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FRICTION CHARACTERISTICS OF SPUTTERED SOLID FILM LUBRICANTS

by Talivaldis Spalvins
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Conference and School on Industrial Applications of Sputtering sponsored by Materials Research Corporation Tarrytown, New York, June 1-3, 1970

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Solid film lubricants Au, MoS_2, and WS_2 were deposited by d-c triode sputtering and MoS_2 and PTFE by rf sputtering on metal and glass surfaces. The chemical composition of sputtered MoS_2 films was very close to the original material. These films had a low coefficient of friction and displayed exceptionally long endurance lives. Electron microscopy, electron diffraction and scanning electron microscopy were used to analyze the films and their friction characteristics. Rf sputtered MoS_2 film can be deposited on complex geometrical specimens (e.g., ball bearing cages) completely coating surface cavities and around corners with adherent film. PTFE was also rf sputtered onto glass and metal surfaces with strong adherence and a very slight change in chemical composition from the original PTFE.

I. INTRODUCTION

The purpose of applying a solid film lubricant to sliding or rotating surfaces is to reduce the coefficient of friction and wear and obtain a long wear life of the film. The efficiency of the solid film lubricant depends on the degree of adherence of the film to the surface to be lubricated. The degree of adherence determines the durability and wear of the sliding components. Adherence is directly related to:

1. Surface pretreatment
2. Energetics of the sputtered material
3. Film and substrate materials
4. Type of interface formed

Many coating techniques ranging from simple burnishing to electrolytic deposition have been used to apply solid lubricants. The method which is selected to apply the film determines the bonding characteristics which directly affect the performance of the film. The sputtering techniques show

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the greatest promise to satisfy the above parameters for strong adherence.

On the basis of their electrical conductivities, solid lubricants can be divided into three categories:

1. Conductors: Au, Ag, Pb, etc.
2. Semiconductors: MoS_2, WS_2, NbS_2, etc.
3. Insulators: CaF_2, BN, PTFE, etc.

All three categories can be sputtered directly by radiofrequency (rf) using rf potentials. Only conductors and semiconductors can be sputtered by dc methods.

Two types of solid film lubricants can be distinguished, based on their lubrication mechanisms:

1. Lamellar (by slippage between layers of crystallites): MoS_2, $MoSe_2$, $MoTe_2$, WS_2, WSe_2, WTe_2, NbS_2, BN, Graphite, etc.
2. Non-lamellar (soft films)
   a. Soft metals: Au, Ag, Pb, Sn, etc.
   b. Plastics: PTFE, polyimides, etc.

The objective of this paper is to discuss triode d-c sputtering of Au, MoS_2, and WS_2, and r-f sputtering of MoS_2 and PTFE and illustrate their film formation characteristics and the behavior of the films during sliding friction experiments. Thin sputtered films of Au, MoS_2, and WS_2 (2000 Å thick) and PTFE (15,000 Å thick) were deposited on various metallic surfaces. The lubrication characteristics and durability of these films were tested by ultra-high vacuum friction experiments. A hemispherical metal rider was in sliding contact with a disk surface on which the film had been sputtered. The coefficient of friction was measured as a function of time and that data provides an indication of the effectiveness and durability of the films for lubrication.

II. ULTRAHIGH VACUUM FRICTION APPARATUS

The vacuum friction apparatus shown in Fig. 1 was used for determining the coefficient of friction and the durability of the sputtered coatings. The basic components of the apparatus are the specimens, a 2-1/2-inch diameter flat disk, and a 3/16-inch radius rider. The disk specimen was mounted on the end of the rotatable horizontal shaft in the vacuum chamber. A 3/16-inch hemispherical rider specimen was loaded against the disk. The rider was supported by a bellows-sealed, rigid arm which projects through a port in the side of the vacuum chamber. A removable gimbal assembly containing a strain gauge measuring device was used to load the rider against the disk surface and to monitor the frictional force. The friction tests were conducted at various speeds of 20-40 ft/min using loads of 250 and 500 grams in a vacuum of 10^{-11} torr. The vacuum chamber pressure was measured by a triggered discharge gauge.

III. TRIODE DIRECT-CURRENT SPUTTERING APPARATUS

The sputtering apparatus used in this investigation utilized a three electrode (triode) geometry consisting of a thermionic cathode, an anode and a target. The system is shown schematically in Fig. 2(a) and photographically in Fig. 2(b). The thermionic cathode, which is a tungsten filament, is mounted inside a water-cooled cylindrical enclosure. The sides of the water cooled cylinder prevent the evaporated filament material from reaching the target and specimen. The distance between the cathode and the specimen is 12.5-inches. The target is a cylindrically shaped compact 0.5-inches in diameter and about 2.25-inches in length. The MoS_2 or WS_2 cylindrical compacts were made of powders which were previously dried in a vacuum furnace at 250° F. These dry powders were then pressed into cylinders at pressures of about 80,000 psi. The target is held in a water-cooled holder. Target to specimen distance is about 1-inch. The specimen was not cooled and was not heated by means other than the discharge itself. Two thermocouples were used to measure the temperature of the target and of the specimen. The temperature of the specimen was about 275° F. Before depositing the lubricant film, the surface of the specimen is cleaned by reverse sputtering. After the cleaning process, the sputtering parameters used were: target voltage, 3000-4000 V; target current, 18-20 mA; and argon pressure, 6 microns. Film thickness was continuously monitored by a water cooled oscillating quartz crystal. A glass slide was also included in each experiment and the film thickness determined by interference microscopy.

IV. RF SPUTTERING SYSTEM WITH DC BIAS

The sputtering system utilizes a rf-diode mode with a superimposed dc-bias voltage. The system is shown schematically in Fig. 3(a) and photographically during sputtering with the glow discharge in Fig. 3(b). The system can utilize 5 or 6 inches diameter targets which are water cooled. The rf power supply has 1 kilowatt capacity. The specimen to be coated is connected to the negative terminal of the high voltage dc power supply, thus a negative potential is applied to the specimen. A third electrode which is a screen with a hole in the center to allow the sputtered material to reach the object to be coated is inserted between the target and the specimen and it is at a positive potential. The distance between the target and the screen is 2 inches and the target and the specimen 3 inches. A negative potential of (2-5 kV) at 20 microns Ar with respect to the screen is applied to the specimen and a glow discharge is established and sputter etching of the surface takes place. After the surface is cleaned the rf power source to the target is energized and film deposition by rf sputtering begins. The dc voltage can be turned off or reduced and the argon pressure during rf sputtering can be also reduced if necessary. The film thickness of the sputtered film was measured by interference microscopy on reference glass slides.

