ASLE TRANSACTIONS

ISSN: 0569-8197 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/utrb19

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M. J. Furey

To cite this article: M. J. Furey (1961) Metallic Contact and Friction between Sliding Surfaces, ASLE TRANSACTIONS, 4:1, 1-11, DOI: 10.1080/05698196108972414

To link to this article: https://doi.org/10.1080/05698196108972414

Published online: 25 Mar 2008.

ASLE TRANSACTIONS 4, 1-11 (1961)

Metallic Contact and Friction between Sliding Surfaces*

By M. J. FUREY[1]

A new device has been developed and used to study metallic contact and friction between sliding, lubricated surfaces. The system consists basically of a fixed metal ball loaded against a rotating cylinder. The extent of metallic contact is determined by measuring both the instantaneous and average electrical resistance between the two surfaces. Friction between the ball and cylinder is recorded simultaneously with contact.

In general, the electrical resistance was found to oscillate rapidly between an extremely low value and infinity, suggesting that metallic contact is discontinuous. The average resistance of an oil film is therefore a time-average, that is, a measure of the per cent of the time that metallic contact occurs. The results indicate that metallic contact is much more prevalent than would have been expected from other published studies in which electrical resistance or discharge methods were employed.

Using this apparatus, the entire region from hydrodynamic (no metallic contact) to pure "boundary" lubrication (continuous metallic contact) can be readily investigated. Load, speed, mineral oil viscosity, the presence of additives, and operating time were found to be important variables influencing metallic contact.

The apparatus is particularly useful in studying the action of antiwear and "extreme pressure" additives. It allows one to measure not only the effectiveness of these compounds in reducing metallic contact, but also the rate at which they act and the durability of protective films which may form.

Introduction

IN spite of the fact that preventing metallic contact is probably the most important function of a lubricant, there is still much to be learned about the transition from a condition of "no-contact" to one of continuous contact. This is the region where lubrication goes from the desirable "hydrodynamic" condition to the less-acceptable "boundary" condition, where increased metallic contact usually leads to higher friction and wear. Consequently, it is important to learn as much as possible about the factors which determine or influence the extent of metallic contact in a lubricated system.

The present paper describes the results of studies which have been made of metallic contact, friction and surface damage between sliding, lubricated surfaces. The object of this investigation was fourfold: (*a*) to develop a simple device for measuring both metallic contact and friction; (*b*) to determine to what extent metallic contact actually occurs under these conditions; (*c*) to find out what are the important factors influencing the degree of contact (e.g., load, speed, time, lubricant composition); and (*d*) to relate metallic contact, if possible, to friction and/or surface damage. Future papers will deal with the importance of lubricant variables—including viscosity as influenced by temperature, pressure, shear rate and time effects, and the action of various antiwear additives.

The system used consisted basically of a fixed metal ball loaded against a rotating steel cylinder. The extent of metallic contact was determined by measuring both the instantaneous and average electrical resistance between the two surfaces. Friction between the ball and cylinder was recorded simultaneously with contact. Before describing the experimental equipment and techniques, however, it may be helpful to review briefly the basic principles in more detail and some of the work which has already been done with similar techniques.

Background

The use of electrical resistance measurements to study the formation and breakdown of lubricant films between rubbing surfaces is not new. However, relatively little has been published in this area. Using this method, studies have been made of the lubrication of piston rings and cylinders in an engine (*1, 2*), thrust bearings (*3*), journal bearings (*4*), gears (*5, 6*), and discs (*7*).

As an illustration of the basic principle involved in these studies, the specific electrical resistance for petroleum products ranges from about 10^{11} to 10^{16} ohm cm, whereas for the common metals, it is usually less than 10^{-4} ohm cm. For example, the value for iron at 20 C is about 10^{-5} ohm cm. From this, the electrical resistance may be calculated where applicable by means of the expression $R = \rho L/A$ where $R =$ resistance,

* Presented as an American Society of Lubrication Engineers paper at the Lubrication Conference held in Boston, Massachusetts, October 17-19, 1960.

[1] Research Engineer, Products Research Division, Esso Research and Engineering Co., P.O. Box 51, Linden, New Jersey.

L = length, A = cross-sectional area and ρ = specific resistance. However, according to Maxwell (*8*), the normal resistance formula does not apply when two large metallic conductors make contact over a small area of their surface. Maxwell showed that constriction of the current stream introduced a "spreading resistance" equal to $\rho/2r$ where r equals the radius of a circular contact area. This was also shown later by Holm and is discussed in his classic work on electrical contacts (*9*). Bowden and Tabor (*10*) use this idea and express the resistance of a metallic junction as the sum of a "spreading" and "film" resistance where the latter is due to oxide layers and other contaminant films. Their work with nonlubricated metals suggested that this "film" resistance was negligible perhaps because of rupture of the oxide layers. Nevertheless, the resistance of a metallic junction is very small when compared to that of an oil film as shown by the calculated data in Table 1.

It can be seen that the oil films in this example have a resistance of about 10^6 to 10^{18} times as great as the metal junctions. However, another important factor must be kept in mind. If the voltage gradient is too high, electrical discharge may occur through the oil film. Courtney-Pratt and Tudor (*2*) and Tudor (*4*) found that in their particular systems, electrical discharge oc

TABLE 1
Effect of Oil Film Thickness and Extent of Metallic Contact on Electrical Resistance[a]

Area of actual metallic contact (cm^2)	Oil film thickness (cm)	Calculated resistance[b] (ohms)
0	10^{-2}	10^9–10^{14}
0	10^{-3}	10^8–10^{13}
0	10^{-4}	10^7–10^{12}
0	10^{-5}	10^6–10^{11}
0	10^{-6}	10^5–10^{10}
10^{-8}	—	10^{-1}
10^{-6}	—	10^{-2}
10^{-4}	—	10^{-3}
10^{-2}	—	10^{-4}

[a] Geometrical cross-sectional area = 1 cm^2.
[b] Based on $\rho = 10^{11} - 10^{16}$ ohm cm for oil films and the spreading resistance for an iron junction.

