kc. The CSEM-Al coating lubricated very poorly in nitrogen. The uncoated block gave a life of 0.3 kc and when it was slid against the block coated with CSEM-Al, it failed immediately. The Surftech coating also lubricated poorly in nitrogen and failed after 0.6 kc of sliding.

Table 3: Block-on-Ring Test Results

MoS_2 Coating	Average Friction Coefficient		Endurance Life (Kilocycles)		Block Wear Rate ($m^3/m \times 10^{-18}$)	
	Non-Coated Block	Coated Block	Non-Coated Block	Coated Block	Non-Coated Block	Coated Block
Movic	0.01	0.01	1166 $\pm$ 45	360 $\pm$ 70	2 $\pm$ 0.5	190 $\pm$ 160
Surftech	0.04	---	0.6 $\pm$ 0.4	---	---	---
Hohman	0.01	---	5556 $\pm$ 3570	---	1.2 $\pm$ 1.0	---
Teer-Ti	0.03	---	303 $\pm$ 110	---	9.5 $\pm$ 7.0	---
CSEM-Ti	0.02	0.02	323 $\pm$ 321	6132 $\pm$ 950	24,000 $\pm$ 23,955	0.7 $\pm$ 0.3
CSEM-Al	0.07	Failed	0.3 $\pm$ 0.1	Failed	---	Failed

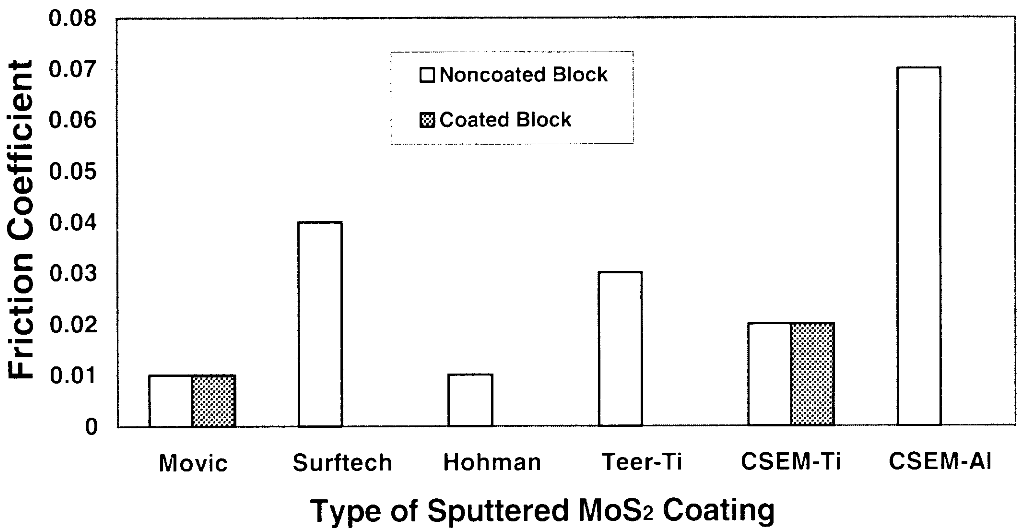


Figure 13. Average friction coefficient for different sputtered MoS_2 films (obtained from various vendors) and tested in dry nitrogen on a block-on-ring Tribometer.