V. RESULTS AND DISCUSSION

The objectives of this investigation was to sputter Au, MoS_2, and WS_2 by dc triode sputtering and MoS_2 and PTFE by rf sputtering. These films showed improved lubrication properties in terms of long endurance lives over films applied by other methods (ref. 1,2). The average coefficient of friction for sputtered gold film was 0.15 and for sputtered MoS_2 and WS_2, 0.03 to 0.07 depending on the substrate material. These values are in agreement with the values reported in the literature for these films applied by other techniques.

To determine the film formation characteristics, Au and MoS_2 were sputtered under identical experimental conditions, not only on metal surfaces used in friction tests but also on glass, mica and polystyrene substrates. Electron transmission microscopy, electron diffraction, and scanning electron microscopy techniques were used to examine these films.

VI. EVALUATION OF DC SPUTTERED GOLD FILMS

A film of gold about 300 Å thick was sputtered on a glass slide and a mica sheet. The sputtering parameters were: target voltage, 1000 V; target current, 12 mA; argon pressure 15 microns; and the temperature of the medium was about 220° F. Electron transmission micrographs in Fig. 4 illustrate the film structure in regard to the substrate. These micrographs reveal that the substrate does affect the rate of grain growth. The crystallite size of gold on the mica substrate ranged from 40 to 400 Å, with the 100 to 200 Å size predominating. Gold sputtered on the glass substrate had crystallites ranging in size from 60 to 600 Å, the 200 to 400 Å size predominating.

Another set of experiments were performed where a gold film of about 600 Å thick was sputtered simultaneously on a glass slide, mica sheet and electropolished nickel foil. The sputtering parameters used were: target voltage, 3000 V; target current, 20 mA; argon pressure, 10 microns; and the temperature of the medium was about 275° F. These were the sputtering parameters normally used in applying dc sputtered lubricant films. All three preparations had a similar structure and particle (crystallite) size. A typical structure of these sputtered films is shown in Fig. 5. One hundred particles were measured of each of the three samples and in each case the average particle size diameter came to 100 Å. It is interesting to note that at the higher sputtering energies and with films over 600 Å thick, the films had the same structure irrespective of the substrate used.

The friction characteristics and endurance life of the sputtered gold films were examined by conducting friction tests in ultra high vacuum. The sputtered gold film 2000 Å thick was compared against a gold film of the same thickness deposited by vapor deposition on a surface cleaned by electron bombardment. The coefficient of friction and the endurance lives of these films are shown in Fig. 6. It is interesting to observe that for the vapor deposited film, once the rider has worn through the film, the coefficient of friction rises very steeply towards the 1.2 value for the bare metal combination. For the sputtered films, the increase is more gradual. Depending upon the degree of slope the curve approaches the curve for the bare metals, one may relate the degree of the slope partially to penetration and adherence of the sputtered material. The higher arrival velocities of the sputtered material bring with them a certain activation energy for reacting with the substrate material (ref. 3). The higher energies of the sputtered material contribute to film characteristics in a favorable manner - such as increased adhesion with the surface. Also the sputter etching effect on the surface and the continuous glow discharge itself during deposition has a deciding effect on the surface, promoting stronger film to substrate bonding. From these friction curves (Fig. 6) one may consider that friction tests give a qualitative measure of film adherence.

VII. EVALUATION OF DC SPUTTERED MoS_2 AND WS_2 FILMS

Films of MoS_2 and WS_2 were dc sputtered on Ni, Ni-Cr and Nb disks. The sputtered MoS_2 films were qualitatively and quantitatively analyzed by chemical and spectrographic methods. The weight percentages of the starting MoS_2 and the sputtered MoS_2 material are shown in table I. The results indicate a very small compositional change between the bulk and sputtered material. The surfaces in all instances were highly polished and sputter cleaned before depositing the films. MoS_2 films under the same experimental conditions as used for metal surfaces were deposited on glass, mica and polystyrene surfaces. These films were examined by electron transmission microscopy and electron diffraction. Electron transmission micrographs of sputtered MoS_2 on Ni, glass and mica gave identical patterns at a magnification of 154,000X. Figure 7 shows a typical transmission micrograph of a sputtered MoS_2 film of about 500 Å thick at a substrate temperature of 275° F. Since no grain structure or any other characteristic features can be observed in these micrographs, a particle size determination or any orientation effects could be determined. Previous work has shown that in a dark field, one can image crysstals down to 30 Å diameter. In these particular micrographs of sputtered MoS_2 films, all that can be concluded is the particle size is less than 30 Å. The electron transmission patterns of sputtered MoS_2 on mica and glass were very similar and Fig. 8 shows a typical braod, cloudy ring which also failed to indicate the crystallinity of the film.

Electron transmission micrographs at high magnifications (X500, 000) were made of a thin MoS_2 film deposited on nickel, and polystyrene. The MoS_2 film on polystyrene was used as an internal standard to check the effect of the etchant used ($FeCl_2$ - HCl) to free the MoS_2 film from the nickel surface. It remained essentially unchanged after treatment in the etchant used to remove the MoS_2 film from the nickel substrate. Figure 9 shows a comparison of sputtered MoS_2 film under identical conditions on nickel and polystyrene surfaces. Slight changes in the structure can be seen. The sputtered film on the nickel surface indicates some texturing (orientation) and possibly some more granularity as compared to the film on polystyrene. Electron diffraction pattern of MoS_2 film on Ni is shown in Fig. 10. This pattern shows diffraction spots superimposed on the diffuse rings. This pattern may indicate that a reaction product has formed between the sputtered MoS_2 and the nickel. On the other hand only diffuse looking rings were obtained for the sputtered MoS_2 film on polystyrene. The significance of the diffraction pattern can not fully be interpreted yet.