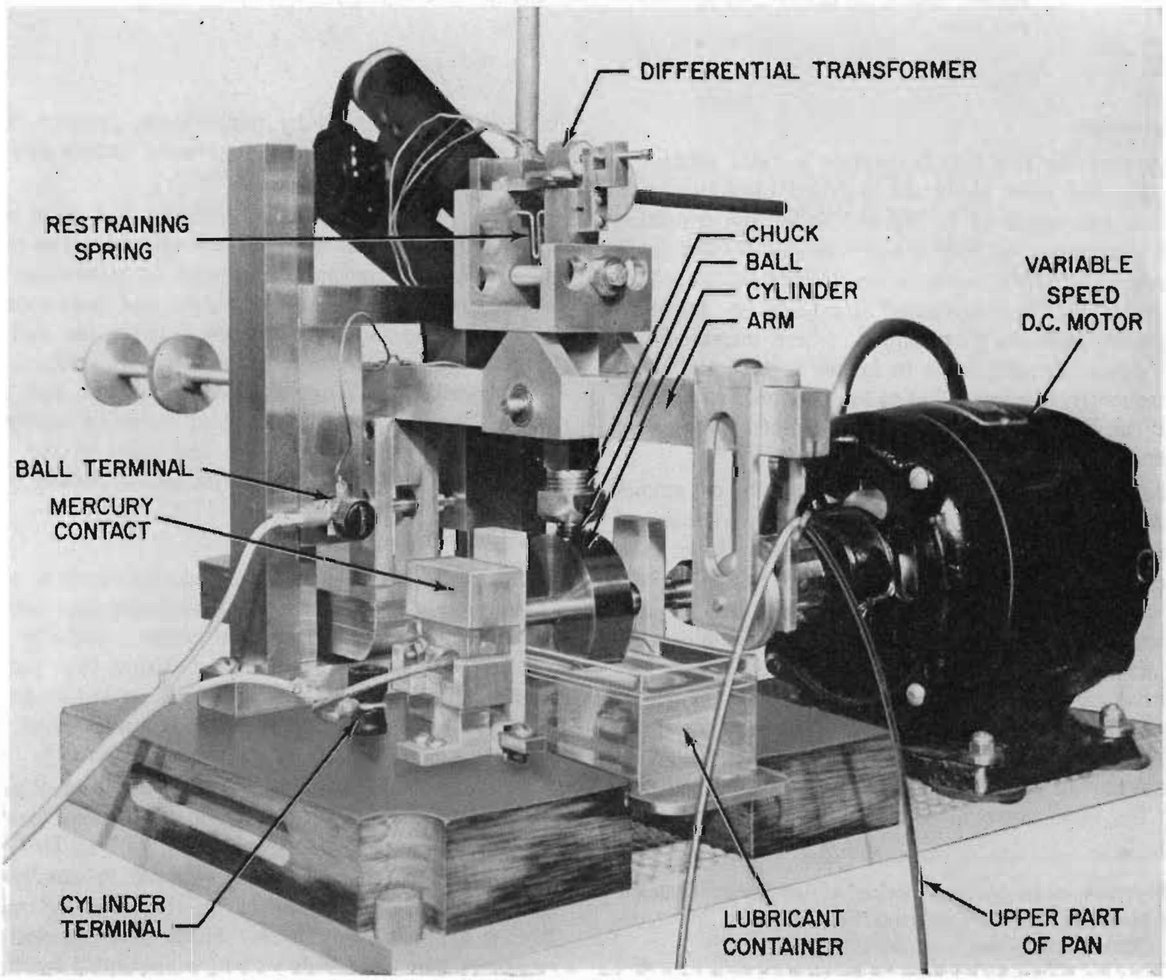

FIG. 1. Rotating cylinder device used in metallic contact and friction studies.

curred at voltages above 0.2 to 0.3 volts. Although little is known about the discharge characteristics of thin oil films, Cameron *et al.* (*11–13*) have used this method in an attempt to determine the thickness of oil films between rubbing metal surfaces under a condition of "no contact." In this work, "discharge voltage" was defined as the voltage drop across a thin oil film when a constant current of one ampere is passed through this film. It was found that the "discharge voltage" for several oils was about 4½ volts per 0.001 inch or 1.8 kv/cm(*11*). This "discharge voltage" is not the same as the dielectric strength. Dielectric strength is defined as the maximum potential gradient which a dielectric will sustain without permitting a visible or audible electrical discharge under a given set of standard experimental conditions. Commercial lubricating oils usually have a dielectric strength of about 60–150 kv/cm, although for highly purified oils this value may go as high as 380 kv/cm (*14*). The significance of these various electrical methods which have been used will be discussed in a later section of this paper.

Experimental

General Description of the Mechanical Device

As seen in Fig. 1, the device consists essentially of a test piece—in these experiments, a fixed metal ball ½ inch in diameter—resting on top of a rotating cylinder which dips into the test lubricant. The load between the ball and cylinder is obtained by first counterbalancing the supporting arm and then adding weights to a pan—the upper part of which is shown. The applied load can vary from a few grams to several thousand. With steel-on-steel, the loads are equivalent to calculated mean Hertz pressures of about 11,000 to 141,000 psi (for loads of 2 and 4000 grams, respectively).

The cylinder is mounted on a horizontal shaft and can be rotated at speeds from about 60 to 3000 rpm by means of a DC motor which has continuously variable speed. The speed is measured by means of a light beam which is reflected from small mirrors attached to the shaft. The reflections are detected by a photoelectric cell and counted with a pulse counter. This system has the advantage of being entirely frictionless and quite accurate at both low and high speeds.

The entire device is simple and yet quite flexible. If necessary, the supporting arm which holds the upper test specimen can be moved up and down to accommodate cylinders of different diameters. Furthermore, different chucks may be used to hold spheres of various sizes or other geometrical shapes such as cylinders, concave surfaces or flat blocks.

Measurement and Recording of Metallic Contact

The electrical resistance between the ball and cylinder is determined by a voltage drop method. The electrical circuit used for the resistance measurements is shown in Fig. 2. A 1½ volt dry cell is used as the voltage source or DC input. The resistance scale switch box

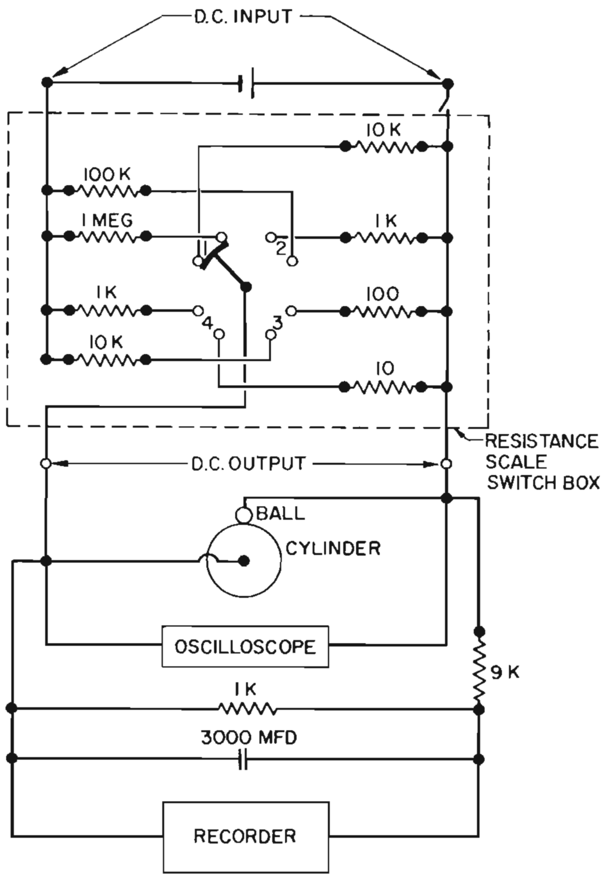

Fig. 2. Circuit used in measurement of electrical resistance.

