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Sputtered Cadmium Oxide as a Surface Pretreatment for Graphite Solid Lubricant Films

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SPUTTERED CADMIUM OXIDE AS A SURFACE PRETREATMENT FOR GRAPHITE SOLID LUBRICANT FILMS

by

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Abstract

Sputtered films of cadmium oxide were applied to sandblasted AISI 440C HT stainless steel disks as a surface pretreatment for the application of rubbed graphite films. For comparison, rubbed cadmium oxide films were also evaluated as a pretreatment. In addition, mixtures of cadmium oxide and graphite were applied to the nonpretreated sandblasted metal and evaluated. These results were then compared to graphite films applied to other commercially available surface pretreatments. It was found that sputtered CdO pretreated surfaces increased the endurance lives of the graphite films and decreased the counterface steady-state wear rate of the pins almost an order of magnitude compared to commercially available pretreatments. CdO additions in general improved the tribological properties of graphite, but it was found the greatest benefit occurred when it was applied to the substrate rather than mixing it with the graphite. Sputtered films of CdO performed much better than rubbed CdO films.

INTRODUCTION

The object of solid film lubrication is to provide low friction and wear by separating relatively moving surfaces with a solid material which has a low shear strength. The most widely used solid lubricants with low shear strengths are the layer-lattice or laminar solids, such as graphite or molybdenum disulfide (1-3). Both have hexagonal crystal structures, and, when rubbed under pressure, the basal planes orient on the surface so that they become parallel to the sliding interface (4-7). This facilitates shear and the crystals' ability "to flow into themselves."

Having a layer-lattice structure, however, does not ensure a solid of having good lubricating properties. Both boron nitride and mica have a layer-lattice structure, yet neither is considered a good solid lubricant (1,3,4,8,9). Some evidence suggests they are not good lubricants because they do not adequately adhere to the surfaces to be lubricated (8). Thus, another important consideration is the ability of the solid lubricant to adhere to the surfaces to be lubricated. How well they bond to the surface is one of the factors that determines the endurance life of the solid lubricant film.

Peterson and Johnson in 1956 showed that mixtures of some metallic oxides or salts with graphite could improve the tribological properties of graphite films up to 540 °C (10). Cadmium oxide in particular was found to give very good results. Since that time others (11-13) have also found good results using cadmium oxide as an adjuntive to graphite films. It is not well understood why improved performance is obtained. Is it due to improved adherence of the graphite films to the metallic substrate or does the oxide or salt interact with the graphite itself to improve the film forming properties?

The purpose of this paper was to investigate the effect of cadmium oxide on the tribological properties of rubbed graphite films. Of particular interest was the effect of using a sputtered film of cadmium oxide as a metal surface pretreatment for the application of the rubbed graphite films. It was felt from results of a previous study on surface pretreatments (14) that sputtered cadmium oxide would be beneficial in helping the graphite adhere to the surface. For a comparison, graphite films were applied to cadmium oxide films (which were first rubbed onto the metallic substrate as a surface pretreatment) and to films prepared by mixing together graphite and cadmium oxide powder and then rubbing the combination onto the metallic surface. Talivaldis Spalvins of NASA Lewis sputtered the cadmium oxide films.

MATERIALS

Natural flake Madagascar graphite with a mean particle size of 15 μm (size distribution, 4 to 40 μm) and a specific gravity of 2.25 was used in this study. The cadmium oxide used was of technical grade and had a maximum impurity level of less than 0.5 percent, a specific gravity of 8.15, and a mean particle size of 1 μm (size distribution, 0.5 to 1.5 μm).

The pin specimens were made from SAE 1045 steel with a Rockwell hardness of B-90. The disk specimens were made from ASTM A-355(D) steel with a Rockwell hardness of C-28. The surface roughness of the pin was 0.10 μm. The disks were sandblasted and lightly polished to a surface roughness of 1.1 to 1.2 μm before the application of the graphite films.

APPARATUS

A pin-on-disk tribometer was used in this study. The device has been described in detail by the author (15). A schematic of the friction specimens is shown in Fig. 1. They consisted of a flat disk (6.3 cm diam) and a stationary, hemispherically tipped pin (0.467-cm rad). The pin slid on a 5.0-cm-diam track on the disk at a rotational speed of 100 rpm which translates into a linear sliding speed of 0.26 m/sec.

The apparatus used to mechanically rub (burnish) the solid lubricant powder onto the disks has also been described in detail by the author (15). The device consisted of a vertically mounted electric motor to which the disk was attached by means of a cup-shaped holder. The solid lubricant powder was applied to the disk as it rotated by means of polishing cloths attached to a floating metal plate. Two vertical rods attached to the same mount as the motor were used to restrain the metal plate. The rubbing load was applied by placing two 1-kg weights on top of the metal plate. The rubbing apparatus was designed to fit within the bell jar of a vacuum system. The bell jar was evacuated to 1000 Pa and then backfilled to atmospheric pressure with a 50-percent relative humidity air.

PROCEDURE

Specimen Cleaning

The steel disk surfaces were cleaned by washing with ethyl alcohol before sandblasting. After sandblasting they were scrubbed with a brush under running water to remove any adhering sand particles. The surfaces were then lightly rubbed on a polishing wheel using a water paste of levigated alumina to remove the sharp sandblasted asperity tips. Again they were scrubbed with a brush under running water to remove any adhering levigated alumina powder. Clean, dry air was used to quickly dry the surfaces. The disks which were given the sputtered cadmium oxide pretreatment were also sputter cleaned before applying the cadmium oxide film. The other films (rubbed CdO, graphite, or the mixtures) were applied to the surfaces that had been cleaned with levigated alumina.

The pins were washed with ethyl alcohol and then scrubbed with a water paste of levigated alumina. They were then rinsed in distilled water and dried with clean, dry compressed air. Solid lubricant films were not applied to the pins.

Sputtered Film Application

The sputtering apparatus used to apply the cadmium oxide films was a radio frequency-diode system with a superimposed direct-current bias. The apparatus is described in Refs. 16 and 17. The sputtering target consisted of a water cooled 12.7 cm diameter copper electrode to which was bonded a compressed circular sheet of compressed cadmium oxide powder. The disk to be coated was placed about 3.2 cm from the sputtering target. An argon pressure in the range of 20 torr was maintained in the chamber.

To improve adherence of the film the disk surface was first cleaned by dc sputter etching at -1200 V for 15 min. The dc power was then turned off and the rf power and bias voltage parameters were set and the deposition initiated. The conditions were an rf frequency of 7 MHz, rf power input of 400 W, dc input voltage of 500 V, and a target ac voltage of 1.2 kV. The films applied were in the range of 0.05 to 0.10 μm thick.

Rubbed Film Application

The procedure for applying the rubbed films was as follows:

(1) Apply a small amount of powder (either CdO, graphite, or the mixture of the two) to the disk and spread it evenly over the surface with the back of a polishing cloth.

(2) Apply 0.5 g of powder to the contact zone of the applicator and distribute it evenly.

(3) Assemble the apparatus and apply two 1-kg weights for the load.

(4) Evacuate the bell jar to 1000 Pa and then backfill it to atmospheric pressure with an atmosphere of moist air (50 percent relative humidity). Continue to purge the bell jar with moist air until the disk is removed from the apparatus.

(5) Set the disk into rotation by gradually increasing the speed to 15 rpm and rub for 1 hr. (Because very thick films of CdO tended to buildup, CdO films were only rubbed for 10 min.)

Test Conditions

The specimens were inserted into the tribometer, and the chamber sealed. Moist air of 50 percent relative humidity at 25 °C was purged through the chamber of 2000 cm^3 at the rate of 1500 cm^3/min for 15 min before commencing the test. The disk was set into rotation at 100 rpm (0.26 m/s), and a 9.8 N load was gradually applied. The test temperature was ambient (24 + 3 °C). Each test was stopped after 1 km of sliding and the pin wear volume was measured. The pin wear rate calculated for this interval was deemed the "run-in" wear rate.