When friction tests were conducted on these dc sputtered MoS_2 and WS_2 films, the average coefficient of friction was 0.05 for both types of films and the endurance life of the films was over a million cycles. A typical wear track of sputtered MoS_2 film on (Ni-Cr) disk which did not fail after running for 5.8×10^5 cycles is shown in Fig. 11. It has been observed in all these experiments and shown in Fig. 11 that the sputtered MoS_2 which is worn off tends to agglomerate at the edges of the wear track and also around the rider. A typical appaerance of the scraped sputtered MoS_2 film in a powder form is shown in Fig. 12. A tendency for agglomeration is evident. This might be interpreted as being due to the submicroscopic size of the sputtered material. Particles of this submicroscopic size build-up an electrostatic charge, which would enhance the tendency for agglomeration. It has been shown (ref. 4) that certain semiconductor compounds like CdS and group III-V compounds exhibit a polar nature of certain crystallographic faces. This agglomeration effect should be beneficial in lubrication from a reservoir point of view.

Figure 13 graphically illustrates the endurance lives (cycles to failure) of sputtered MoS_2 film compared with films applied by other commonly used methods. In this comparison, the (Ni-Cr) surfaces had the same finish; the only variable was the method of application. Sputtered MoS_2 films as seen in Fig. 13, show longer endurance lives than films applied by burnishing or by using resin bonding. The resin bounded films were about 130,000 Å whereas the sputtered ones were only 2000 Å thick.

Scanning electron microscopy was used to determine the general surface topography of the MoS_2 sputtered coatings and the surface of the coating which had been friction tested.

Figures 14 and 15 give a comparison of the as sputtered MoS_2 and a wear track of the coating after friction tests. The wear track micrographs illustrate the mechanism by which the film starts to wear off.

A typical wear track of a sputtered WS_2 film before it breaks through is shown in Figs. 16 and 17 shows the same after it breaks, and metal-to-metal transfer is taking place.

Typical wear tracks of sputtered WS_2 film are shown in Fig. 18. The friction experiments were conducted both in ultra high vacuum or under atmospheric conditions. When the experiments were conducted in vacuum, the film had an average coefficient of friction of 0.055 and the durability was over a million cycles. But when the same film was tested under identical experimental conditions in atmosphere the coefficient of friction immediately increased to 0.22 and film failure occurred after only 1500 cycles. This premature failure of the film under atmospheric conditions is explained on the basis of H_2SO_4 formation which has a corrosive effect on the surface.

A cold pressed WS_2 sputtering compact was wrapped in a paper and stored under atmospheric conditions. In several weeks the humidity affected the WS_2 compact and the end results are shown in Fig. 19.

VIII. EVALUATION OF RF SPUTTERED MoS_2 AND PTFE FILMS

The rf sputtered MoS_2 films were also quantitatively analyzed and the results are listed in table I. The composition of these sputtered MoS_2 films was in close agreement with the original composition of MoS_2. The following rf sputtering parameters were used for depositing MoS_2 films: rf frequency, 7MHz; argon pressure, 15 to 20 microns; rf power input, 500 to 550 W; reflected power, about 2 W; dc input, 625 to 650 V; target voltage, AC 1.25 to 1.50 kV; target to specimen distance, about 1.5 inch. Ultra high vacuum friction tests were conducted on the rf sputtered MoS_2 films. A typical friction curve is shown in Fig. 20 where a stainless steel, 440 C rider was sliding on rf sputtered MoS_2 (2000 Å) film on a 440 C disk at applied load of 250 grams and speed 25 ft/min. The coefficient of friction at the start of the friction test was 0.08. After about 10,000 cycles there was a continuous drop of the friction coefficient until after about 60,000 cycles the coefficient of friction dropped to 0.03 and remained there until the film failed. All the sputtered MoS_2 films had endurance lives over 250,000 cycles. The drop in the coefficient of friction might be explained due to the orientation effects of the crystallographic planes. It is known that MoS_2 orients under sliding conditions, with the easy cleavage plane parallel to the plane of sliding.

A reproduction of actual data traces from friction experiments are shown in Fig. 21. The trace in Fig. 21(a) is typical for metal sliding on metal without lubricant. The amplitude of the friction curve is relatively large, due to metal-to-metal transfer, and the average coefficient of friction in this particular instance where niobium is 1.1. The friction trace in Fig. 21(b) is for a metal sliding on a metal surface coated with the sputtered MoS_2 or WS_2 film. The coefficient of friction is about 0.05 and the friction curve is smooth, with practically no fluctuations. These actual friction traces in Fig. 21 were used to determine the average coefficients of friction.

An interesting and useful phenomena was observed during rf sputtering (Fig. 3(a)). When the specimen is located about 3 inches from the target and exposed from all sides to the plasma sheath; the specimen is completely coated from all sides. MoS_2 was sputtered on a number of ball bearing components (cages and races). Figure 22 shows the coated ball bearing components which were completely coated including the ball pockets of the cages. The film uniformity of the components is very critical to the potentials used during sputtering and the distance between the target and the specimen.

PTFE (polytetrafluoroethylene) was rf sputtered on glass and metal surfaces. The original and sputtered PTFE was quantitatively analyzed by chemical methods for carbon and fluorine contents. The quantitative results and the corresponding sputtering conditions are listed in table II. It is interesting to note that at lower power inputs the composition of the sputtered film was the closest to the original composition. All these rf sputtered PTFE films had a yellow appearance. A darker yellow color was formed as the sputtering rates were increased (at a higher input potential). The adherence in all the sputtered PTFE films on glass and metal surfaces was surprisingly good. Friction tests were also conducted on sputtered PTFE films on nickel substrates (load 250 grams, speed 20 ft/min). The average coefficient of friction was about 0.25 and the endurance lives were short, since the material is too soft. These preliminary results indicate that rf sputtering introduces a new method for applying PTFE to glass and metal surfaces.

IX. SUMMARY

The sputtering methods for applying solid film lubricants on sliding and rotating surfaces show significant promise. Quantitative analysis of sputtered MoS_2 films indicates that the composition of the elements is very close to the original material. Friction experiments show that the coefficients of friction of the sputtered films are very nearly the same as the values reported in the literature for films applied by other techniques. The durability of the sputtered films which are very thin when compared to the generally used much thicker films applied by other methods, showed superior performance. The strong adherence of sputtered films can be attributed mainly to the cleanliness of the surface (sputter etched) and the higher arrival energies of the sputtered particles. In rf sputtering due to the high magnetic field complex geometrical specimens (races, cages) can be completely coated without rotation. PTFE was rf sputtered on metal and glass with good adherence. This process opens a new approach of how PTFE can be successfully applied to practically any surface.