accomplishes two things. One, it reduces the voltage to 1/100 the input or to about 15 mv in this case. The low voltage minimizes electrical discharge through the oil film. (In a following section, it will be shown that there is no electrical discharge at this voltage.) Two, the mid-scale resistance can be changed without changing the output voltage. For example, when the switch is at the No. 1 position, the resistance corresponding to 7.5 mv is 10,000 ohms. Likewise, for switches 2, 3, and 4, the mid-scale resistances are 1000, 100, and 10 ohms, respectively. This allows one to examine certain resistance ranges more closely during an experiment without changing the applied voltage. A plot of R_x—the unknown resistance at the junction of the two rubbing surfaces—against voltage drop is shown in Fig. 3, where the mid-scale resistance is equal to 10,000 ohms. Although it is obvious that this plot alone cannot be used to determine the values of unknown resistances over the entire range with equal precision, it will be shown later that this does not affect the results of the present study.

The current path from the cylinder is through the shaft and a rotating copper disc immersed in mercury. This method gave a satisfactorily low and constant resistance during operation. The instantaneous resistance can be viewed and photographed from the oscilloscope screen. In addition, one pen of a two-pen recorder is used to record the "average" electrical resistance during

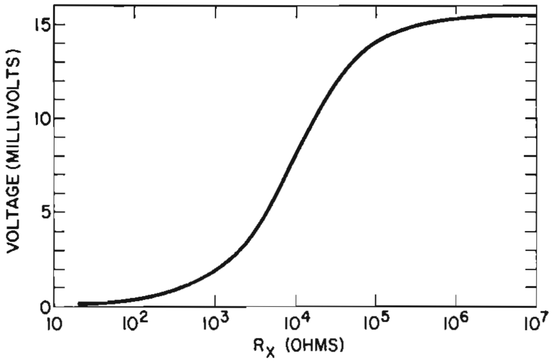

FIG. 3. Variation in voltage across ball and cylinder with resistance.

a test. As will be shown in a following section of this paper, this "average" resistance is meaningless by itself but is directly related to the per cent of the time that metallic contact exists.

Measurement and Recording of Friction

Frictional force between the ball and cylinder can also be determined with this device. As can be seen from Fig. 1, the chuck which holds the ball is free to rotate about precision bearings. However, its motion is restrained by a metal spring. Frictional force on the ball causes a deflection of the chuck depending upon the force and nature of the spring. This deflection is measured by the use of a free-moving iron core inside a small differential transformer. The position of the iron core, which is connected to the chuck, is determined electrically by the changes which occur in the output of the transformer. The signal is amplified and indicated on a bridge monitor. It is also recorded continuously by the other pen of the two-pen recorder. The electrical circuit for the friction measurement is shown in Fig. 4.

The friction-measuring unit is calibrated by inserting a small hook at the bottom of the chuck and hanging known weights on a fine thread passed through this hook and over the pulley at the end of the arm. The calibrations are generally linear, and the working range with a given spring can be altered by varying the bridge sensitivity. If necessary, different size springs can be used for various load ranges. Safety stops prevent the chuck from moving more than 0.001 inch although the deflection is actually less than this in normal operation (ca. 0.00001 inch to 0.0005 inch). Excessive vibration of the chuck at certain loads and speeds is eliminated by viscous damping. This is accomplished by placing a small plate on each side of the chuck parallel to its motion and about 0.004 inch from the chuck. Mineral oil is used as the damping fluid in this clearance space.

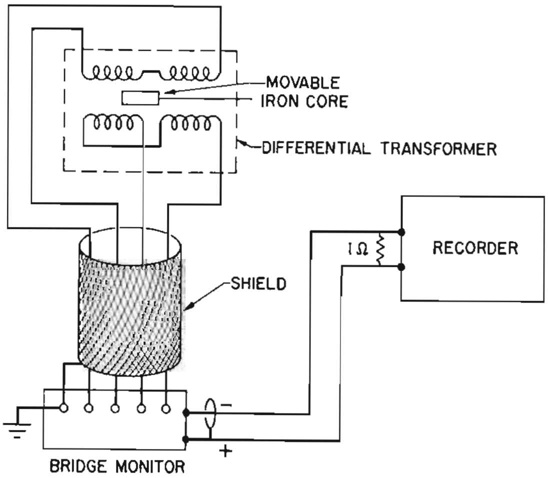

FIG. 4. Circuit used in measurement of friction.

The complete apparatus—including the rotating cylinder device, associated controls and recording equipment—is shown in Fig. 5.

General Test Procedure

The test procedure is quite simple. Before starting a test, a calibration is made of the junction resistance against the recorded voltage drop on the chart. This is done by inserting a decade resistance box between the two test specimens. The test oil is then charged, the proper weights are added to the pan, the desired speed of the cylinder is obtained, and the upper arm is lowered into place. In ending a test, the reverse procedure is used. A new upper test piece and fresh track on the cylinder are employed for each test at a given load and speed. By moving the cylinder longitudinally along the shaft, as many as ten tests can be run on the cylinder.

Test Conditions Used in This Study

A summary of the test conditions used in the work thus far is shown in Table 2. It can be seen that the applied load was varied by over a thousandfold and the speed by a factor of fifty.

TABLE 2
Test Conditions

System	AISI 52100 Steel ½ diam. ball on 1¾ inch diam. cylinder
Speed: (rpm) (cm/sec)	60–3000 14–700
Load (grams)	3.75–4000
Calculated mean Hertz pressure (psi)	13,700–141,000

The test balls were standard Grade 1 balls having a surface finish of about 2 microinches CLA. The cylinders were machine ground to a surface roughness of 8–10 microinches CLA and had a total variation in roundness of less than 0.0001 inch. Before use, the test specimens were rinsed in boiling heptane, boiling methanol containing 5% distilled water, and boiling methanol, in that order. This removes most of the oily and inorganic substances and at least insures a reproducible state of "mechanical" cleanliness.

