NASA Technical Memorandum 87236

How to Evaluate Solid Lubricant Films Using a Pin-on-Disk Tribometer

(NASA-TM-87236) HOW TO EVALUATE SOLID LUBRICANT FILMS USING A PIN-CN-DISK TRIBOMETER (NASA) 22 p HC A02/MF A01 CSCL 11/4

N86-19465

Unclas

G3/27 05543

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Prepared for the
1986 Annual Meeting of the
American Society of Lubrication Engineers
Toronto, Canada, May 12-15, 1986

NASA

HOW TO EVALUATE SOLID LUBRICANT FILMS

USING A PIN-ON-DISK TRIBOMETER

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E-2909

SUMMARY

Over the years, the author has evaluated and compared hundreds of solid lubricant films using a pin-on-disk tribometer. The intent of this paper is to describe to the reader experimental techniques and some of parameters that have been observed to be important for the evaluation and development of new solid lubricant films. Pin-on-disk tribometers will be described and discussed as will experimental methods for evaluating solid lubricant materials. Methods of preparing surfaces for the coating of the films and different methods for applying the films will be reviewed. Factors that affect solid lubricant performance will also be discussed. Two different macroscopic mechanisms of solid lubricant film wear exist. These will be characterized schematically, and methods of measuring wear will be examined.

INTRODUCTION

Lubrication of sliding surfaces by use of films (or coatings) made from solid materials is becoming more common place. Solid lubricant films are needed and used for aerospace, automotive, industrial applications, etc. When evaluating what solid lubricant should be used for a specific application, the only sure way to determine how well it will perform is to evaluate it in its end use application. However, there may be hundreds of possible films which might be used for that particular application; thus it is advisable to evaluate the films first on an pin-on-disk tribometer to determine the best candidates to test in the final end use application.

Many factors, such as load, speed, temperature, atmosphere, geometry, etc. can effect the performance of a solid lubricant film. It thus becomes imperative to evaluate solid lubricant materials with a pin-on-disk tribometer under conditions which approximate the end use condition as closely as possible. These must be determined by the experimenter previous to testing.

Over the years, the author has had considerable experience evaluating solid lubricant materials on a pin-on-disk tribometer. The purpose of this paper is to help those of you who are unfamiliar with the pin-on-disk tribometer by describing typical apparatus and testing procedures. Also different methods of applying solid lubricant films will be explored and different methods of preparing the disk substrate for coating with a solid lubricant film will be discussed. Factors that affect solid lubricant film performance will be reviewed as will macroscopic mechanisms of film wear.

PIN-ON-DISK TRIBOMETERS

The basic geometry of a pin-on-disk tribometer is a stationary hemispherically tipped pin which slides against a flat surface of a rotating disk. The diameter of the pin and the thickness of the disk are arbitrary, but must be chosen to insure rigidity. For the pin, we have chosen a 0.476 cm radius hemisphere on a 0.952 cm diameter metal rod which is 2.54 cm long. We have made the disk 6.3 cm in diameter and 1.27 cm thick. The surface finishes of both pin and the disk should be made as smooth as possible, especially the pin. We specify the rms roughness to be less than 0.10 μm. To prevent extraneous lifting (inertial) forces from the disk, the front and back surfaces of the disk and the center hole must be concentric, parallel and flat. We specify that they must be within 0.0025 cm.

Usually we have the pin slide on a 5.2. cm diameter track on the disk, but by moving the position of the pin or in some cases the position of the disk, several tests can be conducted on the same disk. Also by aligning the pin at an acute angle (45° is typical) to the disk surface, several tests can be conducted using the same pin. This is done simply by rotating the pin to a new position in its holder before each test, e.g. figure 2. Considering that the pins can be quite expensive, this can be a real money saver.

The apparatus that holds the pin-on-disk specimens can be very simple or quite complex, depending on what variables are to be measured and controlled. Figures 1 and 2 show two different tribometers that we have at NASA Lewis. Figure 1 is a rather simple apparatus which was built on a drillpress. The drillpress motor (not shown in the figure) is capable of rotating the disk at speeds of 1/4 to 1000 rpm or faster, which makes the apparatus very versatile. The load is applied to the pin using a lever and gimbal system and the same system transfers the friction force to a strain gauge. A preload, as shown in the figure, increases the inertia and reduces vibrations caused by stick slip friction. The strain gauge, lever and gimbal system, load and preload, etc. are built on a platform that can be translated back and forth to change the diameter of the wear track that the pin generates on the disk. The pin is attached to the lever system by a long, rigid holder, so that the disk can be submerged in a liquid if desired or so that a small furnace can be mounted around the pin-on-disk specimens. A plastic box (not shown) has been also designed to fit around the specimens so that the atmosphere can be controlled. We have found this to be particularly useful in controlling the amount of moisture in the atmosphere, since lab air has been found to vary from 20 percent relative humidity in the winter to 80 percent in the summer.

A high temperature pin-on-disk tribometer is shown in figure 2. The test specimens are the same, but the support hardware is slightly different. For example, the specimens are enclosed in a container made from a nickel based alloy. This is done so that the disk can be heated to temperatures of 1000 °C, and so that positive gas pressure atmospheres of such gases as argon or hydrogen can be maintained. A carbon face seal on the rotating shaft of the disk provides the necessary sealing of the container. The disk is heated to the desired temperature by a low frequency induction unit. The temperature of the disk is monitored by a thermocouple when the disk is stationary and by an optical pyrometer when rotating. A linear variable differential transformer mounted on the lever arm is used to properly position the pin during setup and to give an indication of wear during the experiments. Frictional heating of the specimens, however, makes accurate wear measurements with this instrument impractical. A metal bellows is incorporated to seal the lever arm system which is used to transmit the load and friction force.

APPLYING SOLID LUBRICANT FILMS

There are many ways to apply a solid lubricant film. Probably the simplest method is to use a polishing cloth and burnish (rub) the solid lubricant powder by hand onto a disk surface. A more sophisticated method is to apply the burnished film mechanically. To accomplish this, we have designed an apparatus to apply solid lubricant powders to a disk (fig. 3, ref. 1). The disk is attached to the vertical shaft of a small electric motor by means of a cup-shaped holder. Two vertical rods are used to restrain a floating metal plate to which are attached the solid lubricant applicators (in this case a sponge, but polishing cloths can also be used). The burnishing load is applied by placing weights on top of the metal plate.

It is well known that the atmosphere in which a solid lubricant is applied can effect the quality of the film (refs. 2 and 3), therefore the apparatus was designed to fit within the bell jar of a vacuum system so that the atmosphere could be controlled. This is done by first pulling a vacuum and then backfilling with the desired atmosphere. The burnishing conditions are variable. We have obtained good results using a 19.6 N load, a sliding speed of 15 rpm, and a 50 percent relatively humidity moist air atmosphere.

Another simple way to apply solid lubricant powders is to impel them at high velocities at the disk surface. The method tends to physically imbed the powders into the surface.

Probably the most common way of using solid lubricant films is to incorporate solid lubricant powders into a binder system. The binder functions much like a paint, holding the solid lubricant powders and bonding them to the surface. The binder can function merely as a material which binds the particles to the surfaces; or if the binder is a good lubricating material itself (like the polyimide polymer), the two can mix together to produce an even better lubricating film. Bonded films can be applied by dipping, painting with a brush, or spraying. Any method used to apply paint might be used to apply a bonded solid lubricant film. An important criteria to be considered when spraying, is that the particle sizes must be small enough to pass through the sprayer orfice. Figure 4 gives an example of the steps needed to apply and evaluate a bonded solid lubricant film. Depending on the type of solid lubricant and binder used, step 2 (milling binder and lubricant), may not be necessary.

