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BEARING ENDURANCE TESTS IN VACUUM FOR SPUTTERED MOLYBDENUM DISULFIDE FILMS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1975

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3193		

4. Title and Subtitle	5. Report Date
BEARING ENDURANCE TESTS IN VACUUM FOR SPUTTERED MOLYBDENUM DISULFIDE FILMS	January 1975
	6. Performing Organization Code
7. Author(s): Talivaldis Spalvins	8. Performing Organization Report No.: E-8166
	10. Work Unit No.: 506-16
9. Performing Organization Name and Address: Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Bearings Lubricant Friction	Unclassified - unlimited STAR Category 37 (rev.)

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	10	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

Angular-contact, 440C stainless-steel, ball bearings with sputtered molybdenum disulfide (MoS_2) films 6×10^{-7} meter (6000 Å) thick were evaluated in a vacuum bearing chamber (1750 rpm, 137.9-N- (31-lbf-) thrust load) for endurance. Two types of sputtered MoS_2 films were tested: (1) MoS_2 sputtered directly onto bearing components, and (2) a thin (1×10^{-7} m (1000 Å)) underlayer of Cr_3Si_2 subsequently sputtering with MoS_2. Bearing test evaluations in vacuum showed that endurance lives of more than 1000 hours (10.5×10^{7} cycles) were obtained with bearings (cage, races, and balls) directly sputtered with MoS_2. The same endurance lives were also obtained when only the races and cage (not the balls) were sputtered with an underlayer of Cr_3Si_2 and subsequently with MoS_2.

INTRODUCTION

One of the most recent methods for applying molybdenum disulfide (MoS_2) as a dry-film lubricant for sliding or rotating machinery components is the sputter-deposition technique. The major advantage of sputtering MoS_2 lies in the strong adherence to the surface and strong coherence between the sputtered particles of the film. As a consequence of these characteristics, only thin sputtered MoS_2 films are needed for lubrication In practical lubrication, sputter deposition has several advantages, because these films can be accurately controlled and reproduced in terms of thickness, uniformity, density, etc. It is an attractive technique for coating curved and indirectly accessible surfaces such as bearing balls and the ball pockets of cages. The frictional behavior and endurance lives of sputtered MoS_2 films about 2×10^{-7} meter (2000 Å) thick have been studied in sliding-type experiments (pin and disk) in vacuum (refs. 1 and 2).

No studies establishing the endurance lives of bearings lubricated with sputtered

MoS_2 films have been reported. Many aerospace mechanisms contain bearings which operate at low speeds and light loads. Rotational speeds of a few revolutions per minute are quite common. Even in some of the mechanisms involving higher speed operation (e.g., radiometer bearings), bearings do not exceed speeds of 3000 rpm (ref. 3). The objective of this investigation was to demonstrate bearing endurance for sputtered MoS_2 film lubrication in vacuum. A speed of 1750 rpm and a thrust load of 137.9 newtons (31 lbf) were applied to a 204-size, 440C stainless-steel, ball bearing. For many aerospace mechanisms, such parameters constitute accelerated testing.

APPARATUS AND PROCEDURE

Sputtering Apparatus

The sputtering apparatus used in this study was a radiofrequency planar diode configuration with a superimposed direct-current bias for sputter etching or biasing purposes, as shown schematically and photographically in figure 1. This apparatus is described in detail in references 1 and 2. The sputtering targets which were utilized in this study were 12.7-centimeter-diameter MoS_2 and Cr_3Si_2 disks. The sputtering conditions were kept constant during this investigation. The radiofrequency power density was 3.5 W/cm^2 at a frequency of 7 megahertz and at argon pressure of 2×10^{-2} torr. The distance from bearing to target was maintained at 2.5 centimeters. The bearings to be sputter coated were cleaned by sputter etching at -2000 volts dc for about 10 minutes immediately prior to coating. The balls to be coated were placed in a screen pan (insert to fig. 1(b)) and were kept in constant motion during the sputtering process in order to maintain a uniform film coverage. The thickness of the MoS_2 films was maintained at 6×10^{-7} meter (6000 Å).

Bearing Endurance Apparatus

The bearing endurance test apparatus is shown schematically in figure 2. The bearing test assembly was mounted horizontally in the vacuum chamber. It consisted of two test bearings mounted on a rotatable shaft; the load was exerted by a precalibrated spring. The test bearings were equally loaded by a 137.9-newton (31-lbf) spring. The bearings were rotated through a magnetic drive assembly capable of varying the speeds up to 3600 rpm. The running conditions (smoothness) of the bearing were monitored by the motor current, the endurance life was registered by an automatic timer, and the vacuum during the tests was maintained at 10^{-8} torr.

