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The Wear Process During the “Running-In” of Steel in Lubricated Sliding*

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ABSTRACT

Steel cylinders were slid against flat steel disks, using a liquid lubricant, in order to study the progression of events associated with “running-in”. It was found that, when using mineral oil, the electrical contact resistance varied over a small range of high values indicating no metallic contact, whereas with engine oil a high resistance with an intermittent negligible contact resistance was found. A surface film forms from the additives in the engine oil which produces lower wear, slightly higher friction, a retarded running-in, and a rougher surface finish in the direction of sliding than does the mineral oil. A film which is composed only of Fe_3O_4 is formed when mineral oil is used. In addition, the mineral oil lubricated surfaces develop a conforming waviness across the sliding tracks. The oxide must have enhanced this surface conformity since it was not seen in the surfaces lubricated with engine oil. The role of the oxide may be further seen in experiments in which wear debris that accumulated in the entrance region of specimen contact was removed at frequent intervals. Little conforming waviness was seen in the latter case, suggesting that oxide which gathered in the entrance region abraded grooves in the steel surfaces. After the oxides were dislodged, the friction increased and the contact resistance decreased for a time, indicating that the oxide acted like a solid lubricant.

概 要

“なじみ”に伴う摩擦面の種々の変化を調べることを目的として、油潤滑下で鋼製円板対鋼製円筒のすべり摩擦試験を行った。

潤滑油として鉱油を用いた場合、接触電気抵抗は比較的高い範囲で変動しており金属接触が生じていないことが認められたが、市販のエンジンオイルを用いると、非常に高い抵抗値を示すが、ごく短い時間抵抗がほぼ 0Ω を示す状態が頻繁に現れる。また、鉱油に比べて、摩耗が少ない、摩擦係数がやや大きい、なじみの遅れ、そしてすべり方向の粗さが大きいなどの現象が観察された。エンジンオイル中の添加剤により摩擦表面に生成される被膜によるものと考える。

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鉱油の場合には、 Fe_3O_4 のみから成る被膜が摩擦面上に形成される。さらに、滑り方向と直角方向の摩耗形状が、対向する二つの摩擦面で一致した。エンジンオイルではこのような摩耗形状の一致が認められず、酸化物がこの現象を促進していると考えられる。

酸化物の役割は、接触部入口に集積された摩耗粉を頻繁に除去した実験においてもみられた。摩耗粉を除去した場合、摩耗形状のうねりは小さく、入口部に集まった酸化物が表面に溝を作るように鋼を摩耗させていることを示唆する。酸化物が除去された後は、摩擦の増大と接触電気抵抗の減少が一時的にみられ、酸化物が固体潤滑剤のように働いていることを示唆する。

INTRODUCTION

A lubricated machine surface can be made to sustain high severity of contact (some combination of sliding speed and contact pressure), if it is first operated at low severity for a short time. This early stage of operation is called "running-in" (or break-in or wearing-in). In some instances the running-in stage is defined in terms of a transition in wear rate. Landen¹⁾ demonstrated this phenomenon in a two roller machine where the surfaces began with a roughness of 125-250 nm. When the load was such that the calculated fluid film thickness was 64.8 nm there was a small amount of initial wear but none later. When the fluid film thickness was much less, 19.6 nm, there was continuous high wear: these surfaces did not run-in. Finally, when the fluid film thickness was intermediate, 30 nm, there was some wear at the beginning of operation and very little later. These are all cases where the fluid film thickness is less than the surface roughness, and in which the process of running-in has meaning. For thick fluid films there is usually no wear and thus few surface changes.

It is generally agreed that running-in involves some alternation of surface topography^{2)~5)}, and possibly the formation of protective films on the sliding surfaces^{2), 6)~9)}. But there is little agreement on the role of these changes in bringing about the run-in state. Neither is there agreement on the composition of the protective film although it is generally thought that with engine oil it should be composed of compounds of the

elements in the anti-wear additive in the oil, i.e., P, S, Zn, or a polymeric residue from the oil. The protective films have been shown to be primarily Fe_3O_4 on steel lubricated with mineral oil¹⁰⁾, but the precise properties of any of the films that make them "protective" is not known.