Plasma spraying is another technique being used today to apply solid lubricant coatings. In this method a carrier gas such as argon is passed through a very high electric potential and ionized to create a plasma stream. Solid lubricant powder is injected into the plasma stream before it exits the plasma gun and these particles when they strike a surface become fused to it. A disadvantage of this method is that very high temperatures are produced in the plasma and only materials which have high thermal stability can safely be applied by this method. Figure 5 gives a schematic diagram of the plasma spray process.

Two relatively new methods for applying solid lubricants involving high technology have been advocated by NASA Lewis scientists for a number of years now (refs. 4 and 5). They are ion plating and sputtering. A vacuum system is needed for both methods. The advantage of these methods is that highly adherent, very thin layers of solid lubricant materials can be deposited. For more information about these methods see references 4, 5, and 6.

DISK SUBSTRATE PREPARATION FOR COATING FILMS

An important consideration for the employment of a solid lubricant film is that the film must be well bonded to the surface that it is applied. One requirement is that the surfaces must be clean. Thus, oil, grease, and oxide films should be removed from the surface before coating. For rubbed or bonded films, we do this by cleaning the surfaces using oil dissolving solvents and then scrubbing with levigated alumina (a mild abrasive). Once surfaces are clean they should never be touched with the bare hands as a precaution against contamination with skin oils. An advantage of vacuum deposition methods is that sputtering can be used to remove all oxide films, thus very clean surfaces are obtained.

Cleaning is very important, but improved bonding can be achieved by pretreating the substrate. This can be accomplished either mechanically or chemically. By mechanically, we mean simply roughening the surface by a technique such as sanding or sandblasting. Roughening the surface increases the surface area and provides a reservoir for solid lubricant material. If techniques such as these are used, it is important to remove any high or sharp asperity that is produced. If not, they will abrade the pin and cause high run-in wear. Rubbing the disk surface on a polishing wheel (after sandblasting and removing any adhering sand particles) will remove these high spots and sharp asperities.

Surfaces can also be chemically pretreated. Chemically pretreated surfaces can function in two ways. They can serve as a rough surface to improve bonding and serve as a reservoir (much like a mechanically treated surface); or they can form a conversion surface layer which can mix with the solid lubricant film to improve bonding or actually form a new solid lubricant layer consisting of the two constituents. For more information on pretreated surfaces see reference 7.

FACTORS AFFECTING SOLID LUBRICANT PERFORMANCE

There are many experimental parameters which can affect the performance of a solid lubricant material. Table I lists some of those factors. First of all, the type of material to which a solid lubricant film is applied can determine how well it will function. Some metals are intrinsically hard to lubricate, such as AISI 300 series stainless steel. A solid lubricant applied to this material may fail immediately, but this does not classify the solid lubricant as a bad lubricating material. It just means that it will not lubricate this particular material. The solid lubricant and the metal it lubricates are a system, ideally the type of materials to be lubricated should be chosen just as carefully as the solid lubricant. However, in many instances (if not all) the metals to be lubricated are selected long before the solid lubricants are evaluated for that application. In that case, it behooves the experimenter to find the best solid lubricant for that metal.

In general, hard materials can be lubricated to produce lower wear than soft materials. As a standard material at NASA Lewis, we use AISI 440C HT (high temperature) steel with a Rockwell C hardness of 60 as the pin and the disk material.

The geometry of the sliding specimens can also affect the lubricating ability of the solid lubricant. Geometry can influence contact stress and if the stresses are too high, the solid lubricant film can brittlely fracture or become plowed out of the contact area. A hemisphere sliding against a film can impart very high contact stresses even at relatively light loads. Thus in some cases to obtain lower stresses it may be advisable to slide a flat against the film rather than a hemisphere.

Applying the solid lubricant film to the right surface is also important. For example if the film were applied to the pin instead of the disk, it would be in continuous contact and would be worn away very quickly. If this were the type of contact you wanted to simulate this would be fine, but in most cases you would want to apply the film to the disk surface, or to the surface which could supply the greatest amount of lubricant to the contact.

The disk substrate hardness in relation to the pin and the magnitude of the applied load are very important also. If a high contact stress were applied to a film and the substrate either elastically or plastically deformed, chances are that the film would not follow that deformation and would either brittlely fracture or plastically deform, permitting metal to metal contact to occur. Thus the hardness of the substrate relative to the applied Hertzian contact stress is an important consideration. The pin should also be the same hardness or softer than the substrate so that if any metallic wear does occur it occurs to the pin and not the substrate. A hard metallic pin would abrade a softer substrate.

Substrate surface topography was mentioned in the section entitled "Disk Substrate Preparation." In general, most burnished or bonded solid lubricant films will not adequately bond to very smooth surfaces, so to ensure a good bond the disk substrate surface needs to be roughened in some manner. As mentioned in the previous section this can be done mechanically or chemically. The opposite is true of the surface (pin) sliding against the film. This surface must be extremely smooth or abrasive wear to the film can occur.

Temperature and speed usually go hand in hand. The higher the speed, the higher the temperature. Sometimes higher temperatures are beneficial to a solid lubricant film's performance, but in most cases higher temperatures usually decrease the endurance life of a solid lubricant film. One general statement that can be made is that friction, wear and endurance life are highly dependent on temperature, so this factor must be controlled. Besides affecting the temperature of the film, speed can also affect the rheological properties of the film. The flow properties of solid lubricant films (especially polymer films) can be time dependent. Thus, if the speed is too fast, instead of the film plastically flowing, it can brittlely fracture.

The environment to which a solid lubricant is exposed can also markedly affect the tribological properties. For example, the humidity of laboratory air can vary from 20 percent in the winter to 80 percent in the summer. This can have a marked effect of a film's tribological properties. In addition, inert atmospheres like argon or vacuum can have an even greater effect. Thus, for reproducible results, the atmosphere in which a solid lubricant film is evaluated should be closely controlled.

Most solid lubricant films do not function well in a liquid environment, whether it be water or oil. Even the minute amount of oil deposited by an inquiring finger can drastically affect the tribological properties. Cleanliness in terms of dust and dirt is also important. A small hard particle can imbed itself in a film and severely abrade the counterface pin.

MACROSCOPIC MECHANISMS OF FILM LUBRICATION AND WEAR

In order to properly evaluate a solid lubricant film (especially a bonded film), one must first determine which of two lubricating mechanisms are operating. In the first mechanism, the film itself is capable of supporting the load and the wear process is one of gradual wear through the film. Figure 6 shows a photomicrograph of a wear track on a polyimide bonded graphite fluoride film after 15 kc of sliding. The wear track was produced by a hemispherically tipped pin with a 1.75 mm diameter flat on it under a 9.8 N load (4.1 MPa projected contact pressure). The photomicrograph illustrates that the film asperites are capable of supporting this load. The wear process with this film was a gradual wearing away of the film until the metallic substrate was reached. For more information see reference 8.

Not all films are capable of supporting the load, but they can still provide lubrication by the second mechanism. This mechanism has to do with the formation of a secondary film at the substrate surface from the original film wear debris and from material not worn away. The secondary film is very thin, usually less than 2 μm thick. Figure 7 gives some photomicrographs of a polyimide film wear track which due to thermal exposure has spalled, but still was able to provide lubrication through the secondary film lubricating mechanism (ref. 9). Figure 7 shows that even though the film spalled a very thin layer of the polyimide remained behind. This layer, combined with the wear debris from the spalled polyimide to form a very thin secondary film on the disk surface and this layer provided the lubrication.