So far, the tests have all been carried out at room temperature (ca. 75–80 F). The duration of the tests has varied from 16 minutes to several hours, depending upon the nature of the lubricant and particularly upon the rate of change of contact and friction with time.

Advantages

The new device is simple and straightforward both in construction and in interpretation. The test does not depend on destruction of the test piece, or running until failure. However, the greatest advantage is that the entire history of the test is recorded. Changes in behavior with time can be studied so that the *rate* of action as well as the over-all effect can be measured. This is particularly useful for studying additives where unusual effects may occur with time during a test. For example, with some additives there may be an "induction" period before antiwear activity appears.

In addition, special "carry-over" tests can be run to determine how long the beneficial effect of a particular lubricant additive will last. After a normal test with an additive oil, the lubricant is removed and the test pieces are thoroughly rinsed with hexane to remove residual oil. Then using the same ball and track, a second test is run—this time with the base mineral oil.

Results and discussion

Instantaneous vs. "Average" Electrical Resistance

Examples of electrical resistance results obtained on the oscilloscope screen are shown in Fig. 6. These results represent separate experiments with the same oil at various loads and speeds. It is seen that the instantaneous resistance is either infinite or very low and can oscillate rapidly between these extremes—the duration of low resistance being as short as a millisecond. In these experiments, the low value was found to be approximately equal to the static resistance of the ball/cylinder junction. This behavior is a general one; changes in load or speed were found to change the per cent of the *time* that the resistance was extremely high (or low), but the extremes remained at the same levels. It is believed that this behavior is due to the intermittent nature of metallic contact brought on by surface irregularities. Similar intermittent contact has been shown by Courtney-Pratt and Tudor (*2*).

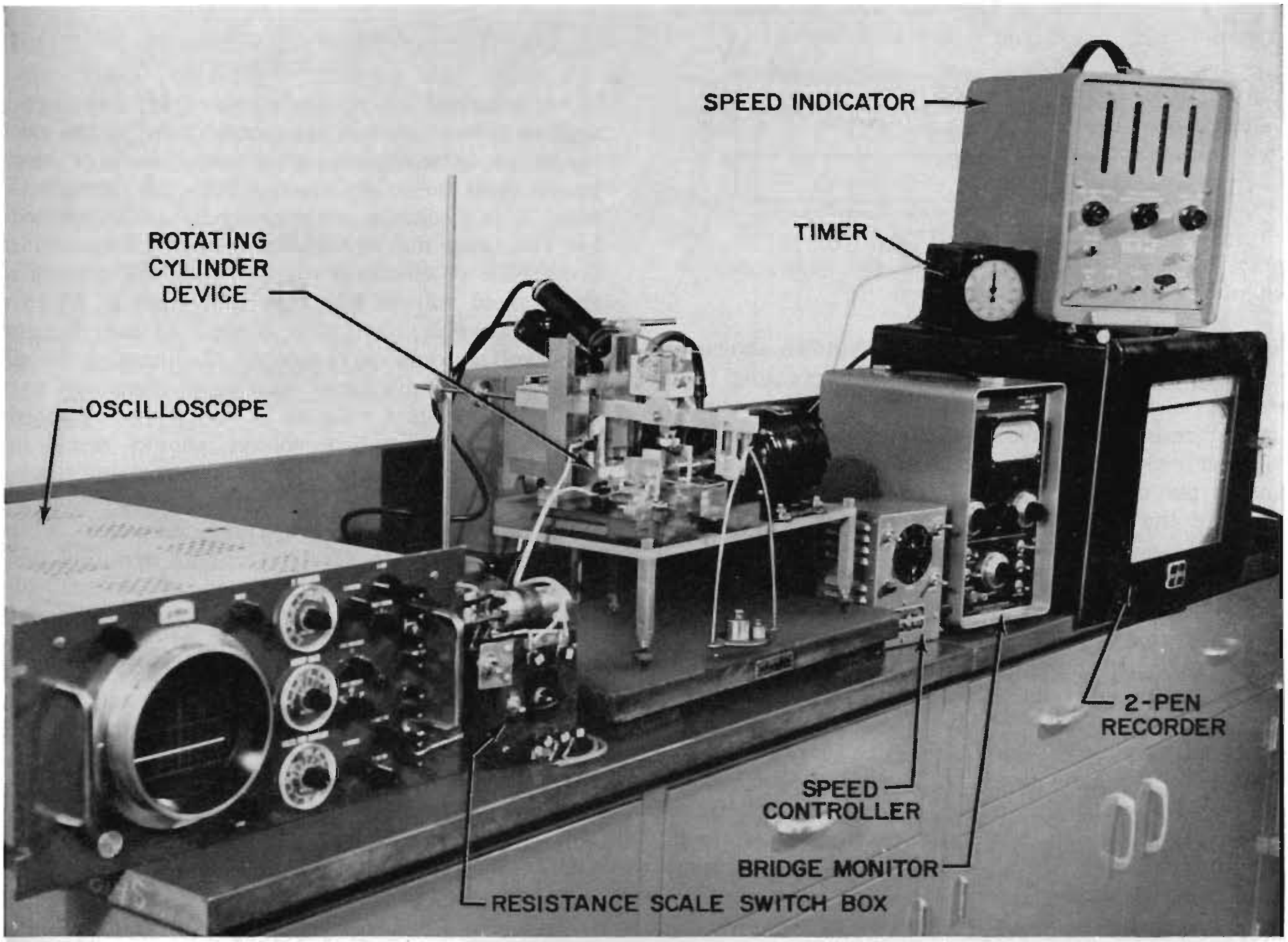

FIG. 5. Complete test apparatus.

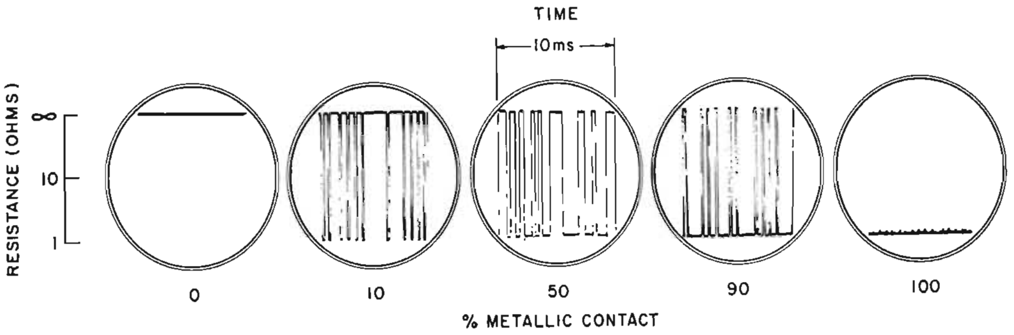

FIG. 6. Examples of resistance vs. time traces on oscilloscope screen.