In the study of the protective Fe_3O_4 films it is difficult to understand how this oxide could act to prevent scuffing or other serious damage. Many oxides are inherently hard and brittle. The formation of oxide does not coincide with smoothing of surfaces in all cases: sometimes surfaces that are running-in become rougher. Thus running-in cannot be attributed exclusively to surface smoothing as was assumed in the older models of lubricated sliding.

This paper reports the results of research on steel sliding on steel, up to and through the regime of contact severity that produces "running-in". Both mineral oil and engine oil were used because in the literature these appear to produce different results, leading to some of the misunderstanding in the discussions of lubricated wear. In the experiments, electrical contact resistance was measured for a number of sliding conditions, along with measurements of the coefficient of friction, the wear rate, the oxide film thickness and surface topography, all with the goal of determining the role of surface finish and film formation on the running-in process.

EXPERIMENTAL APPARATUS AND PROCEDURE

The sketch of the apparatus used in this study

is shown in Figure 1. A lubricating oil was supplied from a supply tube of 3.175 mm diameter, dropwise, on the disk specimen at a point just ahead of contact. The frequency of the oil supply was adjusted to about one droplet per second. This supply was sufficient to provide a continuous film of oil, much thicker than the calculated lubricant film thickness in the contact region. The contact geometry is a cylinder surface (a crowned roller taken from a bearing) sliding on a flat surface in a direction perpendicular to the axis of the cylinder. This geometry was selected to minimize the change in contact area as the surfaces wear.

A 4340 steel of 7-10 Rc hardness was used as a disk specimen. It was polished in random directions with an abrasive paper of 600 grit, producing a surface roughness of $0.04\text{--}0.06\text{ }\mu\text{m Ra}$. The

stationary cylinder is a 52100 steel roller taken from a rolling element bearing, 60 Rc hard, 6.35 mm diameter and 7.3 mm long. The original surface roughness of the roller, in the axial direction was $0.15\text{--}0.20\text{ }\mu\text{m Ra}$. Because of the crowning of the roller, the actual contact length ranged from 3.5-5.5 mm, depending on the applied load.

Mineral oil of 125/135 SSU (about 28 cSt) was usually used as a lubricant. A commercially available synthetic automotive engine oil with additives (Mobil-1) was also used for comparison.

The frictional force was measured by strain gages attached to a cantilever holding the stationary specimen. The electrical contact resistance was also measured. An electric circuit used for the measurement is shown in Figure 2. With this circuit, maximum voltage imposed between two specimens is about 43 mV, which is much lower

Fig. 1 Sketch of Tester

than a sparking voltage¹¹⁾. The maximum current through the contact is 1.3 mA. The polarity of the applied voltage was found to have no significant effect, on either the formation of surface films or on the resistance measurements.

Both frictional force and electrical contact resistance were recorded using an oscillograph. The frequency limit of flat response was about 80 Hz, including the effect of damping resistance which could not be adjusted to a single value because of the variations of contact resistance. An oscilloscope was used for the observation of higher frequency phenomena.

A test was started at a load of 4 N, and the load was increased by 4 N steps. The duration at each load was 10 minutes. The sliding speed was about 0.4 m/s. In several tests, wear debris accumulated in the entrance region of specimen contact was removed by wiping contact surfaces lightly at frequent intervals to clarify the effect of wear debris on the coefficient of friction and electrical contact resistance. This was done with Q-tips and paper towels in order to verify that contaminant from the wiper was not the cause.

After the test, the surface profile and roughness were examined using a surface tracer system, with a stylus of $12.7\ \mu\text{m}$ radius. The system can calculate several statistical parameters, such as center-line-average (R_a), root-mean-square (R_q),

skewness (R_{sk}), kurtosis (R_k), correlation length, etc. The wear amount of the disk specimen was determined graphically from the surface profiles measured by the surface tracer system at four different points around the circular wear track. The wear of the cylinder specimen was calculated from the measurements of width and length of the wear scar. The thickness of firmly attached Fe_3O_4 was measured by null ellipsometry¹²⁾. The basic principle of the null ellipsometry for the measurement of surface film thickness is given in the appendix.