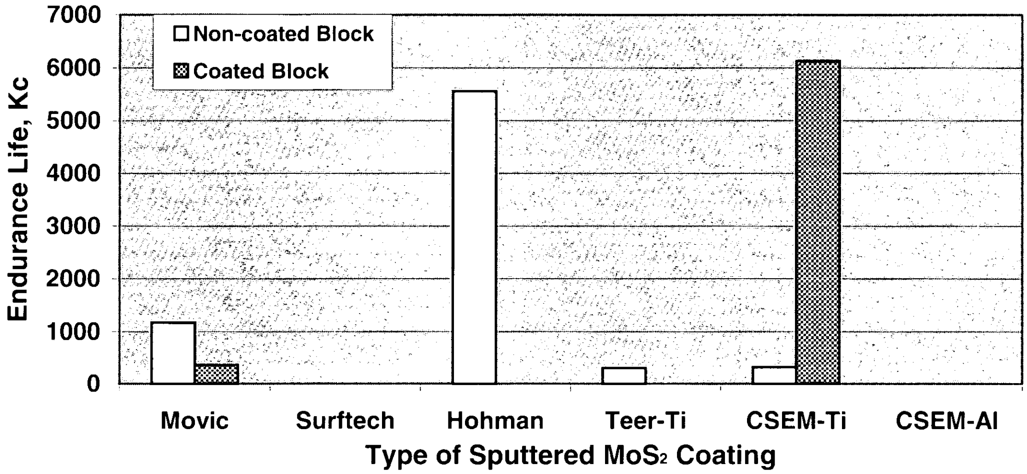


Figure 14. Average endurance life for different sputtered MoS_2 films (obtained from various vendors and tested in dry nitrogen) on a block-on-ring Tribometer.

Block-on Ring Block Wear Rate

The variation of block wear rates for the Block-on-Ring tests are given in Table 3 and the averages in Figure 15. The lowest wear rate was obtained with the CSEM-TI Block sliding against the CSEM-Ti coating ($0.7\pm 0.3 \times 10^{-18}$ m^3/m). The second lowest was with the non-coated block sliding against the Hohman coating ($1.2\pm1.0 \times 10^{-18}$ m^3/m) and the next lowest was obtained with the non-coated blocksliding against the Movic coating ($2.0\pm1.0 \times 10^{-18}$ m^3/m). The coated CSEM-Ti block sliding against the Movic coated ring increased the block wear rate almost 2 orders of magnitude compared to the non-coated block. The non-coated block sliding against the CSEM-Ti coating also had a very high wear rate.

Block-on Ring Surface Morphology

The Movic coatings produced very thin, continuous transfer films on the blocks and very thin, flowing layers of material on the rings. Figure 16 gives photomicrographs of the transfer films on the non-coated block and the film remaining on the ring after 1200 kc of sliding. The wear process on the ring appears to be by very thin layer delamination. Figure 17 gives photomicrographs of the Hohman test specimens after 3700 kc of sliding. The block shows very thin, continuous transfer and the material on the ring appears to be thicker than that found with the Movic coating (Figure 16) but it also seems to be wearing by delamination.

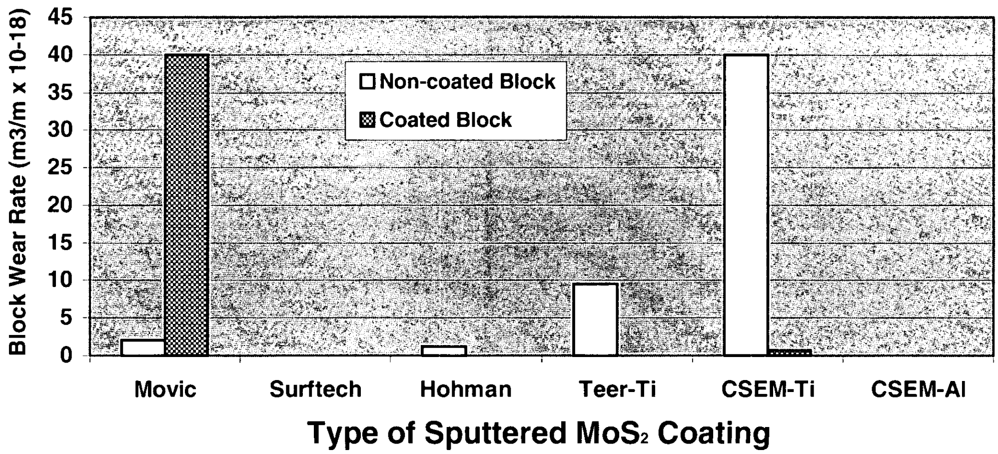


Figure 15. Block wear rate for 440C stainless steel blocks sliding on different sputtered MoS_2 films (obtained from various vendors) and tested in dry nitrogen on a block-on-ring Tribometer.