Cross-sectional area schematic diagrams of the wear areas on a bonded film after 1, 30 and 60 kc of sliding, illustrating the two different types of macroscopic lubricating mechanisms, are given in figure 8. Please note that the vertical magnification is 50 times the horizontal magnification to emphasize the wear process. Depending on which lubricating mechanism is operating you may wish to adjust your experimental procedure accordingly.

EXPERIMENTAL TESTING PROCEDURES

Constant Temperature Testing

The specimens should be inserted in the apparatus and the chamber sealed, thereupon the desired atmosphere should be purged through the chamber continuously until the test is completed. The test should not be started, however, until the atmosphere stabilizes. The time for this will depend on the size of the chamber and the flow rate of the entering gas atmosphere. Once the atmosphere is stable, the temperature can be adjusted to the correct value. We prefer to rotate the disk while heating to achieve a uniform temperature distribution on the wear track circumference. When the temperature has stabilized, the load should be applied gradually to the rotating disk.

Two types of wear testing procedures can then be followed: (1) the tests can be run continuously until some maximum acceptable friction coefficient is obtained (the running time will then be defined as the endurance life or wear life of the film), or (2) an "interval test method" can be employed. Regardless of which method is used a cutoff friction coefficient should first be determined. This can be accomplished by running the metallic specimens unlubricated so that a value well below the unlubricated value can be set as the cutoff friction coefficient. It is also a good idea to determine the wear rate of the unlubricated metals for comparison purposes.

In the continuous testing method only wear at the end of the test (or at one designated sliding interval) can be determined. The interval testing method has the advantage over the continuous testing method in that run-in and steady state wear rates can be easily determined. In addition by using the interval method, it is possible to study the wear mechanisms of the films and the formation of transfer films as a function of sliding distance. The interval method envolves stopping the tests at predetermined intervals, taking the specimens out of the chamber, measuring the wear areas on the pin and on the film, calculating wear volumes, observing the surfaces with a light microscope or with a scanning electron microscope (SEM), and then replacing the specimens into the chamber with the least possible misalignment. We have found that if the pin is attached to a holder and the holder attached to the apparatus by use of locating pins, that the holder can be removed and replaced with minimal misalignment (one must not remove the pin from the holder when it is removed from the apparatus however).

Low Contact Stress Testing

When a hemispherically tipped pin slides against a solid lubricant film it imparts very high initial contact stresses. If the film can not conform (either elastically or plastically) to support those stresses the film will brittlely fracture, and if the film lubricates at all it will be by the secondary film mechanism. To reduce these stresses, a flat can be preworn on the hemisphere and the projected contact stresses can be controlled. This can be accomplished by sliding the pin against a disk with a small amount of lubricant on it. We have used rubbed films of graphite or graphite fluoride to do this. Sliding is continued until the desired pin wear scar is obtained. The pin and holder have to be removed periodically to determine the size of the scar. After the desired scar diameter is obtained, the transfer film should be removed. This can be done by scrubbing gently with a paste of levigated alumina. Care should be taken not to scrub too vigorously, or the flat can be rubbed off of the hemisphere.

Figure 9 shows a photomicrograph of a 1.75 mm diameter flat on the hemispherically tipped pin which slid against the polyimide bonded graphite fluoride film shown in figure 6. A very thin, uniform transfer film can be seen on the flat. Interference films have been observed in the transfer when viewed through a microscope at high magnification, which indicates that the thickness is in the order of the wavelength of light, 0.4 to 0.8 μm.

Temperature versus Time Testing

As mentioned previously, temperature can have a marked effect on the tribological properties of a solid lubricant film. In some instances a quick look at how temperature affects the friction coefficient of a film may be desired. To do this, temperature versus friction coefficient tests can be conducted. In order that frictional heating (and relaxation effects in polymers) is not a factor, a slow sliding speed such as 100 rpm might be chosen (although the purpose of the experiments might dictate some other speed). Also before varying the temperature, the film should first be "run-in" at constant temperature until a stable friction coefficient is obtained.

Once a stable friction coefficient is obtained the temperature can be raised at a constant rate until failure occurs (a predetermined value of friction coefficient). This will give an indication of how friction varies as a function of temperature and an indication of the upper temperature limitation for the film. Friction force versus temperature can be directly plotted on an x/y recorder or friction force can be recorded on a conventional strip chart recorder and the temperature written in at appropriate intervals and later plotted up as temperature versus time. Of course the best way to do this would be to collect the data on a computer data acquisition system and analyze it with a spread sheet. Temperature can be determined by focusing an optical pyrometer onto the disk wear track surface or by embedding a thermocouple into the nonmoving specimen (usually the pin). The rate of temperature increase is up to the experimenter. We have gotten good results increasing the temperature at the rate at about 2 or 3 °C/min.

Many variations of the above procedure can be followed. The film can be run in at some elevated temperature and then decreased or increased from that point. In many instances it is advisable to increase the temperature to a value somewhat below the failure point, and then to decrease the temperature to ambient and then to increase and decrease the temperature a second time. This will help determine if the effects are repeatable. One should make certain that the film has not worn away during this process, however.

Since wear is highly dependent on temperature and sliding distance, this technique is not very useful for wear studies. Unless of course the experimenter can exactly reproduce the temperature versus time cycles. We have found it easier to run constant temperature tests in accessing the wear phenomena.

MEASURING WEAR VOLUMES

The wear of the pin can be determined by measuring the diameter of the circular scar on the hemispherically tipped pin and then using this value to calculate the wear volume. The formula for calculating the volume of a segment of a sphere is where

$$V = \frac{\pi c^4}{64r^2}\left(r - \frac{c^2}{24r}\right). \tag{1}$$

Where V is the volume of the segment, c is the diameter of the circular wear scar and r is the radius of the hemispherically tipped pin. This equation is easily programmed into a pocketsize programmable calculator. However, since we use the same size pin for most of our testing we have tabulated the wear volume results for each wear scar diameter. If the density of the material is known, wear volume can also be determined by taking weight loss measurements. Wear volume of the film can be determined by taking weight loss measurements or by taking surface profiles of the wear track and calculating the volume of material worn away. This is done by determining the worn cross-sectional area from the surface profiles and multiplying that value times the diameter of the wear track of the disk. There are instruments that can be used to trace around the area of the wear track surface profile and which will give an accurate reading of the area. However, for most cases it can be assumed that the worn area is the area of the segment of a circle, since in most cases the wear conforms to the shape of the hemispherically tipped pin, and can be mathematically approximated by measuring the width and the depth of the profile.

METHODS OF DISPLAYING DATA

Generally speaking, friction coefficient and wear are both time or sliding distance dependent. For the friction coefficient there is usually a "run-in" interval with somewhat higher friction, a "steady-state" interval with relatively constant friction, and an interval where friction either suddenly jumps to a very high value (immediate failure) or an interval where the friction gradually increases with sliding time. Therefore rather than specifying a specific value of friction coefficient for a particular film it is useful to plot friction versus time or distance curves for the friction tests. Figure 10 shows a typical friction coefficient versus sliding distance plot for a rubbed graphite fluoride film applied to a sandblasted AISI 440C stainless steel disk. A run-in region, two steady-state regions, and a gradually increasing friction coefficient region can be seen. Since 205 km in this case represents 1250 min of sliding (a relatively long sliding time). The data have been compressed to show the entire sliding duration of the film. Depending on the experimenter's interests, a certain region might be expanded and compared to other solid lubricant films on the same plot (the run-in region for example).