REFERENCES

1. Spalvins, T., "Deposition of MoS_2 Films by Physical Sputtering and Their Lubrication Properties in Vacuum," ASLE Trans., TASLA, vol. 12, no. 1, Jan. 1969, pp. 36-43.

2. Spalvins, T., "Energetics in Vacuum Deposition Methods for Depositing Solid Film Lubricants," Lubrication Engineering, Luena, vol. 25, no. 11, Nov. 1969, pp. 436-441.

3. Wehner, G., "Sputtering," Science and Technology, STNYB, no. 81, Sept. 1968, pp. 32-39.

4. Gatos, H. C., in Surfaces and Interfaces I, Chemical and Physical Characteristics: Proceedings. Sagamore Army Materials Research Conference - 13th, edited by J. J. Burke, et al., Syracuse University Press, 1967, pp. 3-46.

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CHEMICAL COMPOSITION OF DC AND RF SPUTTERED MoS_2 FILMS

EXPT NO.	COMPOSITION OF ORIGINAL MoS_2, WT %	COMPOSITION OF DC SPUTTERED FILM, WT % (EXP COND: 3.5 kV, 20 MA, 20 μAr)	COMPOSITION OF RF SPUTTERED FILM, WT % (EXP COND: 400 W 15 μAr)
1	Mo 58.60 S 39.44 Fe .12	Mo 58.23 S 38.90 Fe .11	Mo 58.8 S 40.3
2	Mo 58.90 S 39.44 Fe .12	Mo 58.55 S 38.65 Fe .10	Mo 60.3 S 38.6
3			Mo 61.10 S 39.20

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Table 1

QUANTITATIVE ANALYSIS FOR ORIGINAL AND SPUTTERED PTFE

NO.	TYPE OF PTFE	CARBON, WT %	FLUORINE, WT %	RF EXPERIMENTAL CONDITIONS
1	ORIGINAL	24.16	75.32	
	SPUTTERED	33.89	65.34	INPUT, 430 W; DC VOLTAGE, 600 V; TARGET (AC), 1.7 kV, 20 μAr
2	SPUTTERED	32.16	67.79	INPUT, 250 W; DC VOLTAGE, 400 V; TARGET (AC), 1.1 kV, 12 μAr
3	SPUTTERED	27.78	71.91	INPUT, 220 W; DC VOLTAGE, 325 V; TARGET (AC), 1 kV, 4 μAr

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Table 2

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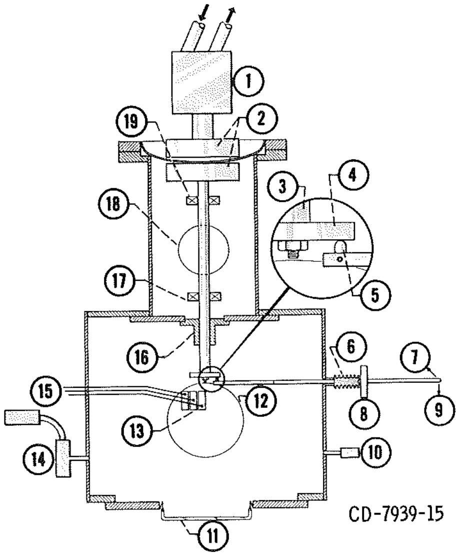
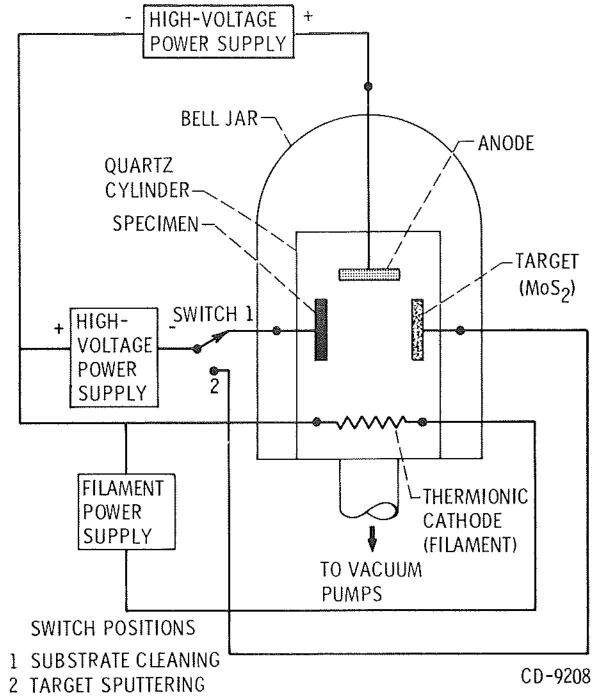


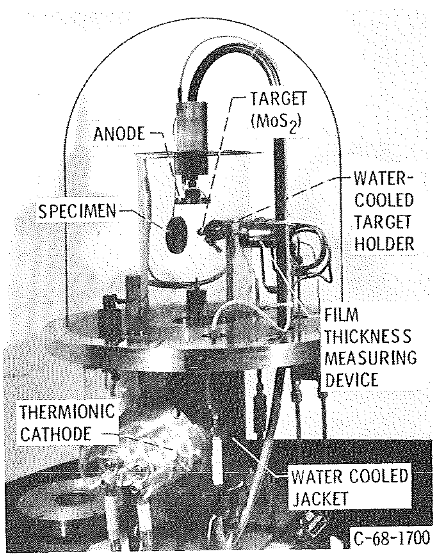
1 HYDRAULIC DRIVE MOTOR
2 MAGNETIC-DRIVE ASSEMBLY
3 SHAFT
4 DISK SPECIMEN
5 RIDER SPECIMEN
6 BELLOWS
7 FRICTIONAL FORCE
8 GIMBAL ASSEMBLY
9 LOAD
10 TRIGGERED DISCHARGE VACUUM GAGE
11 GLASS WINDOW
13 ELECTRON GUN WITH TUNGSTEN FILAMENT
14 MASS SPECTROMETER ASSEMBLY
15 POWER SUPPLY
16 MOLECULAR FLOW SEAL
17 WATER-COOLED SUPPORT BEARING
18 TO ION PUMP AND MECHANICAL PUMPING SYSTEM
19 WATER-COOLED SUPPORT BEARING

Figure 1. - Ultra-high-vacuum friction apparatus.