Each test was also stopped after various other sliding intervals so that wear volume could be measured and surface morphology could be studied by optical microscopy. After studying the surfaces, the specimens were remounted in the tribometer, and the test procedure repeated. The pin was not removed from its holder, and locating pins ensured that it was returned to its original position. EDS (Energy Dispersive X-ray Spectroscopy) spectra of the undisturbed films before testing and of the wear tracks at failure were taken.

RESULTS AND DISCUSSION

Friction Coefficient

Representative plots of friction coefficient as a function of sliding distance for the various combinations of graphite and cadmium oxide films are given in Fig. 2 over the endurance life of the films. The friction for the complete endurance life of the graphite film applied to the sputtered cadmium oxide film is not shown however since the shortest life obtained was 2100 kc. The figure shows that the lowest values of stable friction for the longest periods of time were obtained when cadmium oxide was applied as surface layer to the metallic substrate before applying the layer of graphite. Mixing 10 or 25 wt % of cadmium oxide with graphite and then rubbing (burnishing) the mixture onto the metallic surface initially gave lower friction but on longer sliding durations gave slightly higher values of friction then did graphite alone.

Figure 3 compares the range of average friction coefficients obtained for the different tests (at least three tests were performed on each film) conducted on the various combinations of graphite and cadmium oxide films. Also given for comparison are the friction coefficients obtained on sputtered cadmium oxide and on rubbed cadmium oxide films which did not have graphite rubbed on them. It is interesting to note that sputtered cadmium oxide showed some lubricating ability, giving an average friction coefficient that varied between 0.17 to 0.23; while rubbed cadmium oxide showed little lubricating ability and gave a friction coefficient of 0.50 and higher, a value close to that of the unlubricated steel. The figure also shows that cadmium oxide applied as a intermediate sputtered or rubbed layer between the graphite and the metal substrate gave slightly lower average friction coefficients than mixtures of graphite and cadmium oxide or of graphite alone.

Endurance Lives

Comparison of the endurance lives (wear lives) obtained for 440C HT stainless steel pins sliding against the various graphite and cadmium oxide films is shown in Fig. 4. Endurance life was arbitrarily defined as the sliding time in kilocycles to reach a friction coefficient of 0.25. By far the longest lives were obtained with the graphite films applied to the sputtered cadmium oxide films. The lives for these films varied from 2100 kc up to 4400 kc. The next best endurance lives obtained were for the films that had a rubbed layer of cadmium oxide and then a rubbed layer of graphite. Lives of these films varied from 340 to 560 kc. Rubbed mixtures of 25 percent CdO and 75 percent graphite gave lives that ranged from 125 to 280 kc and rubbed mixtures of 10 percent CdO and 90 percent graphite gave lives that ranged from 45 to 85 kc. This compares to the rubbed graphite films alone which gave lives ranging from 170 to 180 kc. Thus, as far as endurance life is concerned, mixtures of cadmium oxide and graphite gave spurious results, sometimes longer lives sometimes shorter lives. Definitely though, the 10 percent addition of cadmium oxide was deleterious to the life of the films. The life of the sputtered cadmium oxide film alone ranged from 11 to 20 kc and the rubbed cadmium oxide films did not lubricate.

Pin Wear Rates

The run-in wear rate for pins sliding against solid lubricant films is not something that can be rigorously defined as taking place in a certain interval of time or sliding distance. Generally, run-in wear is a gradual process of steadily declining wear rates until some steady state wear regime is reached. For the purpose of comparison in this study, a run-in wear rate has been defined as the amount of pin wear per unit sliding distance occurring during the first kilometer of sliding. Figure 5 compares the pin run-in wear rates for pins sliding against the various films. The lowest values for run-in wear were obtained for the graphite film without any cadmium oxide adjunctives. The values obtained ranged from 3.2 to 6.3×10^{-16} m^3/m of sliding. The sputtered cadmium oxide-rubbed graphite film was next best, followed by the rubbed layer of cadmium oxide-rubbed layer of graphite film. The film produced from the rubbed mixture of 25 percent cadmium oxide and 75 percent graphite gave equivalent results to the sputtered cadmium oxide film (without the rubbed graphite layer) and was next best. The rubbed mixture film of 10 percent cadmium oxide and 90 percent graphite was only better than the rubbed cadmium oxide film to which the rubbed graphite film was not applied.

Figure 6 plots wear volume as a function of sliding distance for the rubbed graphite, the rubbed graphite applied to the rubbed CdO, and for the rubbed graphite-cadmium oxide mixture films. Figure 7 plots the same information for the rubbed graphite film applied to the sputtered cadmium oxide film. Two different plots are needed since the sputtered film produced much lower wear for a much longer period of time. As mentioned previously, the figures show that the run-in wear process is different for each film and that it takes different times for each to reach a steady-state wear value (the linear portion of the curves). For example, even though the sputtered cadmium oxide/graphite film gave very low wear during run-in, it took over 1000 kc of sliding to reach a steady state value.

Figure 8 gives a plot which compares the range of steady-state pin wear rates obtained for the films evaluated in this study. A most impressive fact about the sputtered cadmium oxide-rubbed graphite film is the amount that this film reduced the steady-state wear of the sliding pins compared to the other films. The average value obtained was 5×10^{-19} m^3/m of sliding, while the next best film, the rubbed layer of cadmium oxide-rubbed layer of graphite film, gave a value of 3×10^{-17} m^3/m of sliding. The graphite film (with no CdO) gave a value of 5×10^{-17} m^3/m of sliding, while the film produced by the mixture of 25 percent CdO/75 percent graphite gave a value of 7×10^{-16} m^3/m of sliding and the value of the 10 percent CdO/90 percent graphite mixture rubbed film was 5×10^{-15} m^3/m of sliding. The pin steady-state wear rate from the sputtered CdO film by itself was 2×10^{-15} m^3/m of sliding.

Film Wear Surface Morphology

Figure 9 gives a typical photomicrograph of the wear surface on a graphite film applied to a sandblasted metallic disk. This particular photograph was taken after 90 kc of sliding on the film. The photomicrograph shows that flat plateaus have been worn on the sandblasted metallic asperity tips and that a very thin film of graphite is flowing across the plateaus. The graphite powder is compacted in the valleys between the plateaus and after a period of time tends to crumble and eventually spall from the surface. This spalling may be a major factor in the depletion of the film and its eventual failure.

Figure 10 shows a photomicrograph of the wear track on the sputtered cadmium oxide-rubbed graphite layer film after 200 kc of sliding. The film wear surface is definitely more continuous than that seen on the graphite (no CdO) film and no crumbling of the film is observed. Also the sandblasted asperity tips protruding through the film are smaller and seem to be covered with a thicker and more uniform layer of the film. Thus it appears that the sputtered cadmium oxide has served as an intermediary to better bind the graphite to the metallic surface and to itself.

Figure 11 shows a photomicrograph (taken after 135 kc of sliding) of the film wear track which was produced by first putting down a layer of cadmium oxide and then a layer of graphite. Less cracking and crumbling of the wear track film between the asperities occurred (as compared to the graphite only film); but, thicker layers of solid lubricant were observed on the wear track metallic asperities. As figure 11 shows, these relatively thick layers had a tendency to blister and to spall, thus depleting the surface of solid lubricant.

Figure 12 shows a photomicrograph of the wear track (after 29 kc of sliding) on a rubbed film mixture of 10 percent CdO and 90 percent graphite. The interesting thing about this film is that large blisters formed which tended to crumble and spall, thereby rapidly depleting the lubricant in the contact zone. A similar phenomenon occurred, but to a lesser extent, with the 25 percent CdO and 75 percent graphite mixture film. In general, the mixtures of CdO and graphite tended to produce thicker films, but these films were not well bonded to the substrate. The photomicrographs of the wear tracks tend to indicate that the main benefit of cadmium oxide appears to be as an intermediary layer to help bond the graphite to the metallic surface. Cadmium oxide as a mixture with graphite promoted the adhesion of the graphite powder to produce relatively thick films under the low stress application conditions of this study, but when the higher loads of tribological testing were applied to the films, the films tended to rapidly blister and spall.