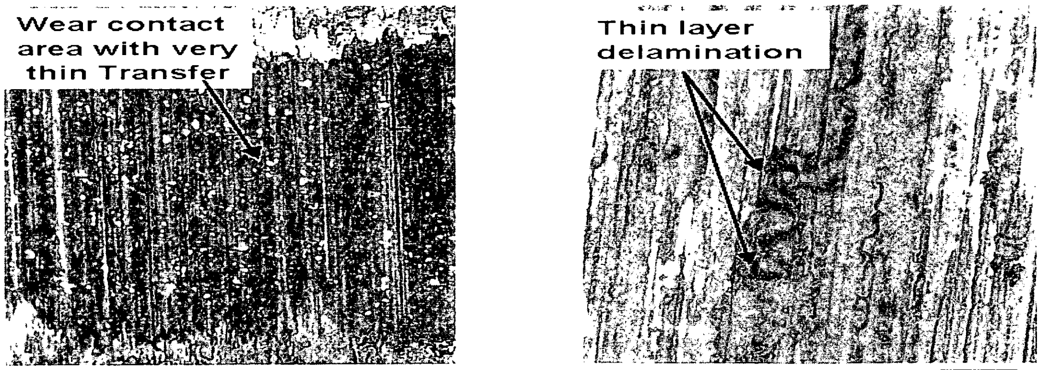


Figure 16. Photomicrographs of the wear surfaces on a 440C block and a Movic coated ring after 1200 kc of sliding in a dry nitrogen atmosphere on a Block-on-Ring Tribometer.

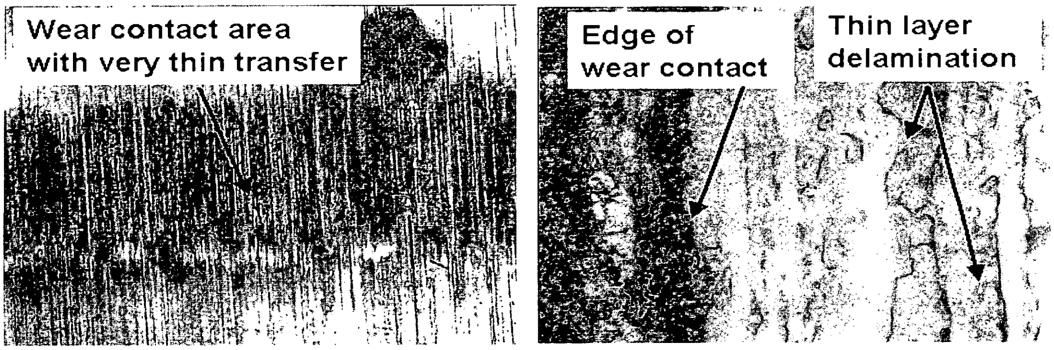


Figure 17. Photomicrographs of the wear surfaces of a 440C uncoated block and a Hohman coated ring after 3700 kc in a dry nitrogen on a Block-on-Ring Tribometer.

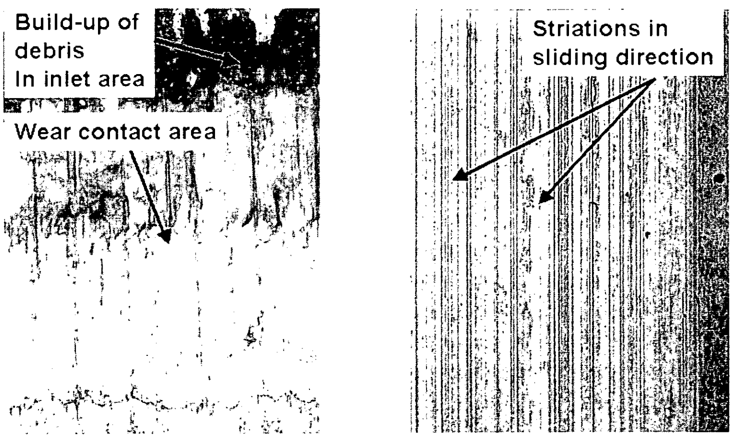


Figure 18. Photomicrographs of the wear surfaces on a 440C CSEM-Ti coated block and a CSEM-Ti coated ring after 3150 kc of sliding in a dry nitrogen atmosphere on a Block-on-Ring Tribometer.