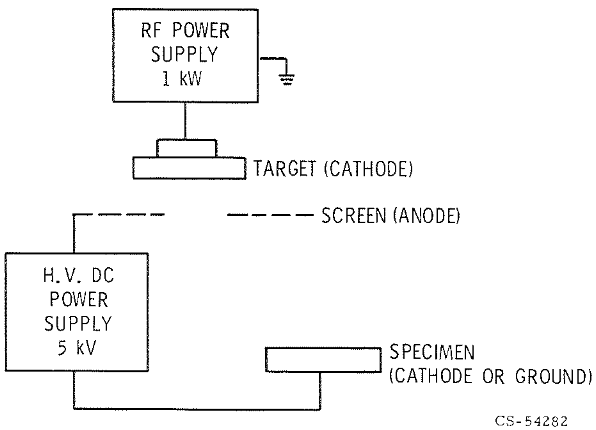
(A) TRIODE DIRECT-CURRENT SPUTTERING SYSTEM.

Figure 2



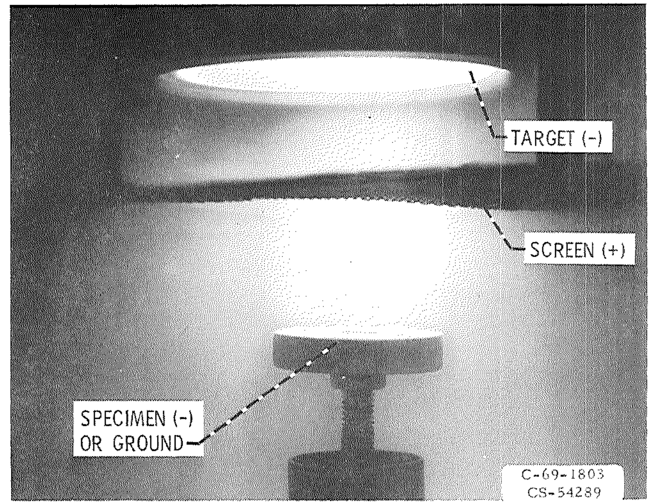
(B) TRIODE DIRECT-CURRENT SPUTTERING APPARATUS.

Figure 2. - Concluded.



(A) RF SPUTTERING SYSTEM WITH DC BIAS.

Figure 3



(B) RF WITH DC BIAS DURING SPUTTERING.

Figure 3. - Concluded.

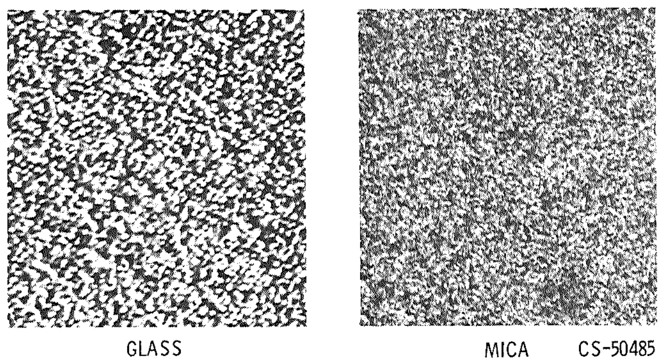


Figure 4. - Comparison of electron transmission micrographs of sputtered gold on glass and mica. X48 300.

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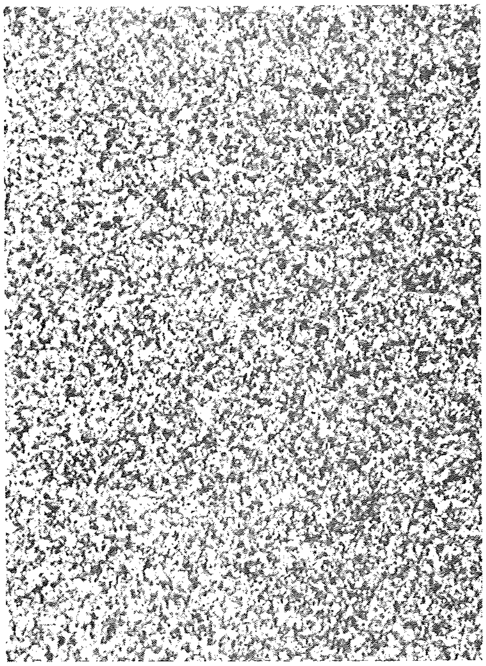


Figure 5. - Electron transmission micrograph of sputtered gold film on nickel surface. X87 000.

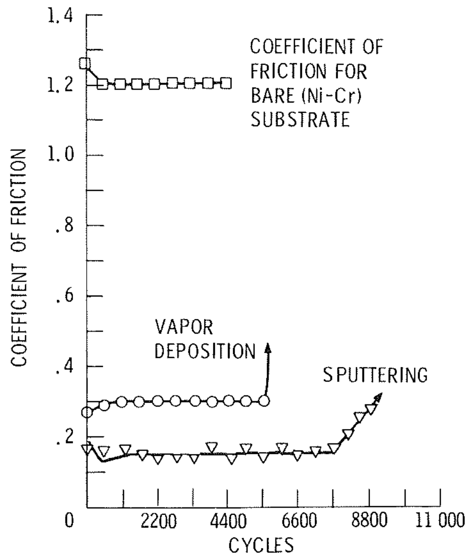


Figure 6. - Coefficient of friction of Niobium sliding on (Ni-Cr) alloy with gold deposited by vapor deposition and sputtering about 2000 Å thick. Load, 250 grams; speed, 5 feet per minute; ambient temperature, 10^{-11} torr.

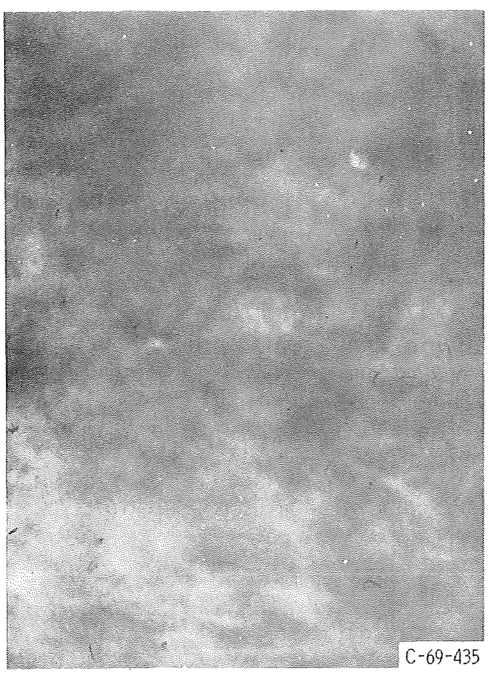


Figure 7. - Dark field transmission micrograph of MoS_2 film. X154 000.