It is a good idea also to plot pin wear volume or film wear volume as a function of sliding distance. This can be done easily if the interval testing method is employed. Figure 11 plots wear volume of a pin whick slid on the rubbed graphite fluoride film mentioned in preceding paragraph. Depending on the film, in some cases there is run-in wear (a higher value of wear rate) and in some cases there is not. This particular film shows a run-in wear rate of 3×10^{-15} m^3/m of sliding which lasted less than 1 km of sliding (shown in fig. 11 by the fact that the curve does not pass through the y-axis). Then there is usually a region of steady state wear (shown in fig. 11 to be 0.13×10^{-15} m^3/m), and then there is a region where wear increases gradually with sliding distance (see increasing values in fig. 11). Figure 11 was for pin wear volume, a similar plot could be made for film wear volume as a function of sliding distance when the gradual wear through the film mechanism is operating. Plotting wear volume values as in figure 11 and friction coefficients as in figure 10 and then comparing them to other solid lubricants gives a much better comparison than just by trying to compare a mean friction coefficient and mean wear rate.

SUMMARY

Basic configurations of pin on disk rigs have been discussed as well as methods of applying films, methods of preparing substrates, factors which affect film performance, and some experimental test procedures. The conditions that one uses to evaluate the films such as values of load, speed, type of atmospheres, type of materials, etc. are factors that need to be chosen and varied by the experimenter. They should be chosen so as to closely approximate the intended end use of the solid lubricant film. The reader should always remember that a pin-on-disk tribometer is a device which is intended to obtain friction and wear information in an accelerated manner, and the only true test of a solid lubricant film is to use it in the intended end use part.

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TABLE I. - FACTORS WHICH EFFECT SOLID LUBRICANT PERFORMANCE

1. Type of materials in sliding contact.
2. Geometry of sliding materials.
3. Contact stress or pressure.
4. Surface to which solid lubricant is applied.
5. Substrate hardness.
6. Substrate surface topography.
7. Temperature.
8. Speed.
9. Environment.
    a. Atmosphere
    b. Fluids
    c. Dirt

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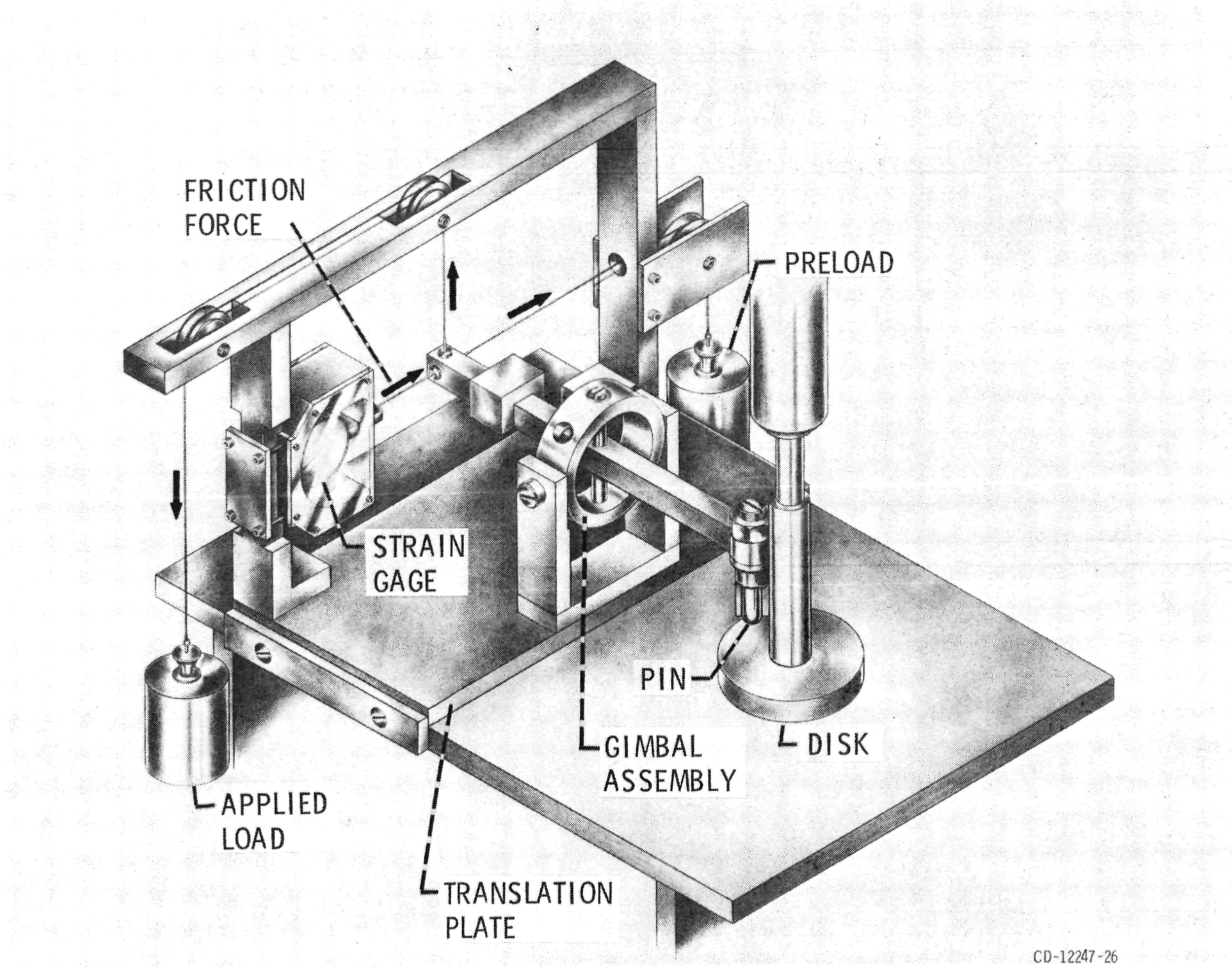

Figure 1. - Slow speed pin-on-disk tribometer.