An example of the recorded resistance and friction results is shown in Fig. 7, which is part of the chart from the two-pen recorder. The resistance values now recorded are "average" and not instantaneous. They have been slowed up purposely by the condenser in the circuit and also by the response of the recorder itself.

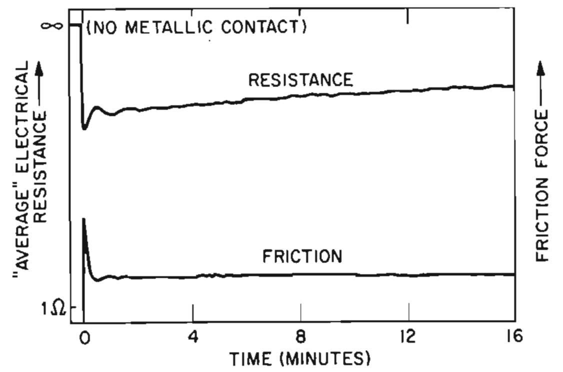

FIG. 7. Example of recorded resistance and friction data obtained with a straight mineral oil.

As we have seen from the oscilloscope pattern shown in Fig. 6, the actual resistance is rapidly fluctuating from one extreme to another. Consequently, the recorded "average" resistance is a time-average and is a function of the per cent of the time that the resistance is low. It is this per cent which will be referred to in the remainder of the paper as "per cent metallic contact."

It is important to note that proper conclusions could not have been drawn from the use of the indicated "average" resistance alone. As a specific example, when the chart reads a mid-scale deflection, the oscilloscope indicates that half the time the resistance is extremely low. In other words, metallic contact is estimated to be occurring 50% of the time. On the other hand, a separate calibration of the chart using various known resistances might indicate that mid-scale deflection corresponds to a resistance of 10,000 ohms. To assume, therefore, that one is in a state of hydrodynamic or full-fluid lubrication when the "average" resistance is 10,000 ohms is, of course, not necessarily correct.

This is a different concept of "average" or "mean" electrical resistance from that reported by other authors. In studies of disc lubrication, for example, Crook (*6*) used the mean value of the instantaneous resistance (averaged over a period of approximately 2 seconds) to show the existence of some form of hydrodynamic lubrication. Although this may have been true, it does not necessarily follow from the value of such an "average" resistance alone. Our measurements tend to the belief that even when the "average" resistance is fairly high a considerable amount of metallic contact can be taking place, and that metallic contact is, in fact, more prevalent than otherwise reported.

EFFECT OF APPLIED VOLTAGE ON RESISTANCE MEASUREMENTS

As discussed in an earlier part of this paper, the applied voltage used in the measurement of the electrical resistance between lubricated metal surfaces must not be so great so as to cause discharge through the oil film. This discharge could easily be misinterpreted as a low resistance due to metallic contact. To minimize the occurrence of electrical discharge in the present study the applied voltage was kept low—that is, at 15 millivolts. However, one could argue that lowering the applied voltage only decreases the thickness of the oil film through which discharge occurs. If discharge were actually taking place even at 15 mv, it was reasoned that decreasing the applied voltage should result in less "apparent metallic contact," while increasing the voltage should cause more.

To investigate this point, the influence of applied voltage from 0.1 to 4500 mv on the apparent per cent metallic contact was determined at several different loads and speeds. An example of the results obtained is shown in Fig. 8, where it is seen that there is no significant effect of voltage from 0.1 to 1500 mv. However at 3000 mv and above, the measured resistance was low (100% apparent metallic contact), presumably because of discharge. It was also found that polarity had no effect on the resistance measurements. These results indicate that electrical discharge is not occurring at the voltage used in this study and that the instantaneous low resistance values are—as previously stated—due to metallic contact. This contention is further supported in a later part of this paper by the results of examinations of the test pieces for surface damage.

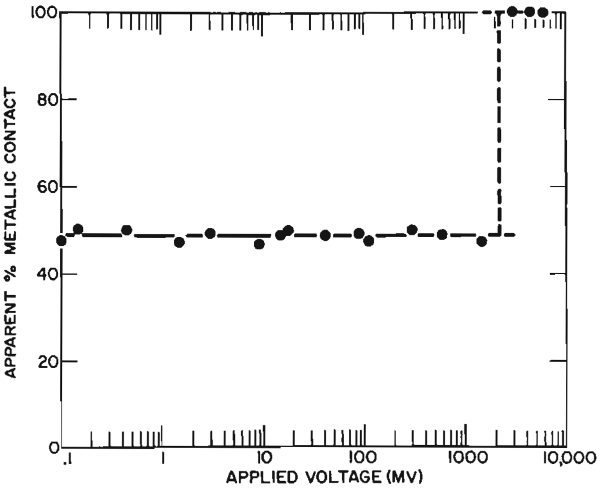

FIG. 8. Influence of applied voltage on apparent per cent metallic contact.

It is of interest to note that when the applied voltage was great enough to cause discharge, both the amount of surface damage and friction increased. Furthermore, in static tests with ½ inch diameter steel balls at known distances apart, it was found that electrical discharge through a mineral oil even at ½ volt could cause black, carbonaceous, high-resistance deposits to form between the balls. These observations, coupled with the previously discussed point that "average" measurements of rapidly varying electrical quantities can be extremely misleading, suggest that the discharge method used by Cameron *et al.* (*11, 12*) to measure oil film thickness may produce erroneous results.

Change of Metallic Contact with Time

In the present study, it was found that metallic contact with straight mineral oils generally decreased somewhat with running time as illustrated by Fig. 9. This is a plot of per cent metallic contact versus time at a constant speed of 240 rpm (56 cm/sec) and at loads ranging from 3.75 to 240 grams (13,700 to 54,700 psi mean Hertz pressure).

As will be seen later, the observed effects of time on metallic contact with straight mineral oils are small in comparison with load, speed, and viscosity effects. Nevertheless, this behavior prompted some additional experiments. First, it was found that in consecutive tests with a single charge of mineral oil—using a fresh ball and cylinder track for each test—essentially identical effects of running time were observed. This showed that the effect of time was not due to a change in the oil. Second, the same time-effect also occurred when the voltage (15 mv) used in the resistance-measuring circuit was applied only near the end of a test. This demonstrated that the effect was not due to the voltage used to measure metallic contact. Third, in subsequent tests with new charges of mineral oil and using the same cylinder track and ball, it was found that there were no significant discontinuities in contact from test to test. This indicated that the observed time-effect was due to the changes which occurred on the rubbing metal surfaces—probably a polishing or wearing effect which allowed the surfaces to be more easily separated by the oil film.