The ball bearings which were sputter coated and subsequently tested for endurance were of the following type: 20-millimeter-bore 440C stainless steel, 11 balls of 0.714-centimeter diameter, radial clearance of 0.0058 centimeter, ball pocket diametral clearance of 0.018 centimeter, and retainer diametral clearance of 0.028 centimeter.

Procedure

Two series of sputtered coating films were prepared, and their endurance was determined. In the first series, MoS_2 films were directly sputtered on the 440C stainless-steel bearing components. In the second series, thin underlayers of Cr_3Si_2 were sputtered on the races and cages, which were subsequently coated with a sputtered film of MoS_2. The bearings to be sputtered were cleaned by sputter etching at -2000 volts dc in 2×10^{-2} torr of argon for about 10 minutes, immediately prior to coating. Where the sputtered underlayer of Cr_3Si_2 was used, the thickness was maintained at 1×10^{-7} meter (1000 Å). The sputtered MoS_2 lubricant films in all instances were about 6×10^{-7} meter (6000 Å) thick.

The bearing running conditions during the tests were monitored by the motor current. At the beginning of the test the motor current was somewhat high, 1.3 to 1.4 amperes. As the test progressed the current generally dropped to 1.2 amperes, and the running conditions were very smooth. As the run became rougher and more noisy the current increased. An automatic cutoff was set at 1.8 amperes, and the test was discontinued when the operating current reached that level. An endurance time limit of 1000 hours (10.5×10^{7} cycles) was set for evaluation purposes. Therefore, if the motor current had not exceeded 1.8 amperes at 1000 hours, the test was terminated.

DISCUSSION AND RESULTS

In this investigation the endurance of sputtered MoS_2 films on bearings was evaluated Two methods of application were used: (1) MoS_2 films were directly sputtered on the bearing components, and (2) first an underlayer of Cr_3Si_2 was sputtered on the bearing components which were subsequently sputter coated with a MoS_2 film.

Bearing Tests with Directly Sputtered MoS_2 Films

In the first series of tests, sputtered MoS_2 films about 6×10^{-7} meter (6000 Å) thick were deposited directly on the races and cage, but not on the balls. When tested for endurance in vacuum at 10^{-8} torr at a speed of 1750 rpm and a thrust load of 137.9 newtons (31 lbf), the average endurance life of these bearings was about 184 hours. When all the components (races, cage, and balls) were sputtered with MoS_2 and tested under these conditions, the endurance life was extended to over 1000 hours. Since 1000 hours was selected as the maximum endurance limit, the tests were discontinued once 1000 hours was reached. Several endurance tests were conducted where only the balls were sputtered with MoS_2. The endurance life for this combination was about 19 hours before failure. A bearing tested without a lubricant under identical experimental conditions failed (very noisily and with high motor current) in about 35 minutes. These results are graphically shown in figure 3.

In several instances when the bearing endurance tests were progressing very smoothly (motor current, ~1.2 A) at 1750 rpm, the speed was increased to 2250 rpm. After the speed was increased, the bearing had a satisfactory performance for only about an additional 95 hours. In several other tests, while the bearing was performing satisfactorily (motor current, 1.2 A), air was introduced into the vacuum test chamber to reach the standard atmospheric conditions. Immediately upon the introduction of air, the bearing began to operate at a high motor current (~1.4 to 1.6 A). In 1 hour the performance was very rough and noisy, and the test was discontinued.

Bearing Tests with Sputtered Underlayer of Cr_3Si_2 with Sputtered MoS_2 Film

In the second series of the bearing endurance tests the races and cages were sputter coated with a thin underlayer of Cr_3Si_2 and subsequently covered with a sputtered MoS_2 film. The balls were left uncoated. This combination showed a significant improvement in endurance when tested under the same experimental conditions as the previously directly MoS_2 sputtered cages and races. The endurance life with the Cr_3Si_2 underlayer was over 1000 hours, compared to 187 hours for the directly sputtered MoS_2 films. A comparison of these endurance lives is shown in figure 4.

The application of the Cr_3Si_2 underlayer was based on the decision to coat the bearing surfaces with a very hard, thin, uniform, glassy surface finish. This finish would serve to contour the surface asperities and would function as a barrier layer during asperity deformation. Direct metal-to-metal contact, which leads to seizure, would be hindered. The Cr_3Si_2 film also has a tendency to act as an inert diffusion barrier layer.