Transfer Film Morphology

The sputtered CdO/rubbed graphite film produced the most continuous, thinnest transfer films. Figure 13 shows a high magnification photomicrograph of the transfer to the metallic pin after 2680 kc of sliding. Broad interference bands in the transfer are observed, indicating the uniformity of the transfer and that the thickness was in the range of the wavelength of light, 0.4 to 0.8 μm.

The initial transfer films formed from the rubbed films which were mixtures of graphite and CdO were relatively thick (up to 3 or 4 μm). Figure 14 shows a high magnification photomicrograph of the transfer film after 1 kc of sliding produced from the rubbed film which was a mixture of 90 percent graphite and 10 percent CdO. The transfer produced for short sliding distances from the 75 percent graphite and 25 percent CdO films was similar. Thus, it is seen that the mixture of CdO and graphite which produced thick rubbed films under low application stresses also produced initial thick transfer films.

Once the applied thick film on the disk wear track (from the mixtures of graphite and CdO) had spalled, a thinner type of transfer occurred on the pin. Figure 15(a) shows a typical transfer film after longer sliding durations, in this case 50 kc of sliding. A buildup of material in the scar inlet and a very thin transfer film but no interference fringes are seen. The transfer had a speckled appearance.

No buildup of heavy transfer occurred with films that consisted of a rubbed layer of CdO and a rubbed layer of graphite. Their appearance was much like that of Fig. 15(a) from the beginning of the tests.

Transfer from the graphite only rubbed films was not as uniform as found with the other films. Figure 15(b) shows a photomicrograph of a typical transfer film from this film after 60 kc of sliding. Medium thick transfer films occurred which had striations in the sliding duration. Again no interference fringes were seen.

Elemental Surface Analysis

To determine the composition of the films and the uniformity of covering, the films and the wear tracks were analyzed using EDS. Figure 16 shows the EDS spectra of the rubbed graphite film applied to the sputtered CdO film (a) before testing and (b) at the end of the test. The film before testing shows very large cadmium peaks and a very small iron peak. Carbon and oxygen are not seen since this system was not capable of detecting them. The fact that hardly any iron is observed indicates that the CdO has uniformly covered the metallic substrate surface, screening out the production of iron x-rays.

Figure 16(b) shows at the end of the test on the wear track that much larger iron peaks are produced and that the cadmium peaks are reduced slightly. This indicates the iron surface is now exposed (or covered with a thin layer of the CdO-graphite film) and that a considerable amount of cadmium oxide is left behind. Most likely this cadmium oxide is in the valleys between the metallic asperities.

Figure 17 shows EDS spectra for the rubbed graphite film applied to the rubbed CdO film (a) before testing and (b) at the end of the test. The film before testing shows much larger iron peaks than did the sputtered CdO-rubbed graphite film, which indicates the rubbed cadmium oxide film did not cover the substrate surface as uniformly or as thickly as did the sputtered cadmium oxide film. The EDS spectra of the wear track at the end of the test shows less cadmium present than for the sputtered CdO-rubbed graphite film and larger iron peaks. This may have been due to the fact that there was less CdO present initially or that the rubbed CdO film was less strongly bonded to the metallic substrate than the sputtered CdO, especially in the valleys, and wore away or spalled away with the graphite.

Comparison to Commercially Available Films

A number of commercially available chemical surface pretreatments were evaluated under identical conditions to those of this study (14) to determine how much they would improve the tribological performance of graphite rubbed films. Table 1 lists the results of that study as well as average results for sputtered cadmium oxide and rubbed cadmium oxide as surface pretreatment. In the previous study the zinc phosphated surfaces by far gave the best results, giving an average endurance life of 460 kc and a steady state wear rate of 5×10^{-18} m^3/m of sliding. The rubbed CdO pretreatment gave an equivalent endurance life (470 kc), but a slightly higher steady-state wear rate (about 6 times greater). The sputtered CdO pretreatment gave an average endurance life of about 7 times longer than the zinc phosphated pretreatment and a steady state wear rate of about 10 times lower.

The mean friction coefficients obtained on all surface pretreatments were about equal, except for the salt nitrided surface which was slightly higher (this was a very rough surface); indicating that the mean friction coefficient was not highly dependent on surface pretreatment. The results indicate that the sputtered CdO pretreatment may be better than any commercially available pretreatment for increasing endurance life of graphite films and decreasing the wear of the counterface.

CONCLUDING REMARKS

Sputtered cadmium oxide films when used as a pretreatment for rubbed graphite films were found to give much longer endurance lives and much lower counterface (pin) steady-state wear rates than rubbed cadmium oxide films or some commercially available surface pretreatments which were evaluated. The reason appears to be that it afforded a better bond between the surface and the graphite. It also was found that a sputtered cadmium oxide film provided considerably better tribological properties than a rubbed cadmium oxide film.

This may have been due to a better bond between the sputtered cadmium oxide and the substrate.

SUMMARY OF RESULTS

Friction, wear, and wear surface morphology experiments were conducted on rubbed graphite films applied to metallic surfaces pretreated with sputtered cadmium oxide films. For a comparison, similar experiments were conducted with graphite films applied to metallic surfaces pretreated with rubbed cadmium oxide films, to rubbed films which consisted of mixtures of graphite and cadmium oxide, and to rubbed films of graphite alone. In addition, these results were compared to a previous study in which rubbed graphite films were applied to commercially available surface pretreatments. The results indicate that:

1. Graphite films which were applied to pretreated sputtered cadmium oxide films gave mean endurance lives about 20 times longer and mean counterface (pin) wear rates about 100 times lower than the same surface without the pretreatment. Friction coefficients were found to be equivalent.

2. Graphite films applied to pretreated sputtered cadmium oxide films gave mean endurance lives about 7 times greater and mean counterface (pin) wear rates about 10 times lower than graphite films applied to the best commercial surface pretreatment (zinc phosphate). Friction coefficients were equivalent.

3. Rubbed cadmium oxide pretreated surfaces gave improved results as compared to nonpretreated surfaces, but the results were not as good as the sputtered cadmium oxide pretreated films.

4. Films consisting of mixtures of cadmium oxide and graphite did not demonstrate a consistent tribological improvement when compared to the results of graphite films alone or the surfaces pretreated with cadmium oxide.

5. The primary beneficial effect of the cadmium oxide on graphite's tribological properties appears to be that it improves the bond between the metallic substrate and the graphite.

6. The cadmium oxide may also improve the bond between the graphite particles themselves, since thicker rubbed films were obtained for the mixtures; but in tribological experiments, these thick films tended to spall from the wear track depleting the surface of lubricant.

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TABLE 1. - COMPARISON OF RESULTS FOR RUBBED GRAPHITE FILMS APPLIED TO CADMIUM OXIDE PRETREATED STEEL SURFACES AND TO OTHER CHEMICALLY PRETREATED STEEL SURFACES

[Experimental conditions: ambient temperature, 25 °C; load, 9.8 N; speed, 0.26 m/s; controlled 50 percent RH air atmosphere.]

Disk surface pretreatment	Mean[b] endurance life, kc	Mean friction coefficient	Mean pin wear rate, m^3/m of sliding	
			Run-in	Steady-state
Sputtered CdO	3300	0.14	800×10^{-18}	0.5×10^{-18}
Rubbed CdO	470	.11	2000×10^{-18}	30×10^{-18}
Sandblasted	175	.14	490×10^{-18}	50×10^{-18}
Zinc-phosphated[a]	460	.13	250×10^{-18}	5×10^{-18}
Salt-nitrided[a]	150	.18	520×10^{-18}	20×10^{-18}
Gas-nitrided[a]	95	.14	1400×10^{-18}	120×10^{-18}
Sulfo-nitrided[a]	35	.13	9200×10^{-18}	2000×10^{-18}

[a]Data from Ref. 14.
[b]Kilocycles of sliding to reach a friction coefficient of 0.25.