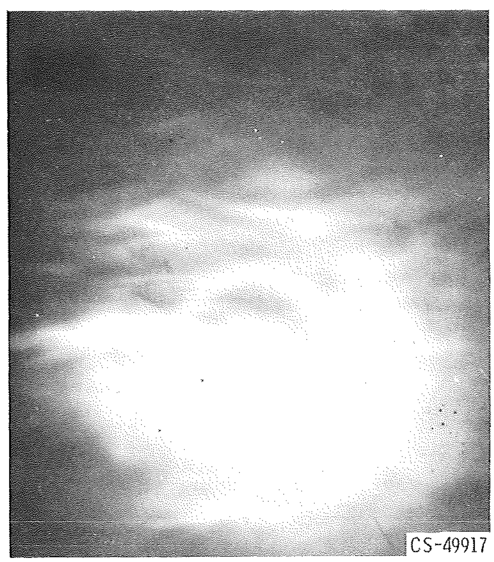


Figure 8. - Electron diffraction pattern of sputtered MoS_2 film.

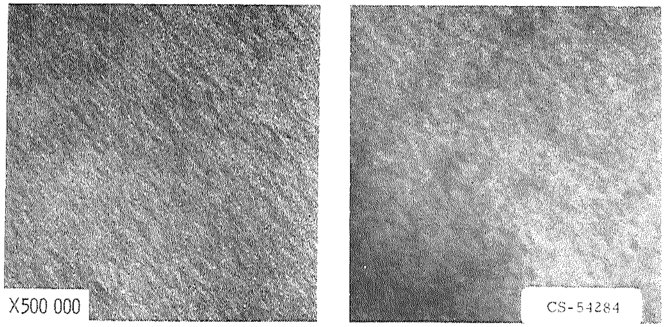


Figure 9. - Comparison of electron transmission micrographs of d-c sputtered MoS_2 film on Ni and polystyrene. X500 000.

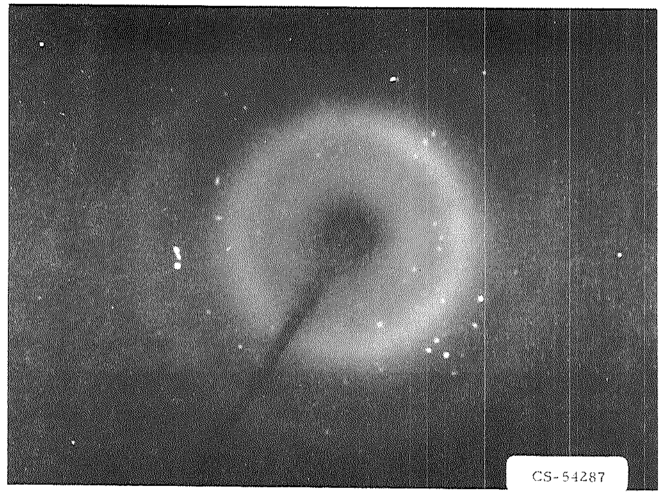


Figure 10. - Electron diffraction pattern of d-c sputtered MoS_2 film on nickel.

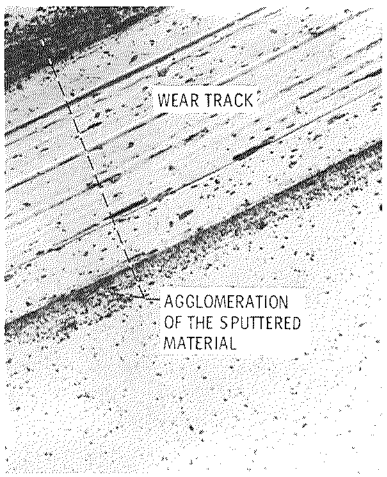


Figure 11. - Section of a wear track on (Ni-Cr) disk with sputtered MoS_2 film before failure, sliding over 0.5 million cycles.

ELECTRON MICROGRAPH OF SPUTTERED MoS_2 POWDER
X27 000

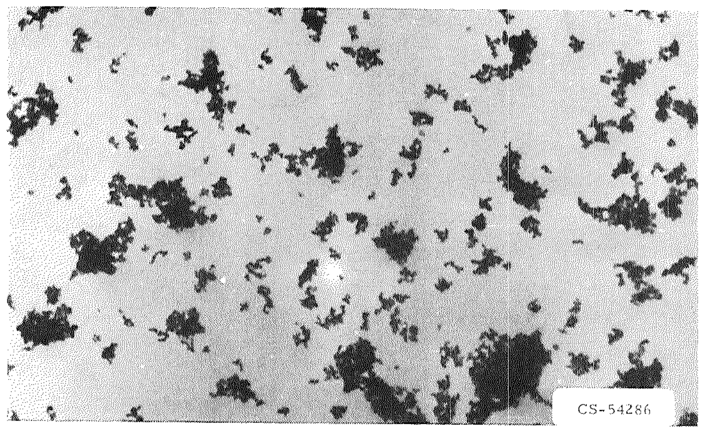


Figure 12

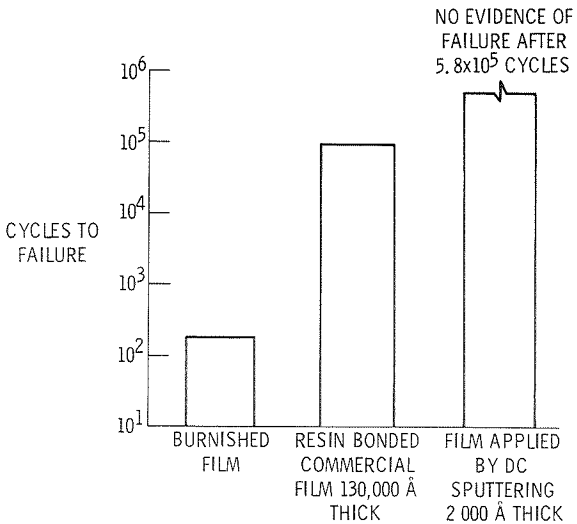


Figure 13. - Endurance lives of MoS_2 films applied by various techniques.