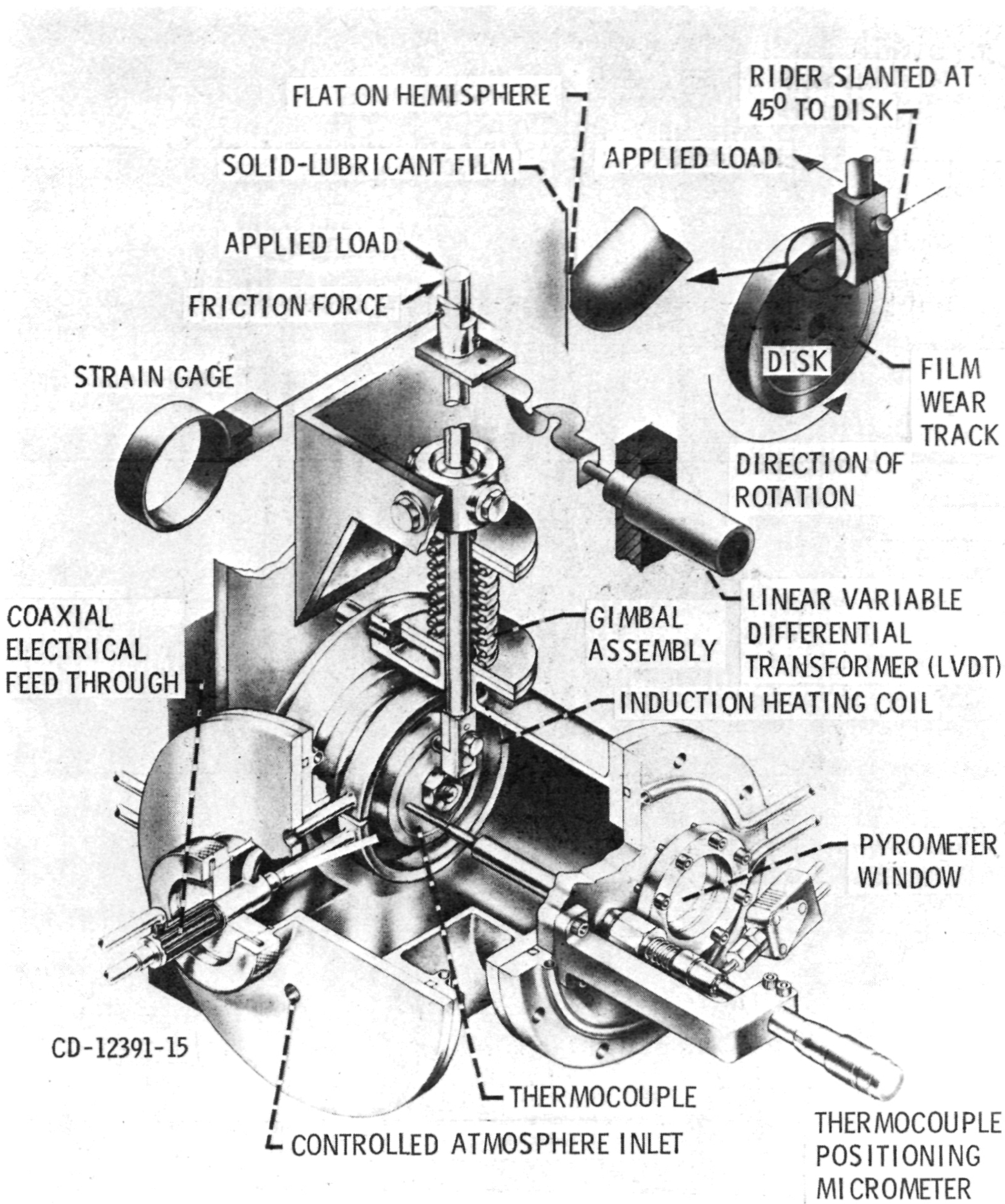

Figure 2. - High temperature pin-on-disk tribometer.

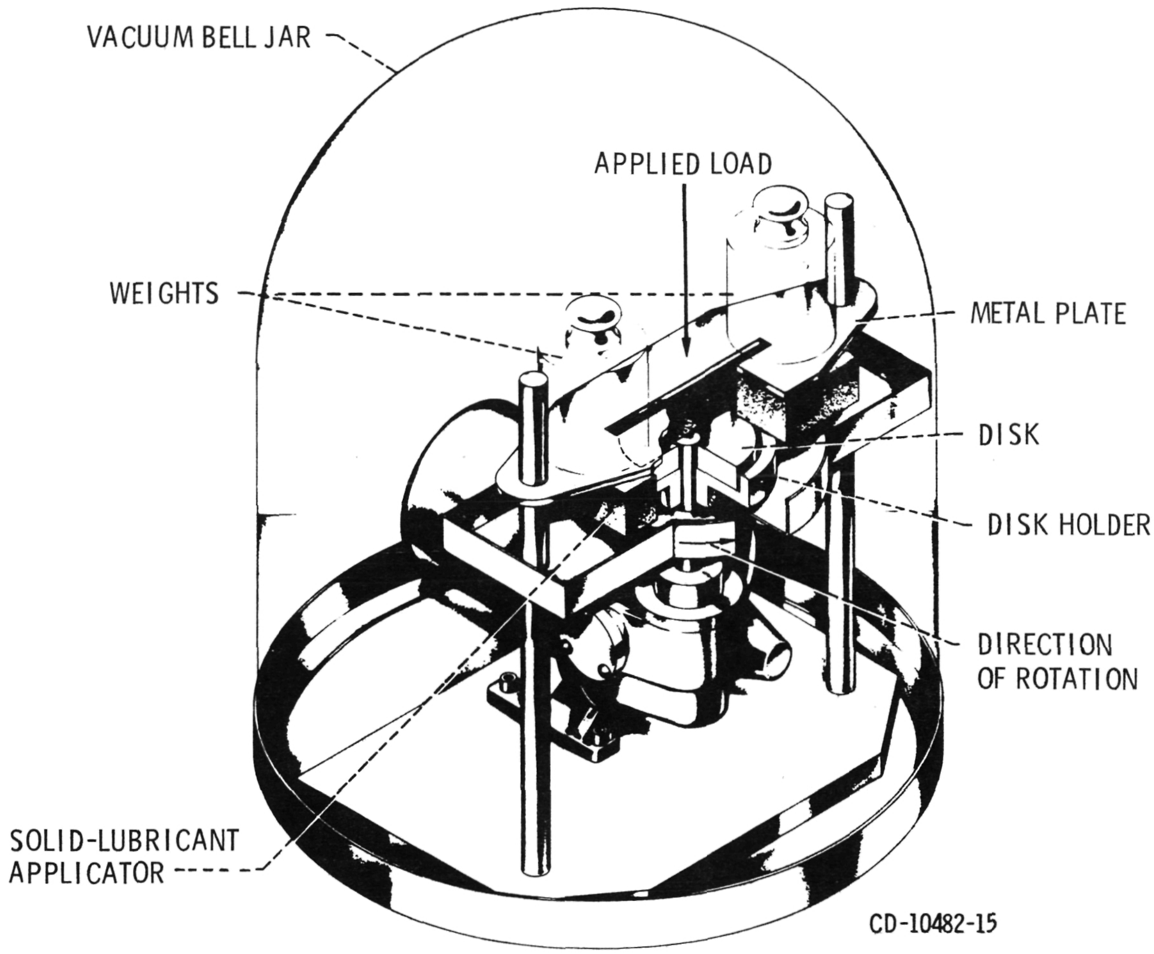

Figure 3. - Burnishing apparatus.