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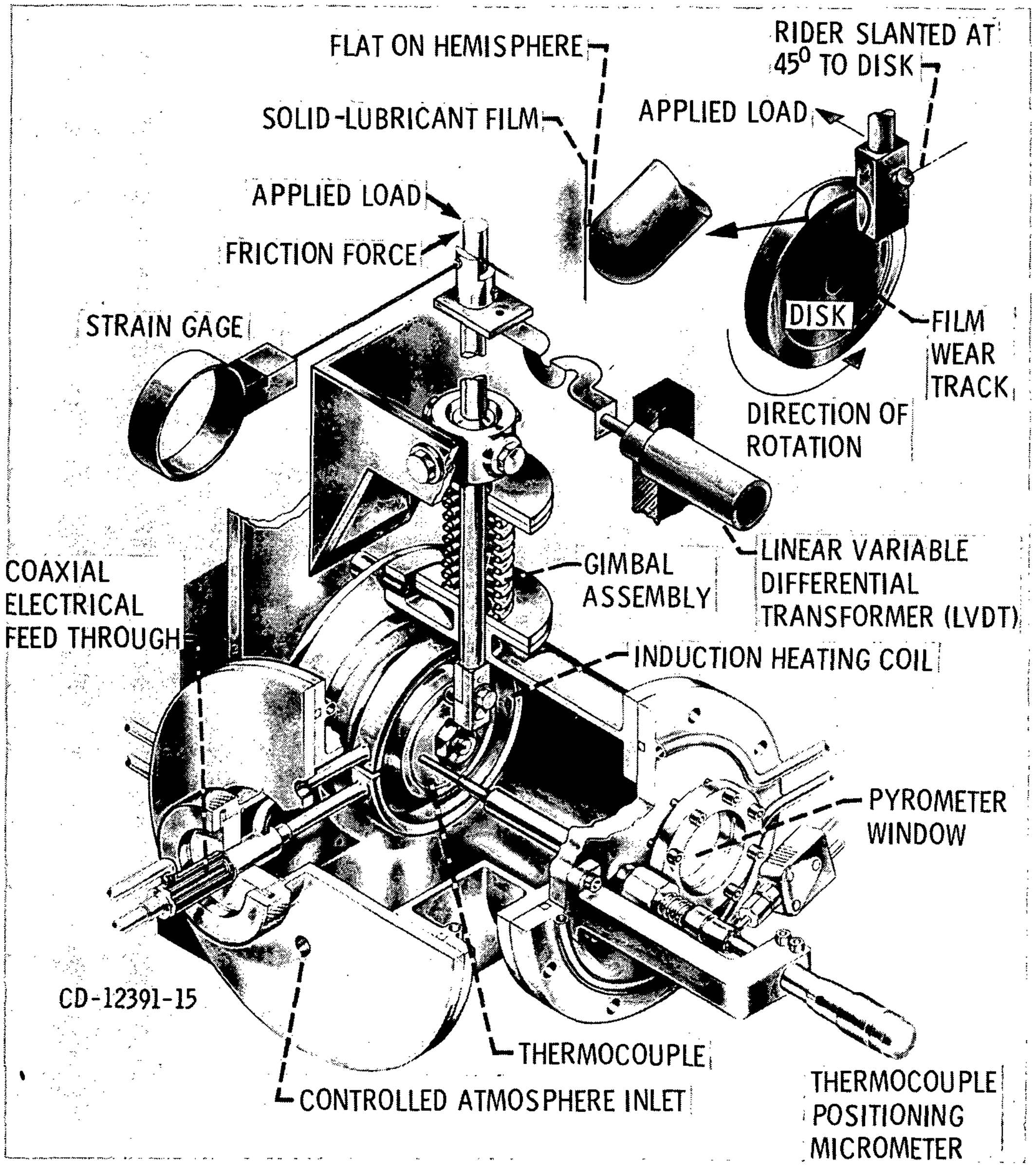


Figure 1. - High temperature pin-on-disk tribometer.

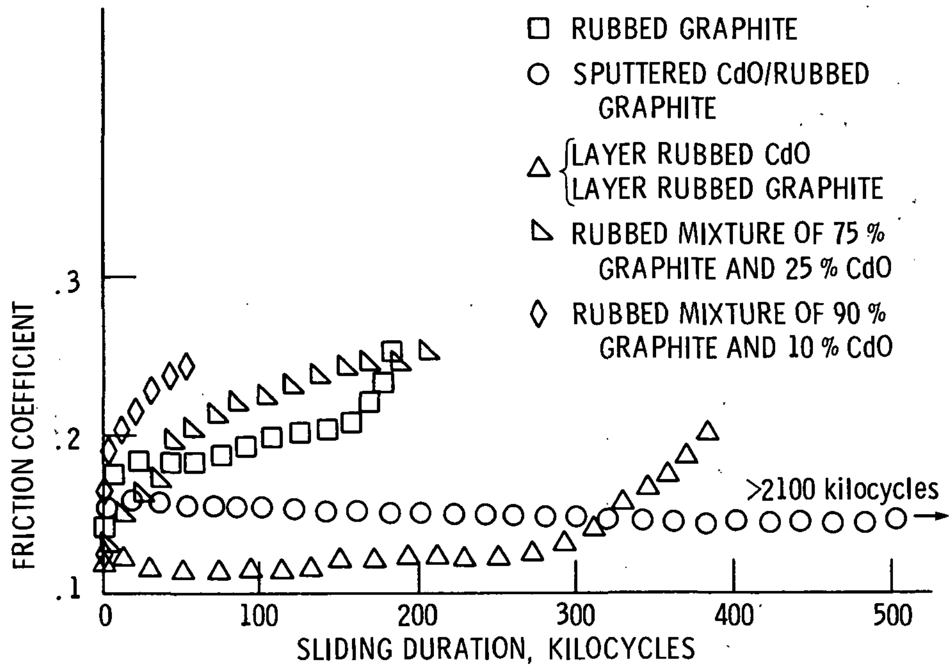


Figure 2. - Friction coefficient as a function of sliding distance for various combinations of graphite and cadmium oxide rubbed films.

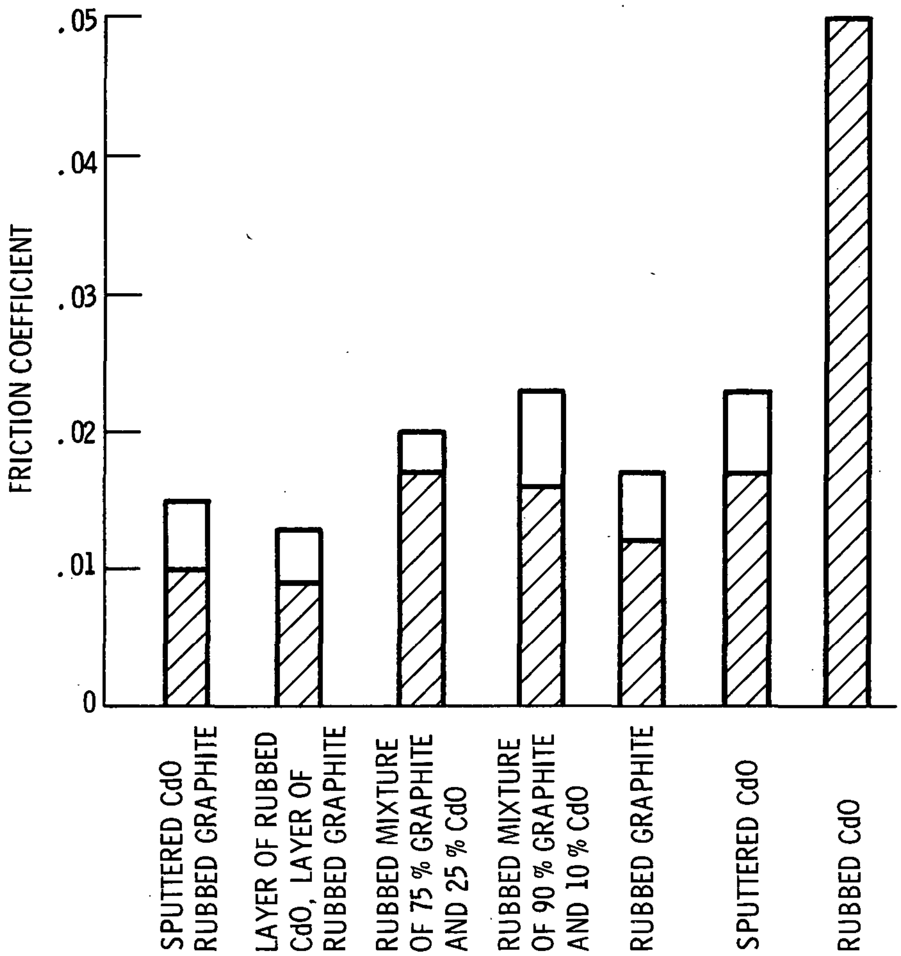


Figure 3. - Comparison of average friction coefficients for SAE 1045 steel pins which slid against various rubbed solid lubricant films.