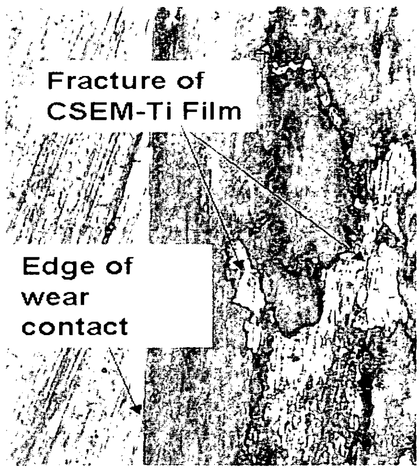


Figure 19. Photomicrograph of the wear surface on a CSEM-Ti coated ring after 0.2 kc of sliding in a dry nitrogen atmosphere against and uncoated block.

Concluding Remarks

The results of this study showed that the CSEM-Ti and the CSEM-Al coatings gave much longer endurance lives in air than the other coatings that were evaluated. As stated earlier, Teer Coatings Ltd has the patent rights to the MoS_2-Ti coating and the technology has been licensed to CSEM. The most probable reason why the Teer-Ti coating gave shorter endurance lives as compared to the CSEM-Ti coating was that the Teer coating was formulated with less titanium for vacuum use, thus it would not be expected to work as well in air. Even so, the coating wear rate was nearly equal between the two coatings in dry air; so if the same thickness of the Teer-Ti coating had been applied, the life probably would have been equivalent. But in moist air, the CSEM-Ti coating wear rate was much less than the Teer-Ti coating, which indicates that in humid air, more titanium is necessary. In dry nitrogen, on the Block-on-Ring Tribometer, the endurance lives for the two films were nearly equivalent, but the wear to the blocks that slid on the Teer-Ti coating was much less than found with the CSEM-Ti coating. The results indicate that there should be a more detailed study to determine how much Ti should be added to prevent degradation and reasonable life in ambient air while giving optimal life and performance in vacuum.

Increased thickness of the coatings which contained additives (and were also able to support the load of the sliding 440C ball counterface) tended to give increased life. It is not believed that increased thickness of the non-additive Movic or Surftech coatings in air would have improved the life considerably because they failed primarily due to degradation of the coatings.

Tests were conducted in nitrogen using the Block-on-Ring Tribometer because this geometry simulates a journal bearing more closely that does a Pin-on-Disk configuration; a journal bearing contact is closer to line contact than point contact. There were several drawbacks with using this Tribometer, however. Misalignment of the block with the ring and wobble or out of roundness of the ring are a couple; thus with this Tribometer, it is very hard to perfectly align the surfaces. Misalignment can cause high contact stress that can prematurely cause failure of a solid lubricant coating. It is felt that the CSEM-Ti coated on both surfaces, helped mitigate this misalignment. Also thicker coatings could be helpful in mitigating misalignment providing that the coating would not experience brittle fracture during the "run-in." The CSEM-Al coating was very brittle thus there was no advantage of sliding it against itself. Sliding a block coated with CSEM-Ti against the Movic coating was not advantages since the CSEM-Ti coating is somewhat rough and very hard, thus it promoted more rapid wear of the Movic coating.

Considering all the results, the Hohman coating, which was developed by the Air Force [18] and licensed to Hohman Plating, functioned overall as the best coating for our application under the conditions of all the experiments. The lowest friction coefficients and longest endurance lives were obtained with this coating. The CSEM-Ti gave exceptional results in air and also exceptional results when both the ring and the block were coated. It may be that the Teer-Ti coating or the other coatings might have worked as well in nitrogen if both blocks and rings were coated with the same material, but in this study those conditions were not evaluated.

The next planned stage for this program is to take the best coatings determined by this investigation and test them in vacuum in a journal bearing at 50,000 rpm under the conditions that they may encounter in a flywheel system touchdown event to determine which will perform the best in the actual end use application. The poor endurance life results obtained in dry nitrogen with the Surftech and CSEM-Al coatings do not make them candidates for the next phase of testing. The short endurance life of the Movic coating in moist air and degradation of the coating on the disk surface in dry air also discourages their use for this application.

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