In a separate test the value of μ was measured at a very low speed on a dry polished surface with a "new" cylinder. Then after 200 minutes of sliding with an applied load up to 80 N in mineral oil, the disk was cleaned of oil and dried and a second friction test was done, again at very low speed using another new cylinder.

RESULTS AND DISCUSSION

Progression of Running-In

To study the progress of running-in, several tests were performed where the load was increased by 4 N steps every 10 minutes. The coefficient of friction, μ , and electrical contact resistance, R , for a period of 200 min or up to a load of 80 N, is shown in Figure 3. The value of

Fig. 2 Electric Circuit for Measurement of Electrical Contact Resistance

μ for very light load is not plotted because of limits of instrumentation. Ranges of values are given because the data varied cyclically with each revolution of the disk. This condition was a great problem in that the cause was never found. It was not due to specimen misalignment (run-out of the disk was adjusted to within $20\mu\text{m}$) because the test device is self aligning. However, this cyclic variation proved to be useful in study-

ing the relationship of μ to R . Invariably the two measurements were out of phase, i.e., when μ was high, R was low, as shown in Figure 4. Both μ and R gradually decreased with an increase in load or test time up to 100 min and then stabilized to $\mu = 0.04$ to 0.12 and $R = 3$ to 50Ω , respectively. This time coincided with the growth of the dark colored regions into a continuous dark surface film over the whole region

Fig. 3 Envelop of Value of Coefficient of Friction and Electrical Contact Resistance; With mineral oil, load step; 4N every 10 min, test time; 200 min (Max 80N)

of rubbing. This dark film has been identified as Fe_3O_4 ¹⁰⁾ in previous work of the same type. An approximate relationship between μ and R may be seen in Figure 5.

At certain times in the testing it was noted that μ and R varied rather irregularly. These occasions were found to correspond to momentary lifting of the upper slider from the disk, whether the disk was rotating or not when the upper

slider was lifted. A smaller effect was seen by simply wiping off the dark residue from the disk while rotating. To clarify the phenomenon, an experiment was performed in which dark residue which accumulated in the entrance region of specimen contact was removed as described in the previous section. Figure 6 shows that after removing wear debris, R was drastically decreased, and μ was increased. The effect was

Fig. 4 Changes of Coefficient of Friction and Electrical Contact Resistance in One Revolution

Fig. 5 Relationship between μ and R in Tests with Mineral Oil showing the Increase in μ due to Debris Effects at Each of Two Loads

greatest when the load was high, but with continued sliding both R and μ gradually changed back to the values seen before the removal of wear debris. It may be noted from the value of R that the surface was covered by a thin oxide film because the values measured were much higher than that of asperity contact of metal

which is measured to be about $10^{-3} \Omega$ for these conditions¹³⁾.

In the separate test described at the end of the previous section, the value of μ measured at very low speed on a dry polished surface with a "new" cylinder, yielding a value in the range of 0.24 to 0.25. After 200 minutes of sliding with

Fig. 6 Envelop of Value of Coefficient of Friction and Electrical Contact Resistance of a Test in which Wear Debris was removed at Frequent Intervals; With mineral oil, load step; 4N every 10 min, test time; 200 min (Max 80N)

an applied load up to 80N in mineral oil, after cleaning and drying the disk surface, a value of μ of 0.12 to 0.13 was measured (again using a new cylinder). This reduction of μ to half the previous value evidently is a measure of the effectiveness of the film of Fe_3O_4 in protecting a surface.

The profiles of rubbing surfaces of various test time with mineral oil are shown in Figure 7.

Up to 50 min or 20N, both the disk and the cylinder showed very little loss of their original profiles although a slight smoothing can be seen. At higher loads some wear became apparent and it takes the form of a conformity between cylinder and disk at 110 min or 44N. The surfaces became microscopically smoother in both directions, but wavy along the length of the cylinder. By 200 min (80N) and 270 min

Fig. 7 Profiles of Rubbing Surface after Tests

(108N), the conformity was complete. Note that the vertical amplitude of the 270 min test is one-fifth that of the other profile. Note also that the hard cylinder (60 Rc) wore into conformity as well as the soft disk (10 Rc) but the softer disk lost 200-300 times more volume than did the hard cylinder. These conclusions agree generally with those of Ram, et. al.¹⁴⁾, however, they did not report the mechanism of material removal.