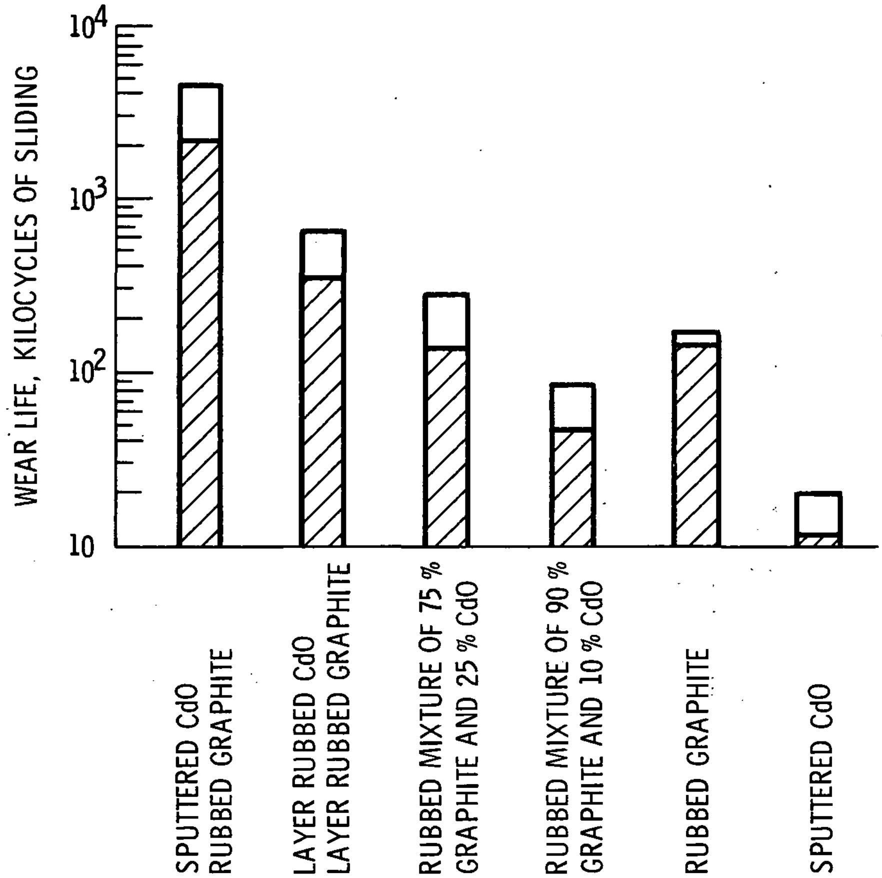


Figure 4. - Comparison of wear lives obtained for SAE 1045 steel pins sliding against various rubbed solid lubricant films.

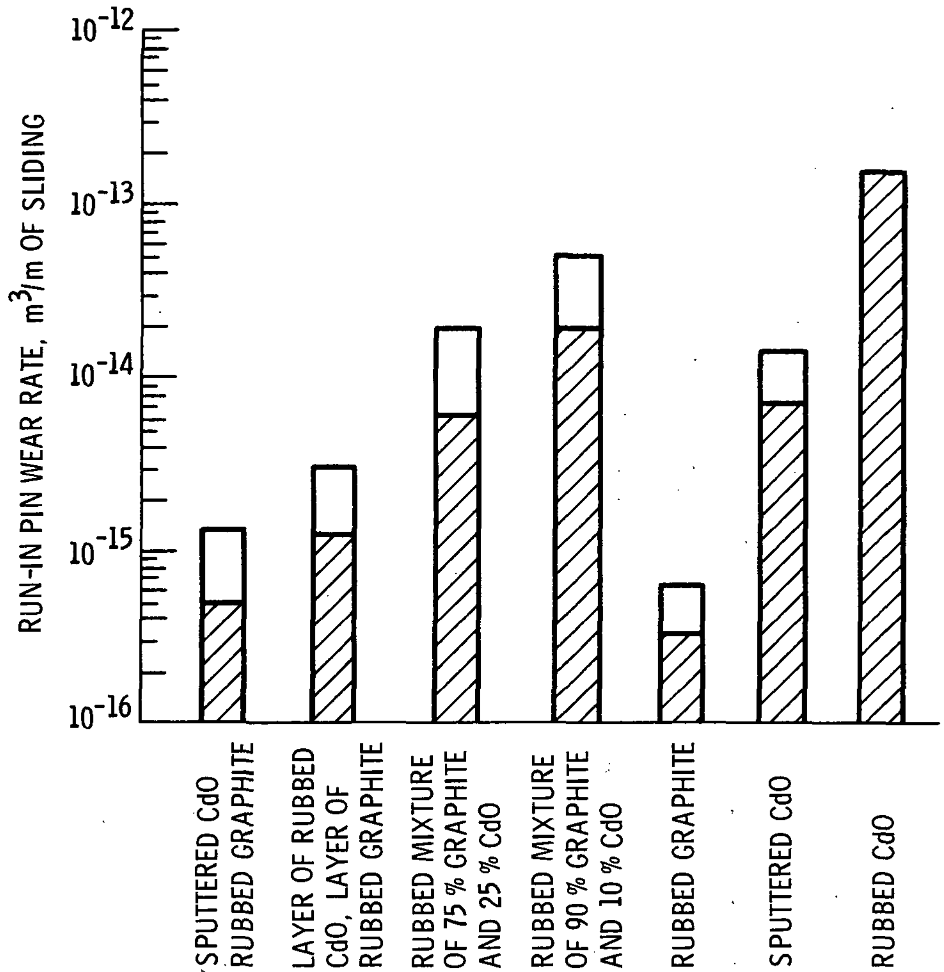


Figure 5. - Comparison of pin run-in (0 to 1 kilocycle of sliding) wear rates for various rubbed solid lubricant films applied to ASTM A-355 (D) steel disks.

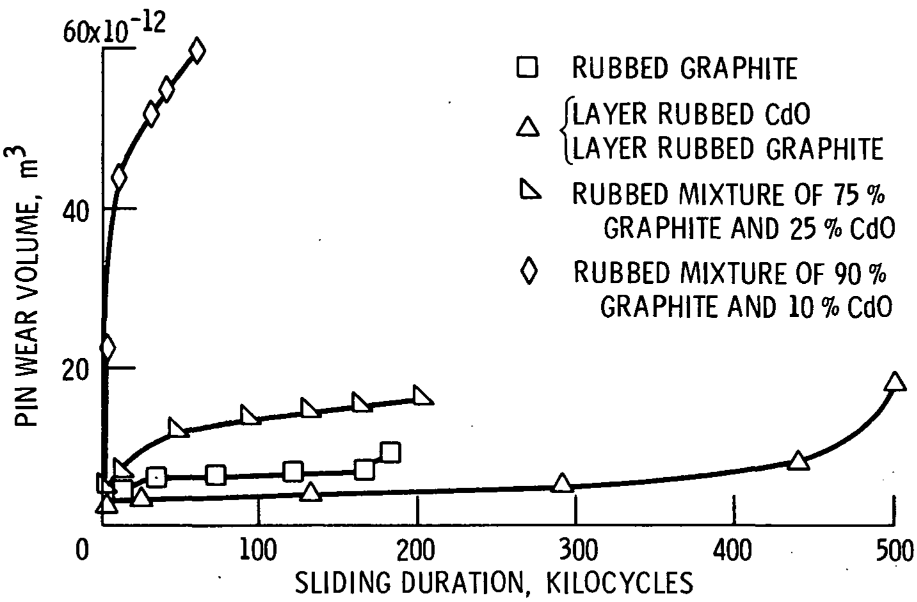


Figure 6. - Pin wear volume as a function of sliding duration for SAE 1045 steel pins sliding against various mixtures of graphite and cadmium oxide in rubbed films applied to ASTM A-355 (D) steel disks.