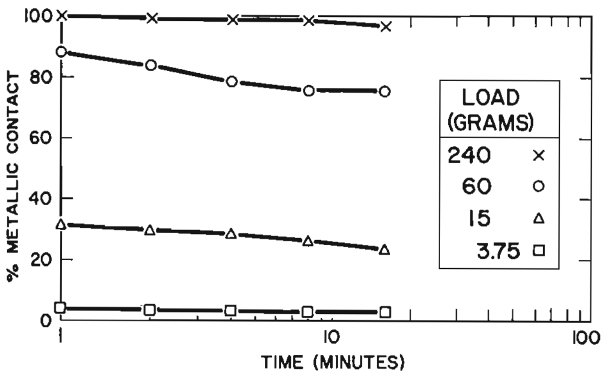

FIG. 9. Effect of operating time on metallic contact with a straight mineral oil.

When antiwear or "EP" additives are present, the change of per cent metallic contact with time is more pronounced. It was found that additives differ markedly in the rate at which they act, and this may be helpful in elucidating their antiwear action. This is illustrated by Fig. 10, which is a plot of per cent metallic contact

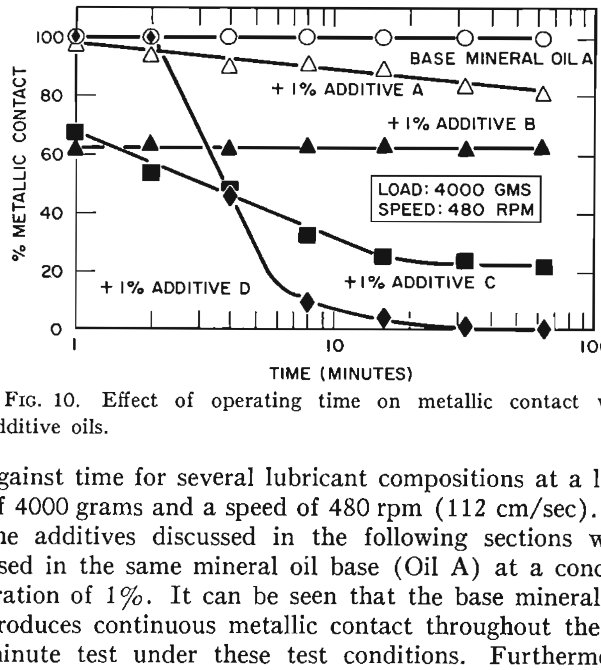

FIG. 10. Effect of operating time on metallic contact with additive oils.

against time for several lubricant compositions at a load of 4000 grams and a speed of 480 rpm (112 cm/sec). All the additives discussed in the following sections were used in the same mineral oil base (Oil A) at a concentration of 1%. It can be seen that the base mineral oil produces continuous metallic contact throughout the 64 minute test under these test conditions. Furthermore, each of the four additives causes a reduction in metallic contact but at considerably different rates. For example, Additive A—a halogen compound—acts very gradually to reduce contact throughout the test. Additive B—a dispersed solid—appears to function instantaneously without further improvement as the test proceeds. Additive C—an organic phosphate—acts very rapidly with its effect leveling off at about 20% metallic contact. On the other hand, Additive D—a metal dithiophosphate—requires a certain induction period and then acts very rapidly to reduce metallic contact to almost zero. In other cases, even longer induction periods are required before an additive begins to reduce metallic contact.

Transition from Hydrodynamic to Boundary Lubrication

The new device is particularly suited for studying the transition between hydrodynamic and boundary lubrication. Whether the lubrication for a given geometry will be hydrodynamic or boundary is often determined by the applied load, the surface speed and the viscosity of the lubricant. Each of these three variables has been studied in the new device.

Load

A typical example of the effect of load on per cent metallic contact with a straight mineral oil is shown in Fig. 11. These data were obtained at a constant speed

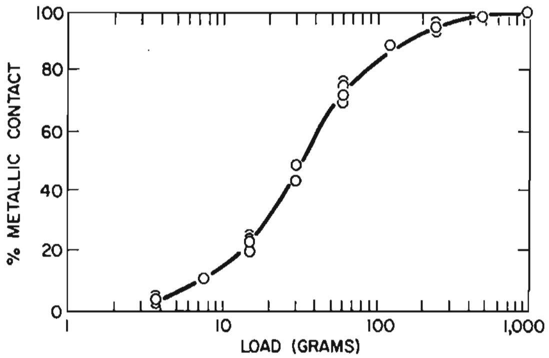

FIG. 11. Influence of load on metallic contact.

of 240 rpm with a straight mineral oil. It can be seen that contact increases markedly with load, forming a curve similar to a cumulative distribution plot. It is also seen that these experiments covered the entire range of metallic contact from 0 to 100%.

Figure 11 also gives an indication of the repeatibility of the contact measurements. Each point represents a separate test with a new ball and fresh cylinder track. Furthermore the results shown were obtained on a total of four different cylinders. As would be expected, the errors were found to be smaller as one approached either a steady state condition of no metallic contact or continuous metallic contact.

Speed

The typical influence of cylinder speed on metallic contact with a straight mineral oil is shown in Fig. 12. The data shown were obtained at a constant load of 60 grams using another straight mineral oil. It is seen that speed, like load, also has a marked effect on metallic contact. Increasing the speed reduces the extent of contact. The curve obtained is somewhat similar to the contact/load plot (Fig. 11) except that it slopes the other way. Again, the entire range from essentially no-contact to continuous contact is represented.

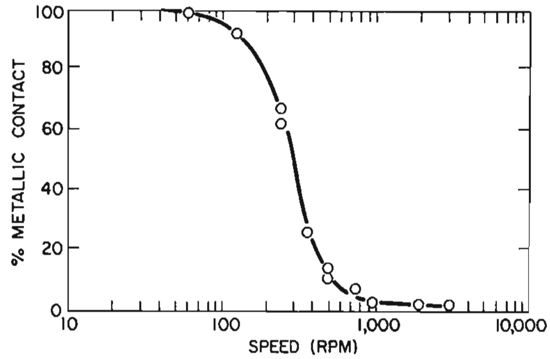

FIG. 12. Influence of speed on metallic contact.