Coefficient of Friction against Atmospheric Pressure for Sputtered MoS_2 Films

It is well documented that the coefficient of friction for MoS_2 increases with the partial pressure of water vapor in the air (ref. 4). The effect of atmospheric pressure on the coefficient of friction for sputtered MoS_2 films was also evaluated. The changes in the coefficient of friction with changes in pressure from atmospheric pressure (760 torr) and a relative humidity of 60 percent to 10^{-9} torr are shown in figure 5. This study was conducted in an ultrahigh-vacuum friction apparatus (ref. 5) with a 0.47-centimeter-radius hemispherical rider sliding on the sputtered MoS_2 flat surface of a rotating 6.35-centimeter-diameter disk. The curve in figure 5 was constructed by starting the friction test at atmospheric conditions and gradually evacuating the chamber and monitoring the change in friction. The reverse procedure was also performed, wherein the friction test was started at 10^{-9} torr and the pressure was gradually increased until atmospheric conditions were reached. The resulting friction curves had a very close agreement in their profile, whether the curve was constructed by increasing the pressure from 10^{-9} torr or by decreasing the pressure from 760 torr. The reversibility in the procedure (evacuating or pressurizing) has no effect on the coefficient of friction. As seen in figure 5, a continuous change occurred in the coefficient of friction between 100 and 400 torr. Above 400 torr the coefficient of friction was steady at ~0.15, and below 100 torr it stabilized at 0.04. Friction tests of sputtered MoS_2 films were also conducted in dry air, nitrogen, and argon. The coefficient of friction under these conditions was the same, 0.04.

SUMMARY OF RESULTS

The following results were obtained from the bearing endurance tests when 204-size, 440C stainless-steel, ball bearings were sputtered with a 6×10^{-7}-meter- (6000-Å-) thick film. Two types of molybdenum disulfide (MoS_2) sputter depositions were performed: (1) direct sputtering with MoS_2, and (2) sputtering with an underlayer of Cr_3Si_2 and subsequently with MoS_2.

1. Endurance lives of more than 1000 hours were obtained with bearings (cage, races, and balls) directly sputtered with MoS_2. The same endurance lives (>1000 hr) were also obtained when only the races and cage were sputtered with an underlayer of Cr_3Si_2 and subsequently with MoS_2. In comparison, an endurance life of less than 200 hours was obtained with the races and cage coated only with MoS_2.

2. When air was admitted into the vacuum bearing chamber during the test, the bearing failed in about an hour. Higher bearing speeds (2250 rpm) appreciably reduced the life.

3. The effect of pressure on the coefficient of friction for sputtered MoS_2 films was determined during sliding (disk and pin) experiments. Below 100 torr the coefficient of friction remained constant at 0.04, above 400 torr the coefficient of friction was about

0.15, and between 400 torr and 100 torr the coefficient of friction gradually changed with pressure.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 9, 1974,
506-16.

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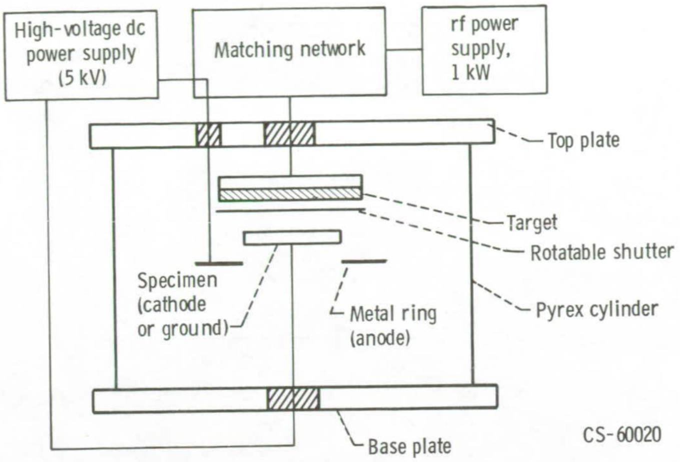
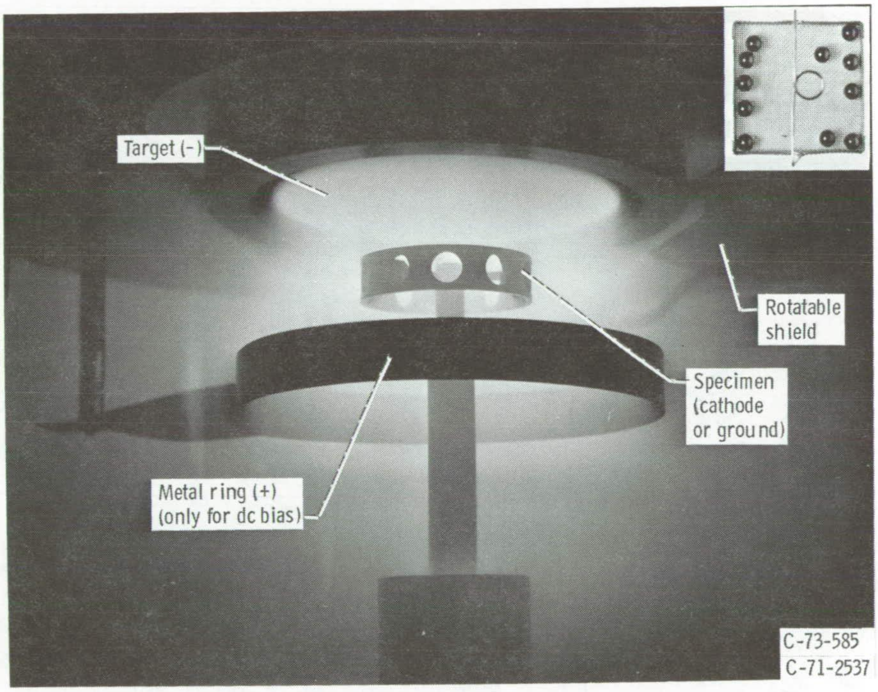