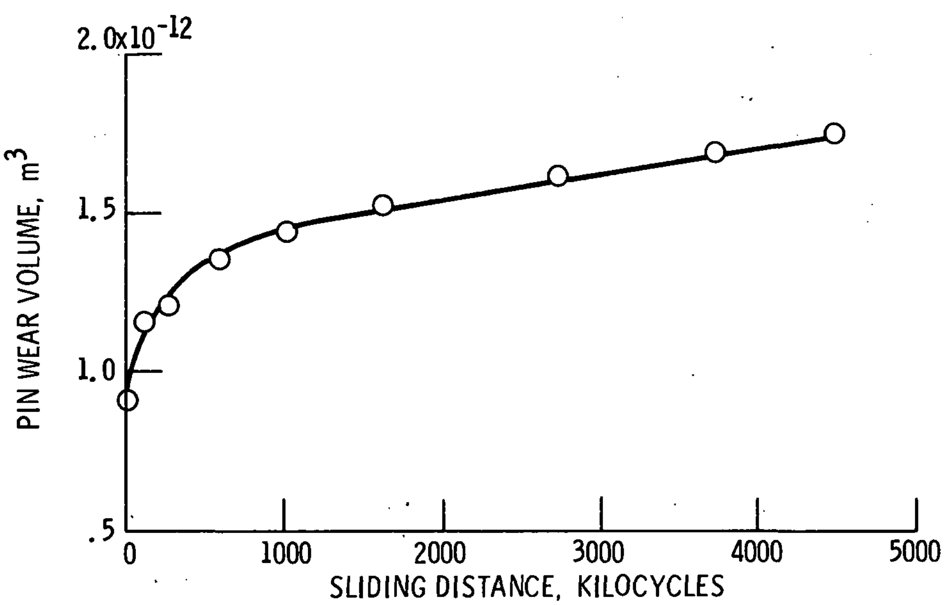


Figure 7. - Pin wear volume as a function of sliding distance for a SAE 1045 steel pin sliding against a rubbed graphite film applied to a ASTM A-355 (D) steel disk with a sputtered cadmium oxide surface pretreatment.

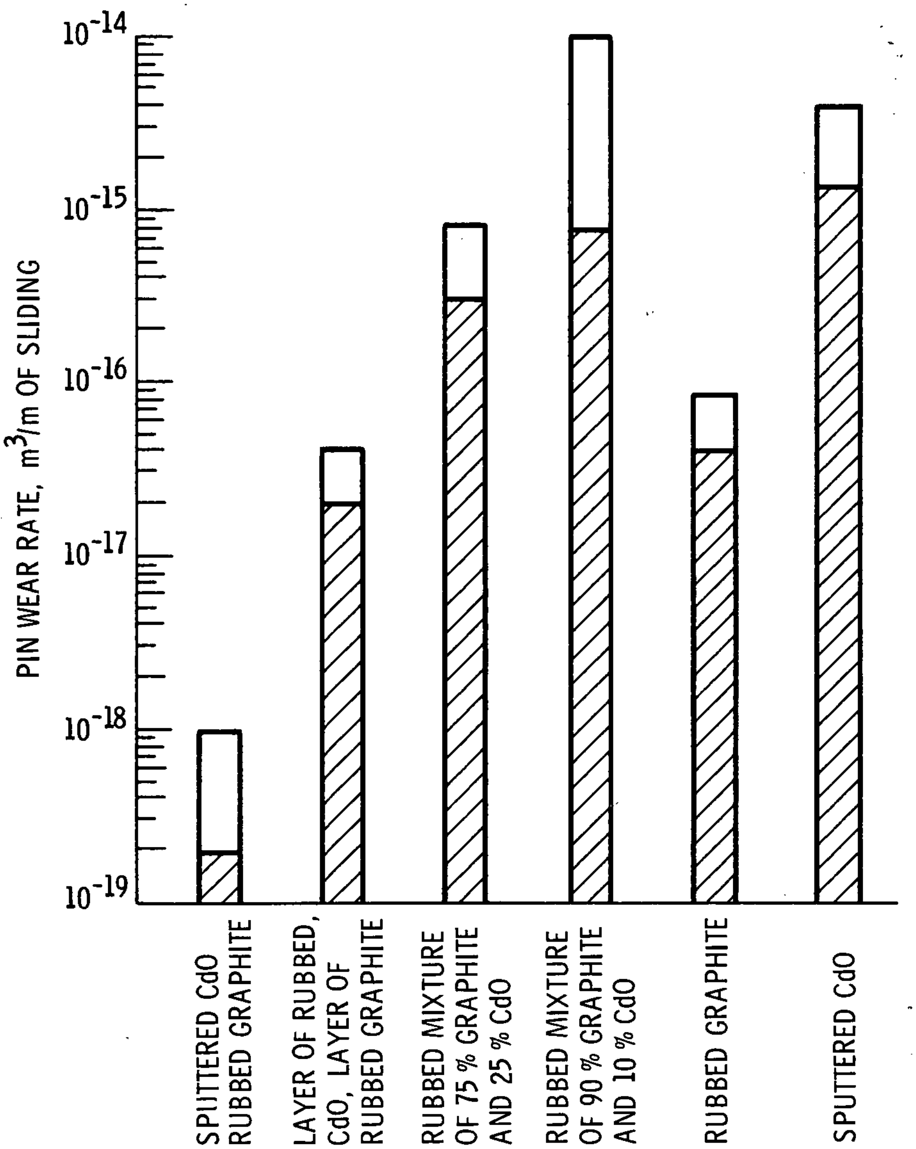


Figure 8. - Comparison of the average steady-state wear rates for SAE 1045 steel pins which slid against graphite and graphite/cadmium oxide rubbed films applied to ASTM A-355 (D) steel disks.

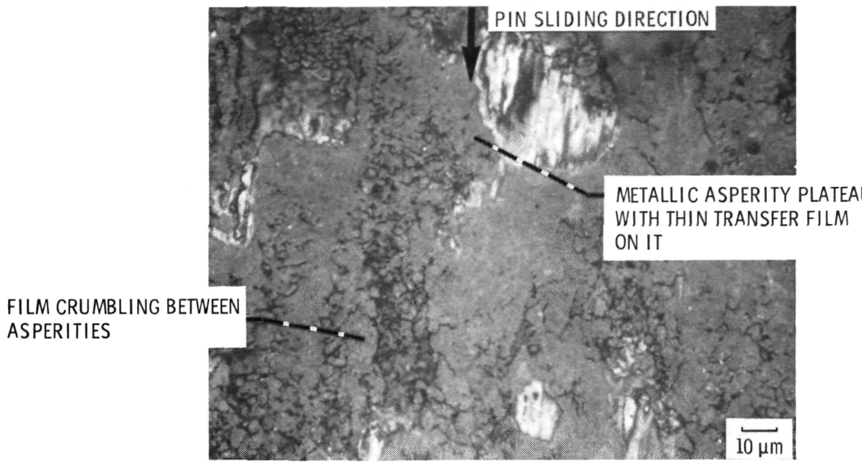


Figure 9. - High magnification photomicrograph of the wear track on a rubbed graphite film after 90 kilocycles of sliding.