COMPARISON OF SCANNING ELECTRON MICROGRAPHS
OF AS-SPUTTERED MoS_2 (2000Å) ON NICKEL SURFACE
AND FRICTION WEAR TRACK AFTER SLIDING

AS-SPUTTERED MoS_2 FILM | WEAR TRACK AFTER SLIDING

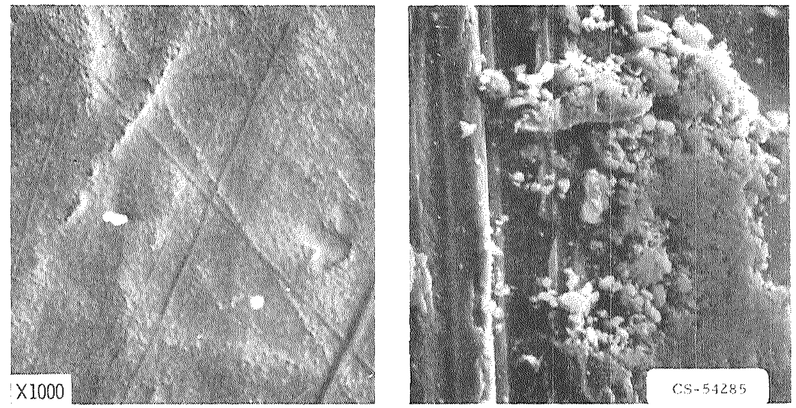


Figure 14

COMPARISON OF SCANNING ELECTRON MICROGRAPHS
OF AS-SPUTTERED MoS_2 (2000Å) ON NICKEL SURFACE
AND FRICTION WEAR TRACK AFTER SLIDING

AS-SPUTTERED MoS_2 FILM | WEAR TRACK AFTER SLIDING

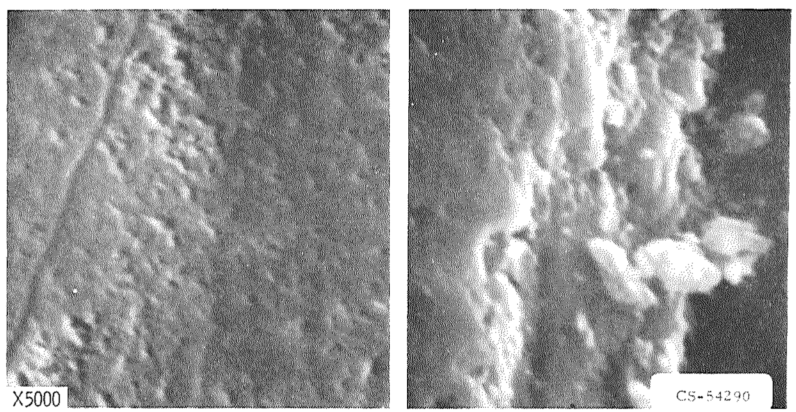


Figure 15

E-5706

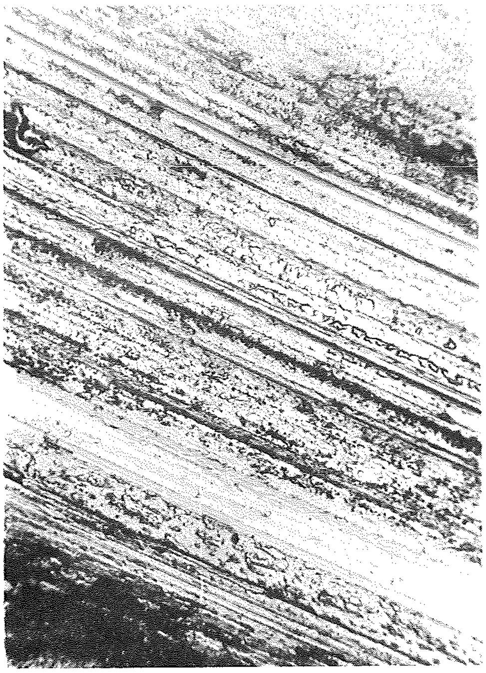


Figure 16. - Wear track of sputtered WS_2 film on Ni-Cr disk before it breaks through. Speed, 40 ft/min; load, 500 grams; pressure, 10^{-11} torr; coefficient of friction, 0.04.

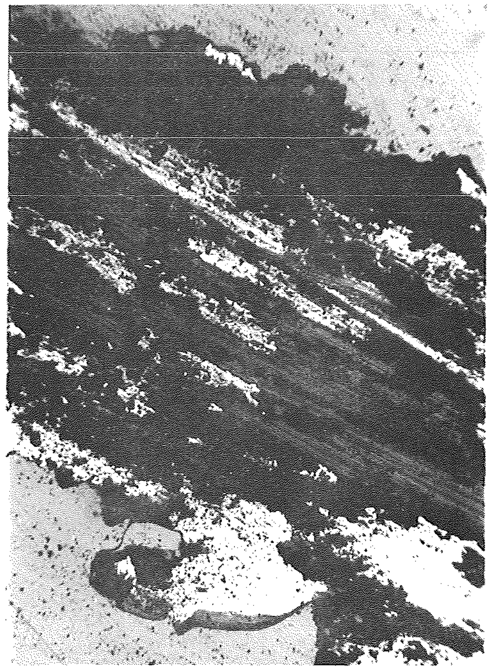
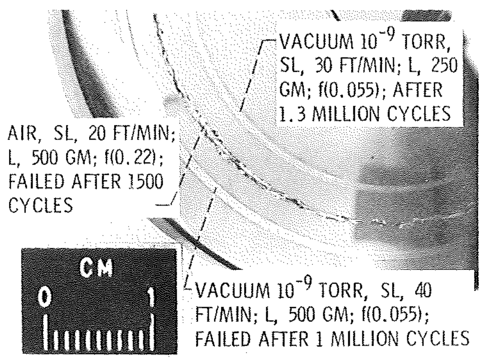


Figure 17. - Wear track of sputtered WS_2 film on Ni-Cr disk after metal to metal transfer.