Viscosity

An example of the influence of mineral oil viscosity on metallic contact is shown in Fig. 13. These data were obtained at a constant speed of 240 rpm. The oils

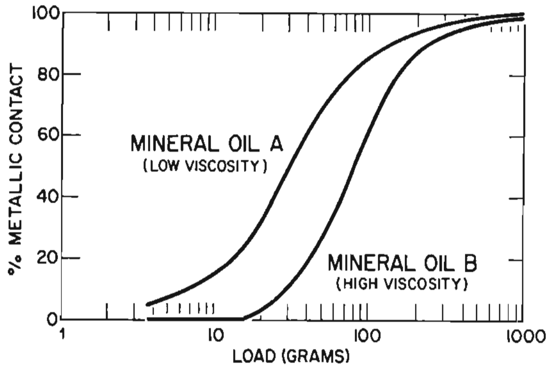

FIG. 13. Influence of viscosity on metallic contact.

were both of the paraffinic type and—as shown in Table 3—varied in viscosity at the test temperature by a factor of about five.

TABLE 3
Mineral Oil Viscosities

Oil	Viscosity (cp) 77° F	210°F
A	35.0	3.5
B	177.6	8.7

It is seen that increasing the viscosity shifts the curve to the right so that there is less contact at a given load In general, the influence of viscosity on contact was found to vary with speed. At low speeds, the viscosity effect was much smaller.

Friction

With straight mineral oils, the average recorded friction force did not vary appreciably during a test (e.g., as shown in Fig. 7), although it was influenced by load speed, and viscosity. An example of the effect of load and speed on friction is shown in Fig. 14. With less viscous oils, the influence of speed on friction was much smaller.

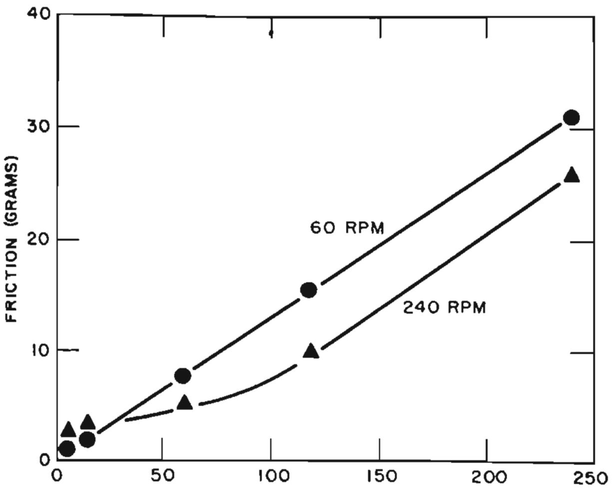

FIG. 14. An example of the effect of load and speed on friction.

In general, it was found that in the hydrodynamic regime—at low loads and high speeds—more viscous oils gave *higher* friction. However, at higher loads (or lower speeds) the more viscous oils produced *lower* friction. In the first case, the friction is probably the result of the viscous drag of the oil; in the second case, the more viscous oil is reducing the extent of metal-to-metal contact and thus decreasing this component of friction.

Although the friction obtained with straight mineral oils was reasonably constant with time, this was not true with many of the oils containing antiwear or "EP" additives. An example is shown in Fig. 15 where both friction and electrical resistance are plotted against time. This test was carried out at a speed of 240 rpm

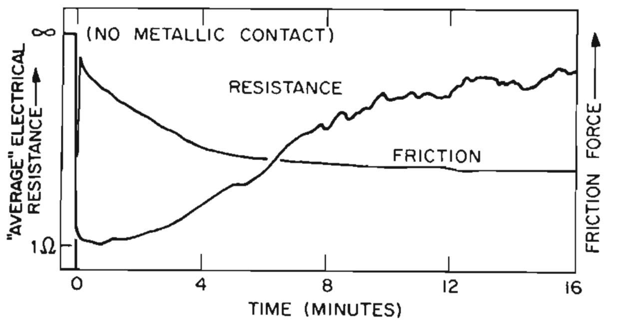

FIG. 15. Example of recorded resistance and friction data obtained with an additive oil.

and at a load of 240 grams. It can be seen that friction —as well as metallic contact—decreased rapidly during the test. With the additive oils, friction was also influenced by load, speed, and additive type but not in a simple manner.

SURFACE DAMAGE AND WEAR

Visible surface damage occurred on the balls and cylinders used in these studies. Examples of wear tracks formed on the cylinders are shown in Fig. 16. These cylinders were obtained from a series of tests at various loads and speeds with two of the mineral oils previously discussed (Oils A and B). It is also seen from this figure that the more viscous mineral oil (Oil B) produces much less damage. Examination of these surfaces under a microscope showed that the width of the wear track is more closely related to metallic contact than to friction. In addition, surface damage was never observed under conditions which resulted in no or very little metallic contact. It was also found that the amount of surface damage was not affected by the low voltage (15 mv) applied between the ball and cylinder.

DURABILITY OF PROTECTIVE ANTIWEAR FILMS WHICH MAY BE FORMED

Another advantage in being able to record contact and friction continuously is in the study of the durability of protective films which may be formed on the rubbing metal surfaces by the additives. An example of some contact data obtained in this type of investigation is shown in Fig. 17. This shows a normal test followed by a test with the base mineral oil (Oil A) for several of the additive oils previously discussed. The tests were run at a load of 4000 grams and at a speed of 480 rpm.

It can be seen that, as expected, the rate at which additives function in reducing contact has nothing to do with the rate at which these beneficial conditions are removed or destroyed. Additive A acts gradually and shows a prolonged, erratic carry-over effect; additive B acts instantly and exhibits no carry-over effect; whereas additive C is quick-acting and has a long-lasting carry-over. In addition, some slow-acting additives were found to show little or no carry-over effects.

Conclusions

In conclusion, a new device has been developed to measure and continuously record both the extent of metallic contact and friction between sliding metal surfaces. This device has proved particularly useful in studying: (*a*) the transition from a condition of no metallic contact (hydrodynamic lubrication) to one of continuous metallic contact ("boundary" lubrication); (*b*) the time history of metallic contact and friction phenomena; and (*c*) the action of antiwear and "extreme pressure" additives.

The device is basically simple and yet extremely flexible. Effects of load and speed can be investigated over a wide range. For example, with the system used in this study, the load was varied from 3.75 to 4000 grams (13,700 to 141,000 psi mean Hertz pressure). In addition, the speed was varied from 60 to 3000 rpm (14 to 700 cm/sec).

Using this apparatus, it was found that appreciable metallic contact of an intermittent nature can occur under reasonably light loads. In addition, metallic contact was indicated to be more prevalent than one might have expected from other published data.