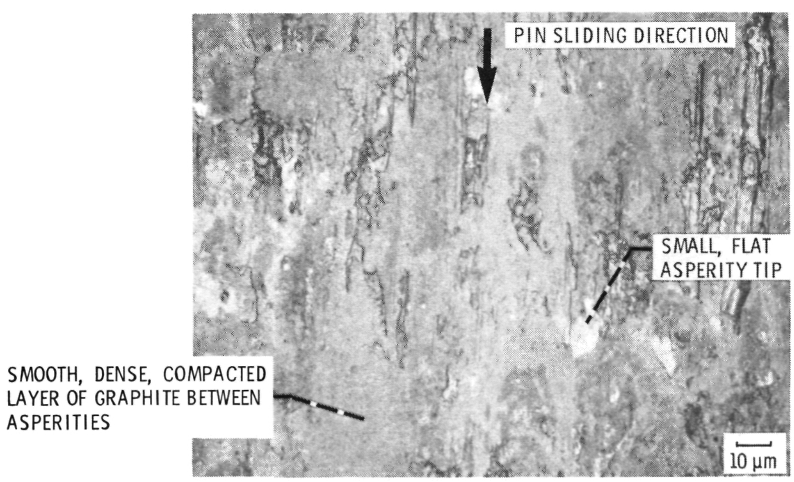


Figure 10. - High magnification photomicrograph of the wear track on a rubbed graphite film applied to a sputtered cadmium oxide film after 200 kilocycles of sliding.

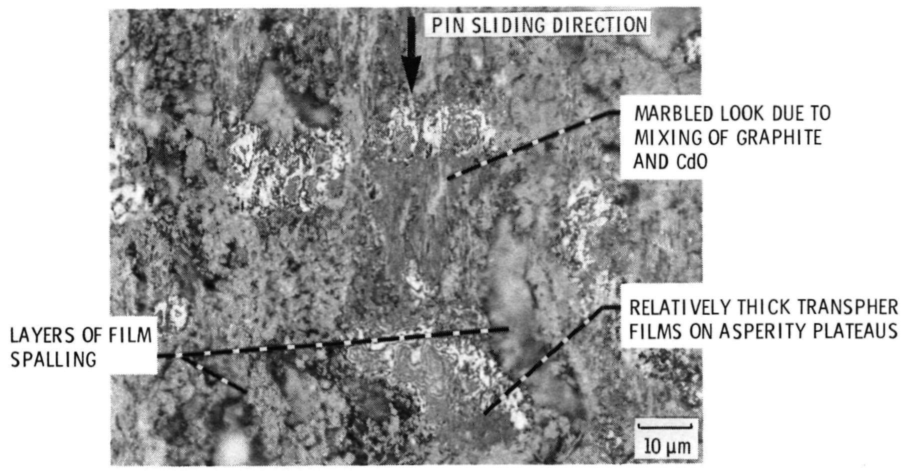


Figure 11. - High magnification photomicrograph of the wear track on a film, which was prepared by first putting down a rubbed layer of cadmium oxide and then a thin layer of graphite, after 135 kilocycles of sliding.

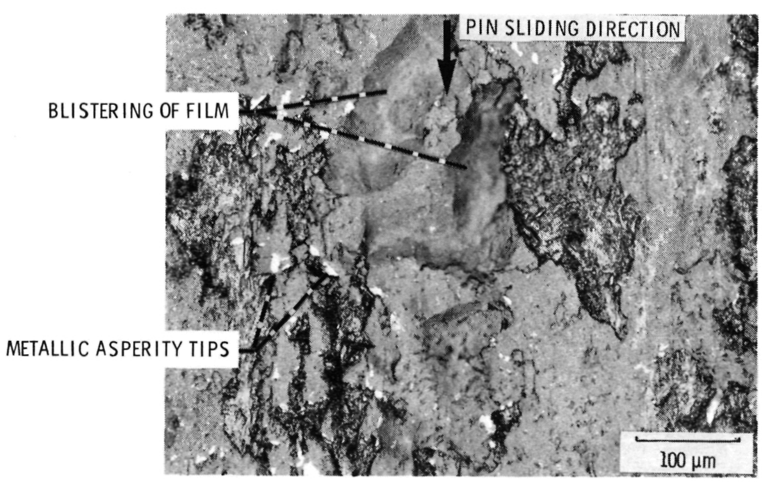


Figure 12. - High magnification photomicrographs of the wear track on a rubbed film which consisted of 90% graphite and 10% cadmium oxide after 29 kilocycles of sliding.

Figure 13. - High magnification photomicrograph of the transfer to a metallic pin from a graphite rubbed film applied to a sputtered cadmium oxide film after 2680 kilocycles of sliding.

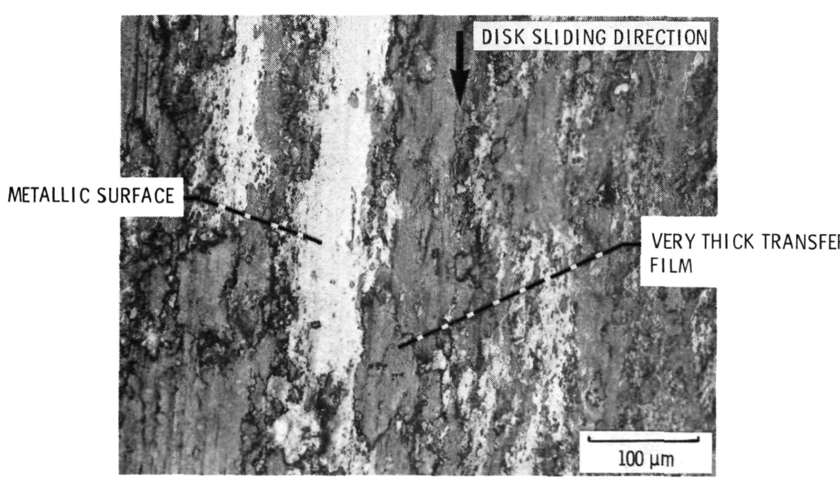
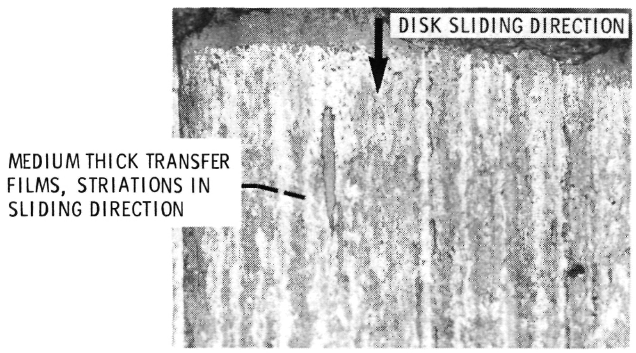
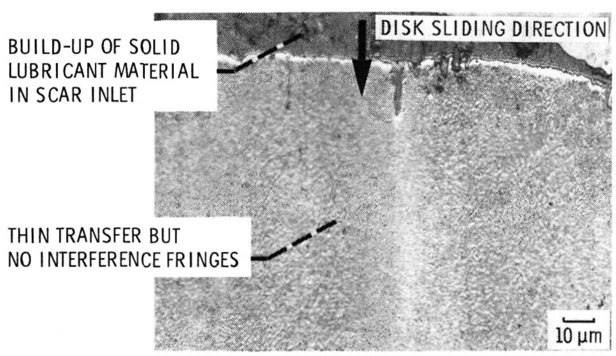


Figure 14. - High magnification photomicrograph of the transfer to a metallic pin from a rubbed film which was a mixture of 90% graphite and 10% cadmium oxide after 1 kilocycle of sliding.