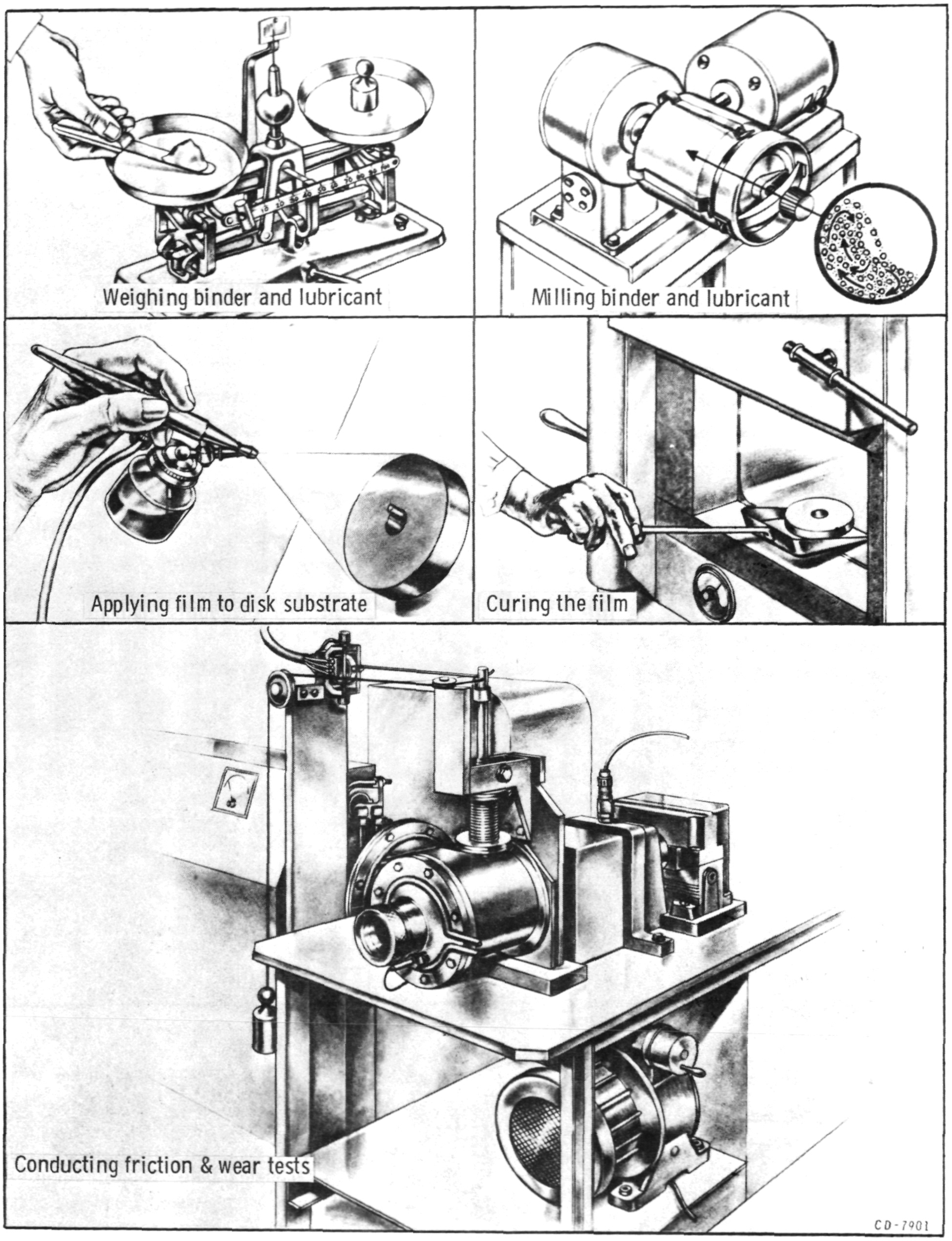

Figure 4. - The application and evaluation of a bonded solid lubricant film.

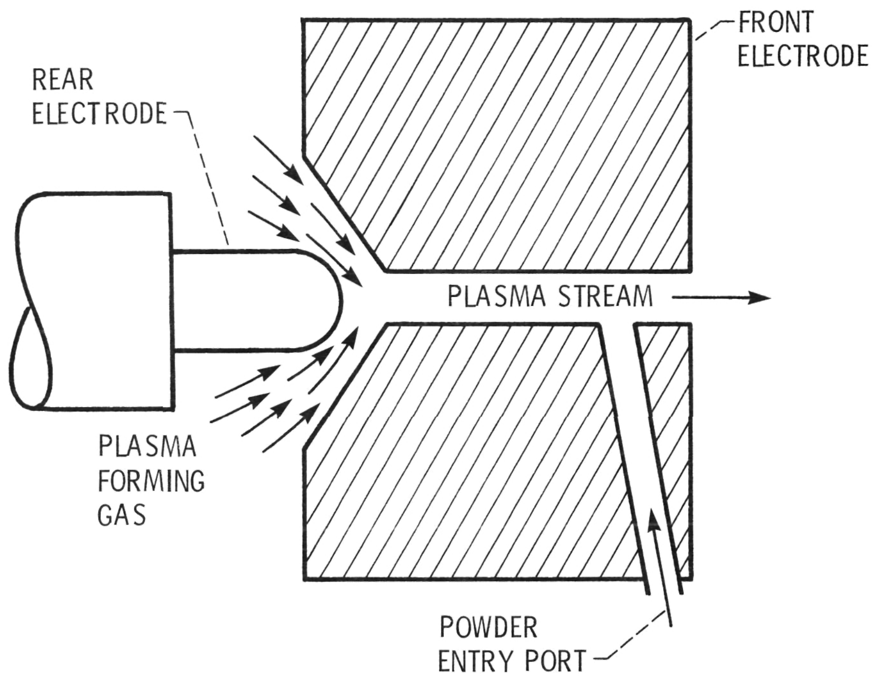

Figure 5. - Schematic of the plasma spray process of applying solid lubricant films.

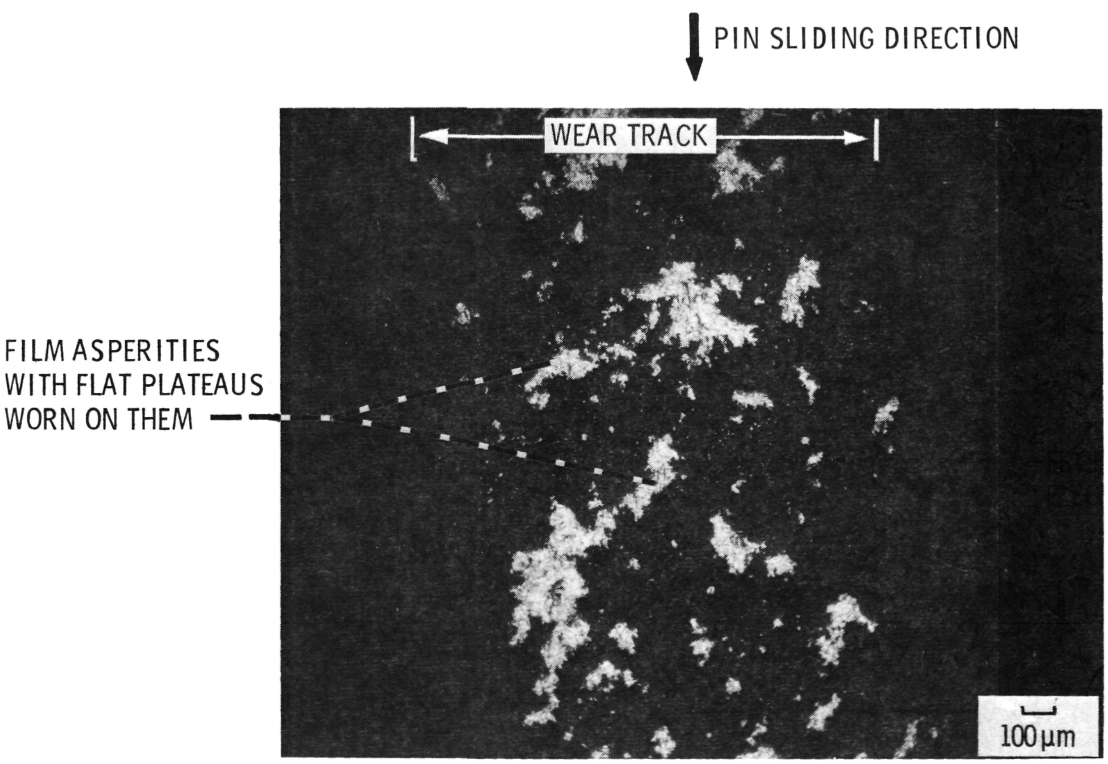

Figure 6. - Photomicrograph of a wear track of a polyimide bonded graphite floride film after 15 kilocycles of sliding showing that only the highest of the film asperites support the load.