Time, load, speed, mineral oil viscosity, and additive type were found to be important variables influencing metallic contact and friction. With straight mineral oils, the influence of operating time on metallic contact appears to be due to a polishing effect due to wear. The effects of load, speed, and viscosity are probably due to changes in the thickness of the oil film. These effects are qualitatively in agreement with what would be expected from hydrodynamic theory. However, it should be pointed out that attempts to correlate the mineral oil data obtained thus far with a single, dimensionless group have not been entirely satisfactory.

Either of two different mechanisms could explain the action of the various antiwear and "EP" additives in reducing contact. One, an additive could promote or accelerate polishing of the metal and possibly allow the surfaces to become more easily separated by oil. Two, an additive could form protective films or substances with insulating properties between the rubbing metal surfaces. Some evidence has been obtained in support of each of these two mechanisms. However, much more work is necessary to resolve this point.

In general, surface damage was found to be more closely related to metallic contact than to friction. In addition, the effects of additives on metallic contact were much more pronounced than their effects on friction.

Using this apparatus, studies are continuing on the effect of lubricant composition on metallic contact, friction, and wear. Included in this work are the effects of (a) viscosity as influenced by temperature, pressure,

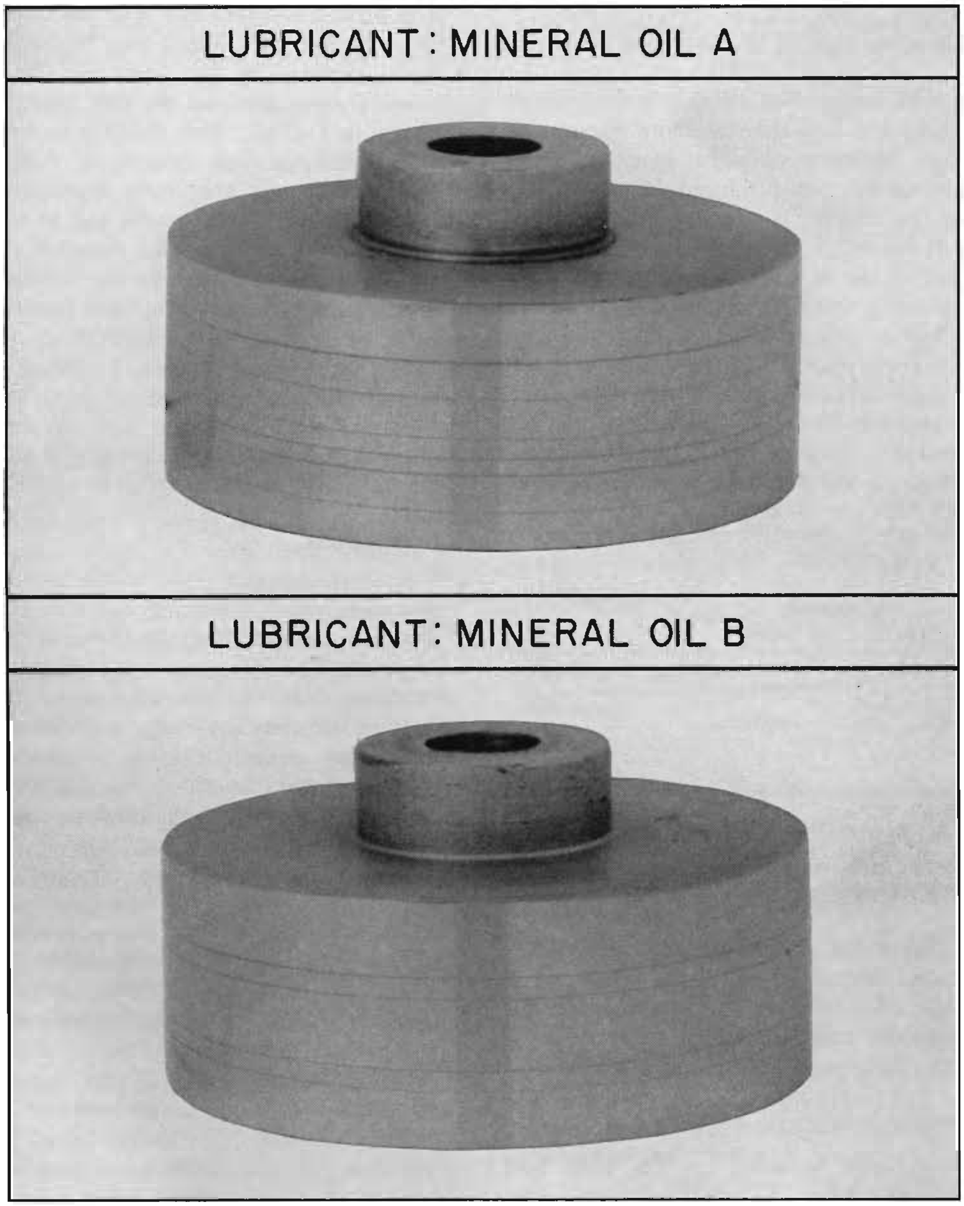

Fig. 16. Used test cylinders.

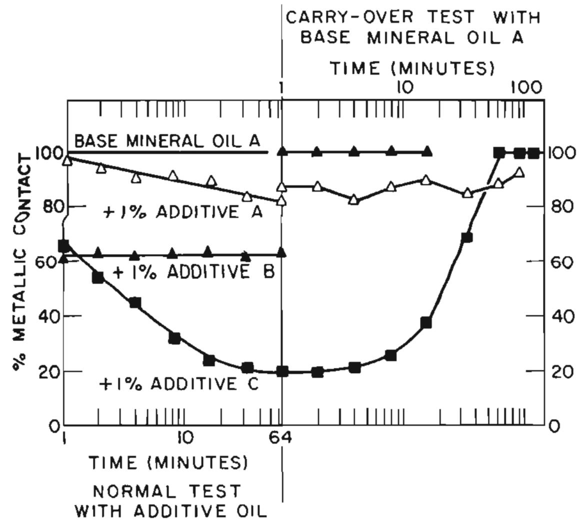

FIG. 17. Example of metallic contact data obtained in normal and carry-over tests with additive oils.

shear, and time effects and (b) antiwear and "extreme pressure" additives with particular emphasis on the mechanisms by which they function. These topics will be the subject of future papers in which some of the points illustrated in the present paper will be dealt with in considerably more detail.

ACKNOWLEDGMENTS

The author is indebted to J. A. Wilson and J. J. Heigl for their assistance with the design of electrical circuits used in this investigation.

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