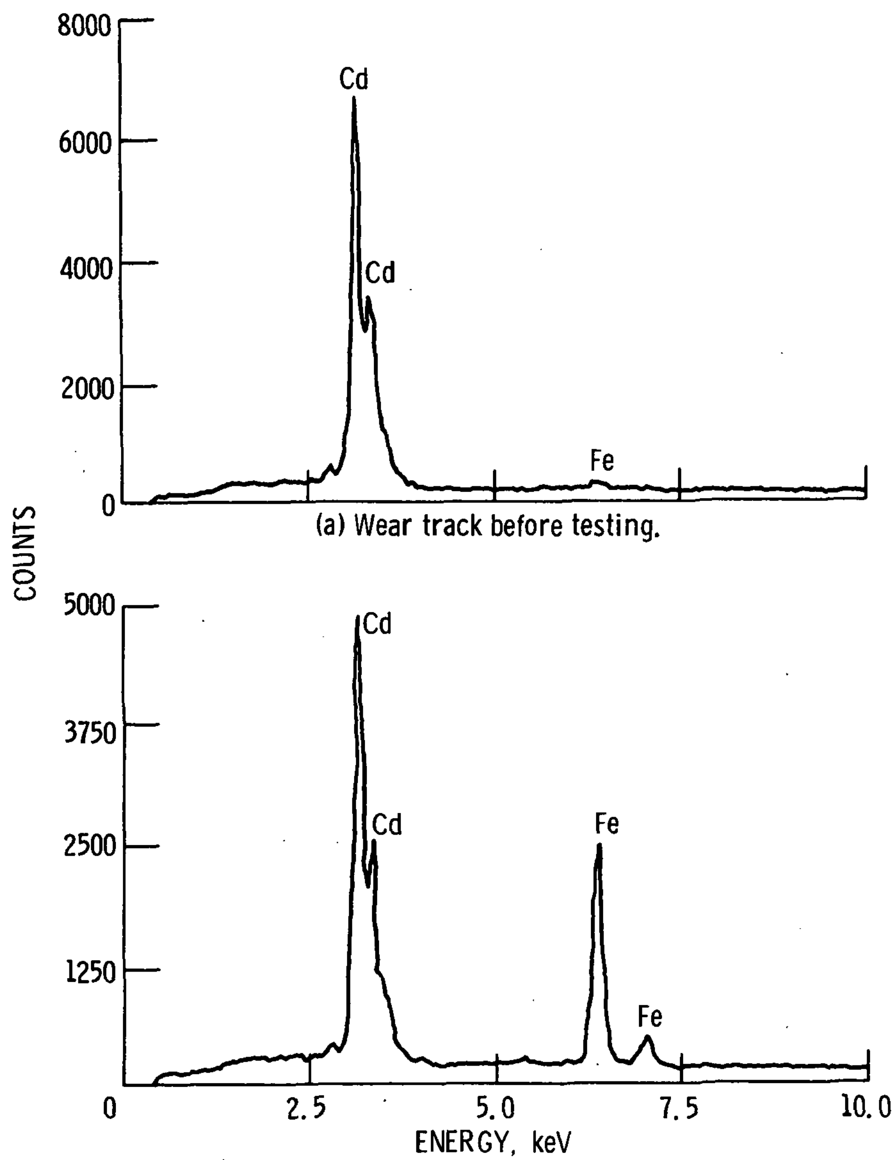


(b) Transfer from rubbed graphite films.



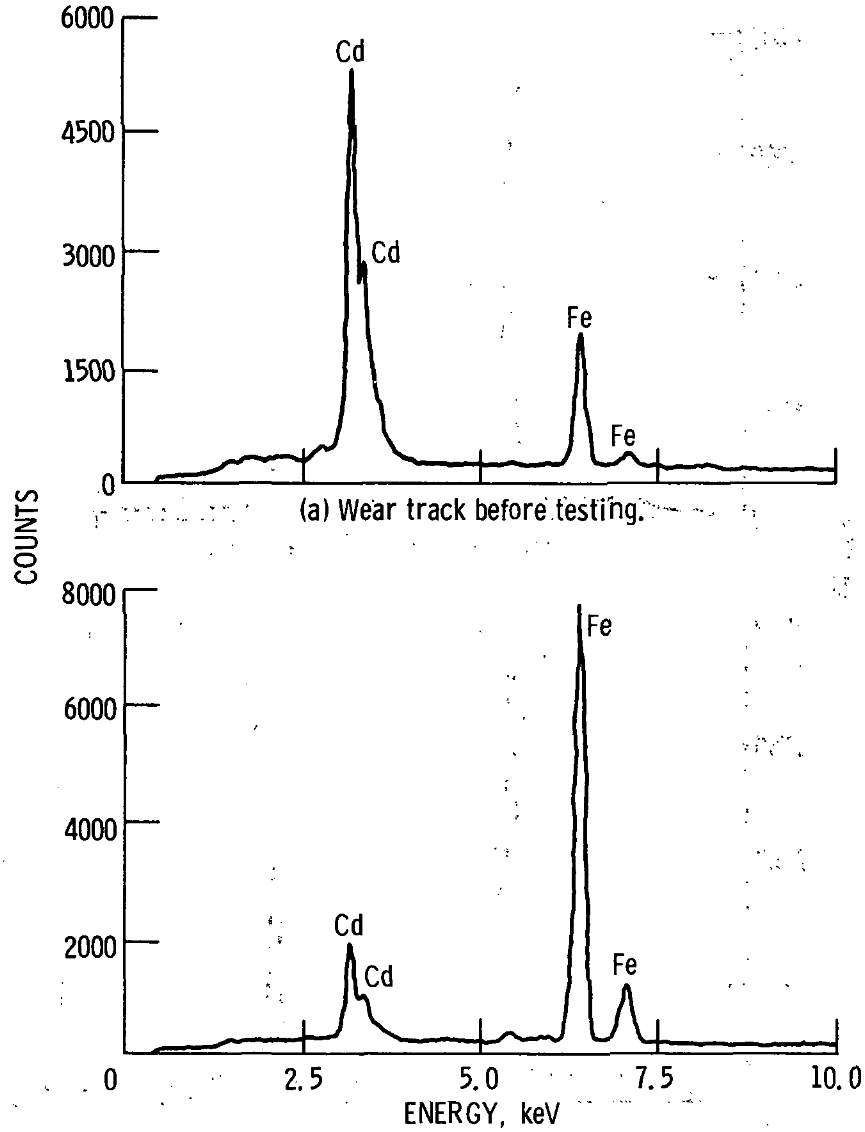
(a) Transfer from rubbed films containing graphite and CdO.

Figure 15. - High magnification photomicrographs of the transfer to steel pins from (b) Rubbed graphite films and (a) Films containing graphit containing graphite and cadmium oxide.



(b) Wear track at the end of the test.

Figure 16. - Energy dispersive x-ray spectra of the wear track of a graphite rubbed film applied to a sputtered cadmium oxide film applied to an ASTM A-355 (D) steel disk.



(b) Wear track at the end of the test.

Figure 17. - Energy dispersive x-ray spectra of the wear track of a graphite film applied to a rubbed cadmium oxide film applied to an ASTM A-355 (D) steel disk.

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16. Abstract

Sputtered films of cadmium oxide were applied to sandblasted AISI 440C HT stainless steel disks as a surface pretreatment for the application of rubbed graphite films. For comparison, rubbed cadmium oxide films were also evaluated as a pretreatment. In addition, mixtures of cadmium oxide and graphite were applied to the nonpretreated sandblasted metal and evaluated. These results were then compared to graphite films applied to other commercially available surface pretreatments. It was found that sputtered CdO pretreated surfaces increased the endurance lives of the graphite films and decreased the counterface steady-state wear rate of the pins almost an order of magnitude compared to commercially available pretreatments. CdO additions in general improved the tribological properties of graphite, but it was found the greatest benefit occurred when it was applied to the substrate rather than mixing it with the graphite. Sputtered films of CdO performed much better than rubbed CdO films.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Graphite; Cadmium oxide; Solid lubricants; Surface pretreatment; Friction; Wear; Films	Unclassified - unlimited STAR Category 27

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