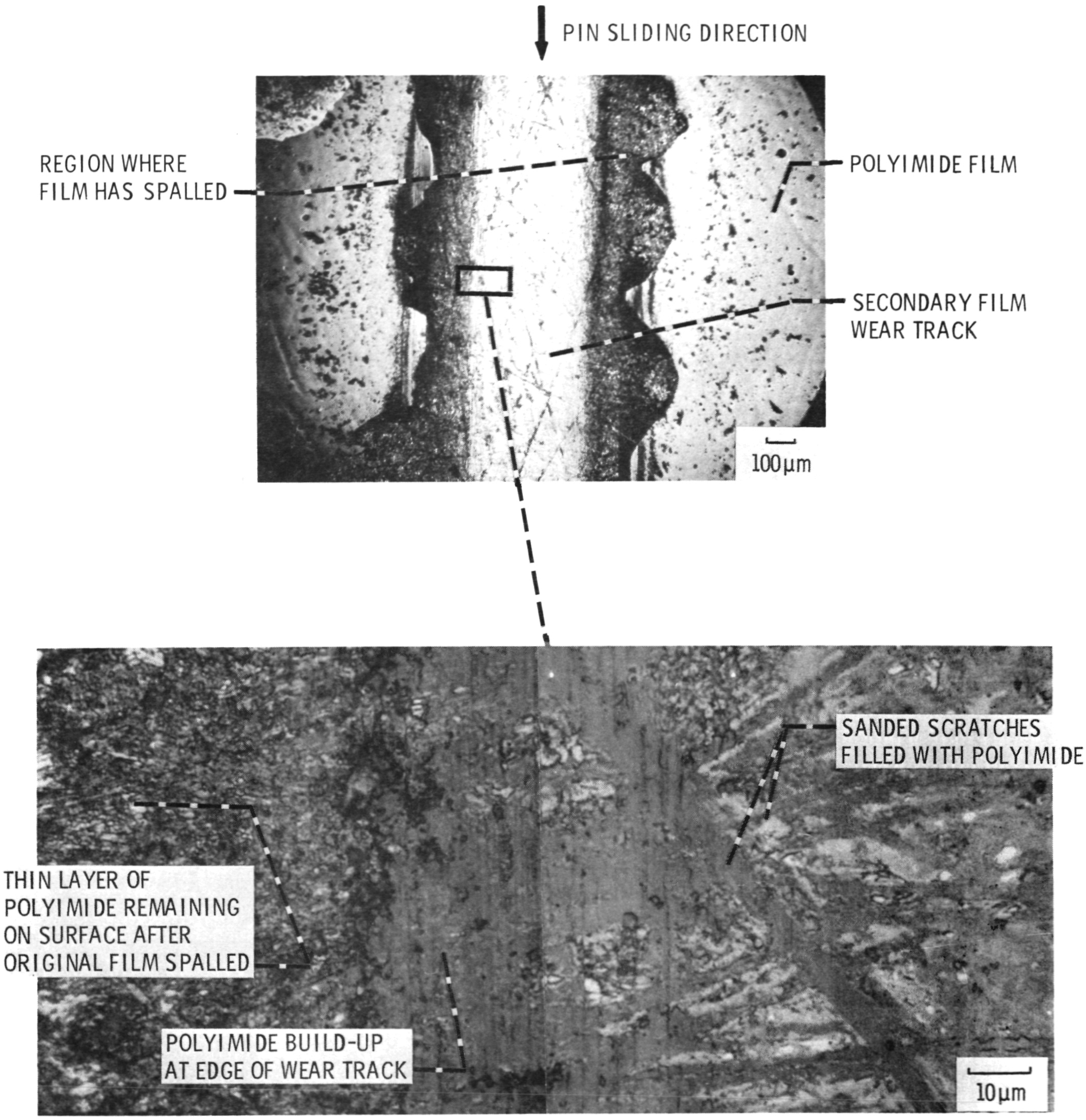

Figure 7. - Photomicrographs of the wear track (after 15 kilocycles of sliding) on a polyimide film which was thermally aged for 100 hours at 350°C before testing. The photomicrographs show the spallation of the film and the formation of a very thin secondary film on the metallic substrate (ref. 9).

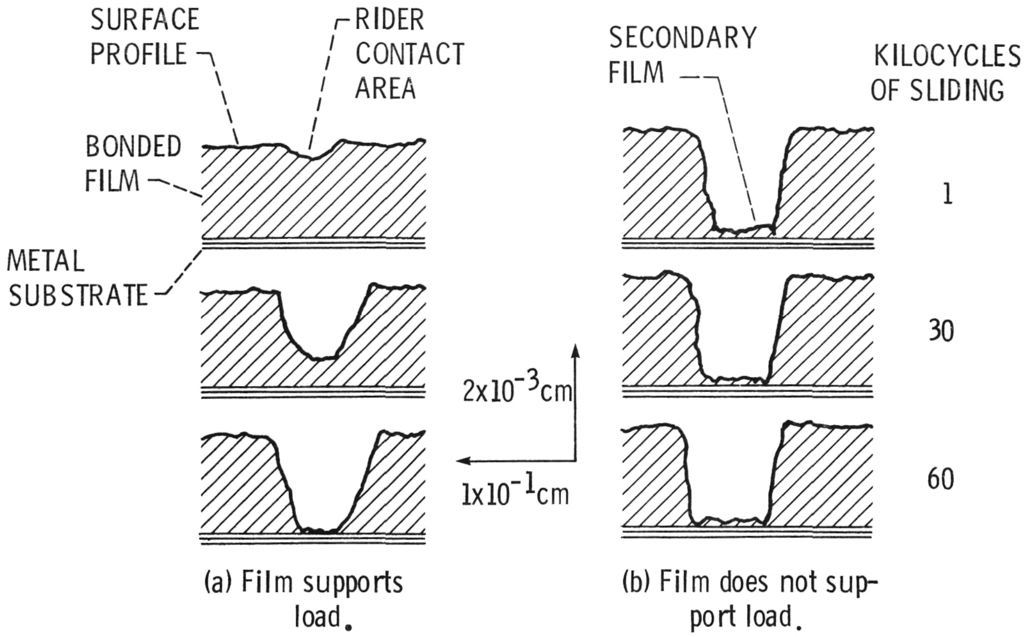

Figure 8. - Cross sectional area schematics of the wear areas on a bonded film (polymer or other type of solid lubricant film) after 1, 30, and 60 kc of sliding illustrating the two different types of macroscopic lubricating mechanisms. (Note that vertical magnification is 50 times horizontal magnification.)