C-69-1171

Figure 18. - Wear tracks on a (Ni-Cr) disk with sputtered WS_2 film (~2500 Å) after sliding against a 3/16 inch hemispherical nickel rider (SL, sliding velocity; L, load).

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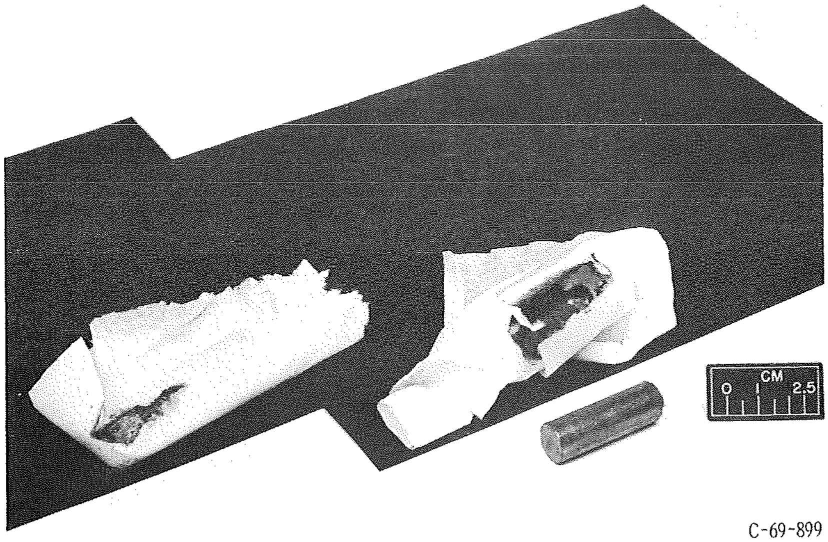
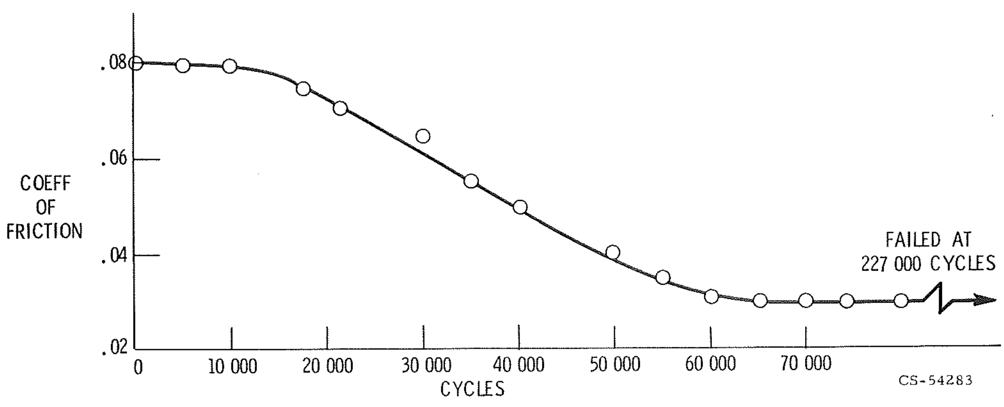


C-69-899

Figure 19. - Effect of humidity on cold-pressed WS_2 compact.

AVERAGE FRICTION COEFFICIENT OF 440C SLIDING ON 440C DISK COATED WITH RF SPUTTERED MoS_2 (2000Å) IN VACUUM (10^{-9} TORR)

LOAD, 250 GM; SPEED, 25 FT/MIN AMBIENT TEMPERATURE

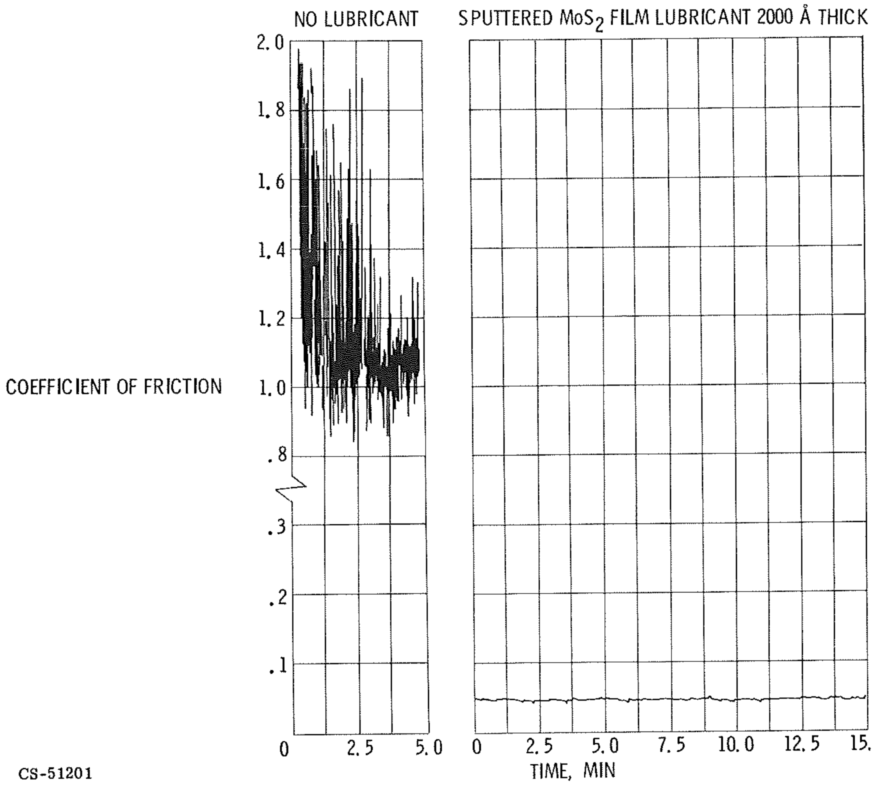


CS-54283

Figure 20

FRICTION OF NIOBIUM SLIDING ON NIOBIUM WITH AND WITHOUT A SPUTTERED MoS_2 FILM

PRESSURE, 10^{-11} TORR; LOAD, 250 GRAMS; SPEED, 5 FEET PER MINUTE



CS-51201

Figure 21

BALL BEARING ASSEMBLY COMPLETELY COATED WITH MoS_2 FILM BY RF SPUTTERING

Figure 22