(a) Schematic diagram.



(b) View of apparatus during sputter coating.

Figure 1. - Radiofrequency diode sputtering apparatus with direct-current bias.

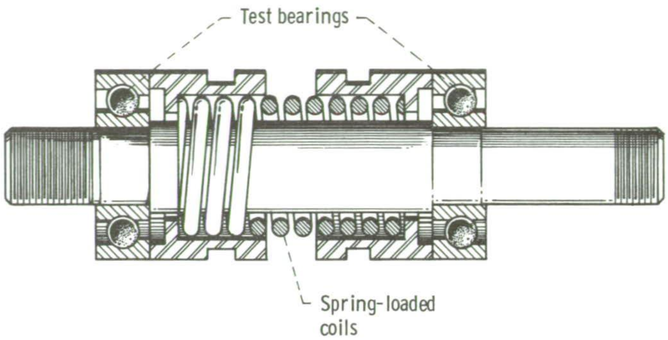


Figure 2. - Schematic of vacuum bearing endurance assembly.

Figure 3. - Endurance lives of 440C stainless-steel ball bearings with and without sputtered MoS_2 films.

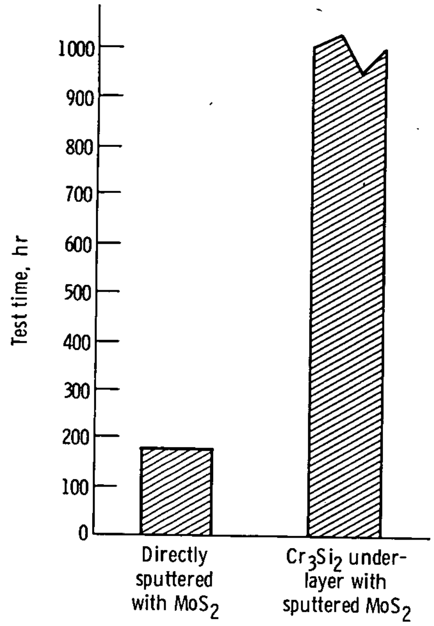


Figure 4. - Endurance lives of 440C stainless-steel ball bearings with sputtered MoS_2 films on races and cage - with and without a Cr_3Si_2 underlayer.

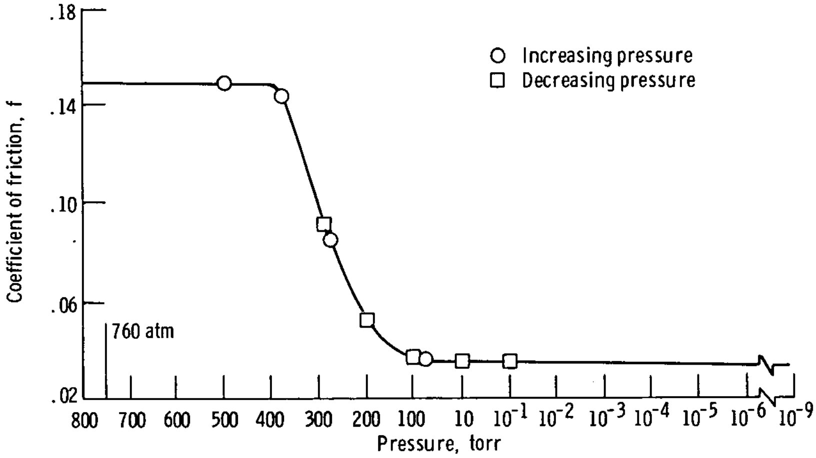


Figure 5. - Effect of pressure on coefficient of sliding friction for sputtered MoS_2. Load, 250 grams; speed, 40 rpm; substrate/rider, Ni/Ni; room temperature.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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