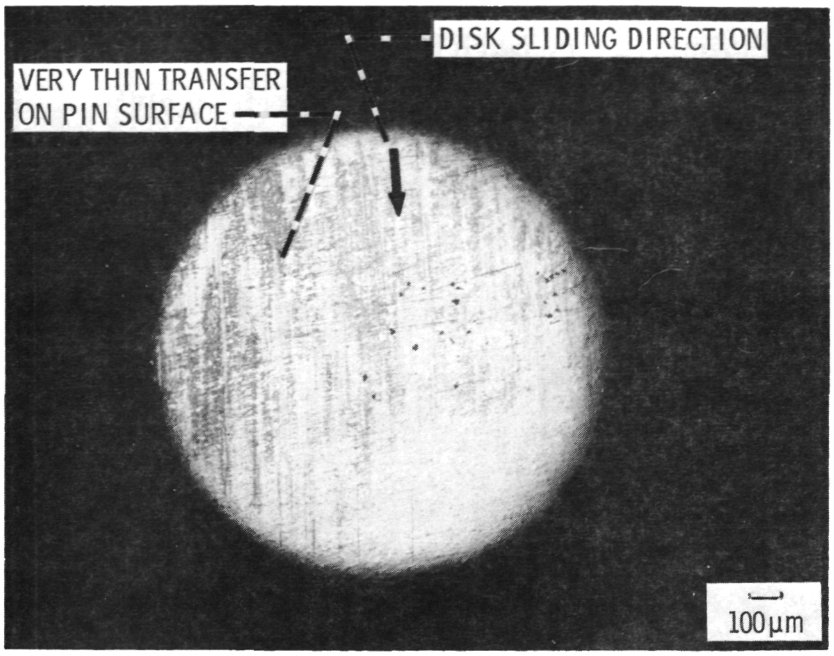

Figure 9. - Photomicrograph of 1.75 mm diameter flat on hemispherically tipped pin after 15 kilocycles of sliding against a polyimide bonded graphite fluoride film.

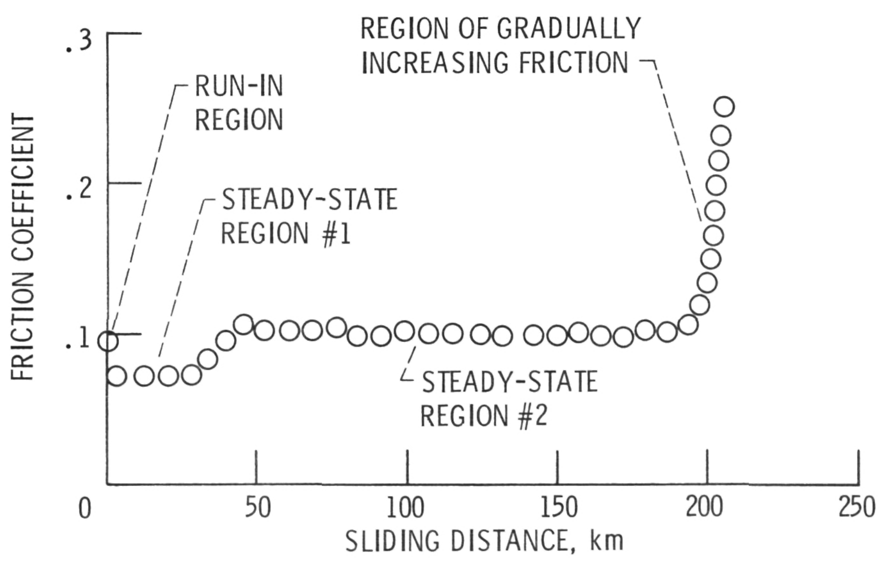

Figure 10. - Friction coefficient as a function of sliding distance for a rubbed graphite fluoride film applied to a sandblasted 440C stainless steel disk. (Experimental conditions: 50% relative humidity air atmosphere, 9.8 Newton load, 1000 rpm (2.7 m/s) sliding speed, and a 440C stainless steel pin.)

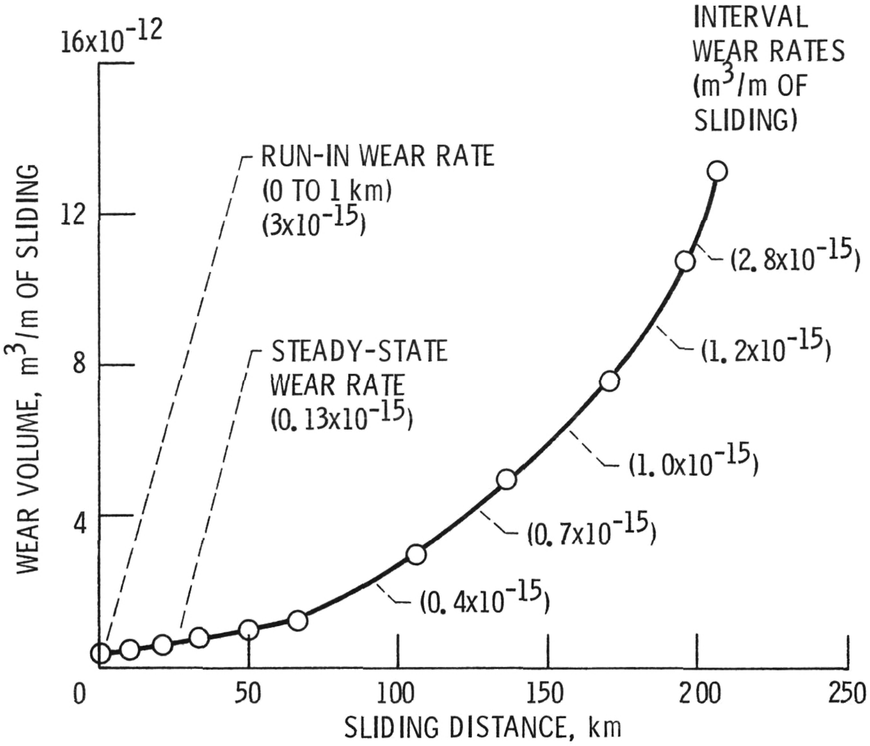

Figure 11. - Pin wear volume as a function of sliding distance for a 440C pin sliding against a rubbed graphite fluoride film applied to a sandblasted 440C disk. (Experimental conditions: 50% relative humidity air atmosphere, 9.8 Newton load, 1000 rpm (2.7 m/s) sliding speed.)

1. Report No. NASA TM-87236	2. Government Accession No.	3. Recipient's Catalog No
4. Title and Subtitle: How to Evaluate Solid Lubricant Films Using a Pin-on-Disk Tribometer		5. Report Date
		6. Performing Organization Code: 505-63-01
7 Author(s): Robert L. Fusaro		8. Performing Organization Report No.: E-2909
		10. Work Unit No
9. Performing Organization Name and Address: National Aeronautics and Space Administration, Lewis Research Center, 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

Prepared for the 1986 Annual Meeting of the American Society of Lubrication Engineers, Toronto, Canada, May 12-15, 1986.

16. Abstract

Over the years, the author has evaluated and compared hundreds of solid lubricant films using a pin-on-disk tribometer. The intent of this paper is to describe to the reader experimental techniques and some of parameters that have been observed to be important for the evaluation and development of new solid lubricant films. Pin-on-disk tribometers will be described and discussed as will experimental methods for evaluating solid lubricant materials. Methods of preparing surfaces for the coating of the films and different methods for applying the films will be reviewed. Factors that affect solid lubricant performance will also be discussed. Two different macroscopic mechanisms of solid lubricant film wear exist. These will be characterized schematically, and methods of measuring wear will be examined.

17 Key Words (Suggested by Author(s))	18. Distribution Statement
Friction; Wear; Solid lubricant coatings; Tribometers; Wear devices; Testing techniques	Unclassified - unlimited STAR Category 27

19 Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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Space Administration

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