The surface roughness (R_a) and the thickness of Fe_3O_4 film of the above described specimens were plotted against test time or load in Figure 8. The roughness of the disk in the sliding direction decreased gradually until the test time reached 110 min, then remained constant. This coincided with the time of forming a continuous Fe_3O_4 film over the rubbing path. The roughness of the disks in perpendicular to the sliding direction, however, gradually increased. The roughness of

the cylinder first decreased drastically and then gradually increased. The increase in roughness with test time was caused by the formation of ridges as shown in Figure 7. The thickness of the Fe_3O_4 film increased gradually with test time and reached an equilibrium value of about $0.03 \mu m$. This was nearly the same as the surface roughness in the sliding direction. A calculated EHD film thickness¹⁵⁾ is also given in the figure for comparison. It is noted that the EHD film thickness was nearly the same as the composite roughness in the sliding direction,

$$\sigma = (Rq_{cyl})^2 + (Rq_{disk})^2 \quad (1)$$

if the roughness of cylinder in the sliding direction was assumed to be the same as that of the disk.

The accumulated wear of the disk and the cylinder were plotted against test time or load in

Fig. 8 Roughness, Oxide Film Thickness after Tests

Figure 9. Average contact pressure calculated from the worn area of the cylinder was also plotted in the figure. The wear of both the disk and the cylinder increased linearly with test time. The linear dimension of wear of the disk was much greater than the thickness of the oxide, except for the test time of 50 min, suggesting that the oxide film of a thickness of about $0.03\mu\text{m}$ was firmly attached to the substrate and oxide above this dimension was rubbed away. In these tests the cylinder wore such that the contact pressure was almost constant at all times.

Surface roughness in the sliding direction, wear of the disk and thickness of oxide film for the tests with periodic removal of wear debris

were about the same as those tests in which oxide was not removed. But the surfaces roughness across the wear path and the wear of the cylinder were much lower than in the tests without removal of wear debris. Apparently removing wear debris prevents the ridging as shown in Figure 7. Evidently the oxide "wear debris" accumulation forms the ridge-like shape across the sliding direction. This constitutes more wear of the cylinder than if the ridges do not form.

The Effect of Sliding Speed

Tests were carried out at different sliding speeds to see the effect of sliding speed on

Fig. 9 Wear Amount and Average Contact Pressure

Fig. 10 Envelop of Value of Coefficient of Friction and Electrical Contact Resistance of a Test with Sliding Speed of 0.20 m/s; With mineral oil, load step; 4N every 10 min, test time; 200 min (Max 80N)

Fig. 11 Envelop of Value of Coefficient of Friction and Electrical Contact Resistance of a Test with Sliding Speed of 1.09 m/s; With mineral oil, load step; 4N every 10 min, test time; 200 min (Max 80N)

running-in process. Figure 10 and Figure 11 show the coefficient of friction and the electrical contact resistance during the test with the sliding speed of 0.2 m/s and 1.09 m/s, respectively. From these figures and Figure 3 (sliding speed of 0.4 m/s), the tendency that the lower sliding speed gave the smaller variation of μ and the greater variation of R can be observed. However, the trend of change of μ and R with test time or load is similar for the tests with three different sliding speed. Note that an abrupt change in μ and R was observed when the upper slider was lifted from the disk, irrespective the sliding

speed. The time or load when a continuous oxide film is formed over the rubbing path was greatly delayed in case of the lowest sliding speed tested. Apparently, the rate of the formation of the oxide is affected, in some way, by the sliding speed.

The wear amount, film thickness of Fe_3O_4 and surface roughness after the test were plotted against sliding speed in Figure 12. At the lowest sliding speed tested, the wear amount of the cylinder is much greater, and the surface roughness is smaller compared with the results of the other two higher sliding speeds. Above the slid-

Fig. 12 Wear Amount, Roughness and Oxide Film Thickness against Sliding Speed

ing speed of 0.4 m/s, the surface roughness and the wear amount of the cylinder are nearly the same, and the wear rate of the disk became much smaller. Thickness of Fe_3O_4 film after the lowest sliding speed test was a little thinner, while the difference was small. These observations may be explained by a smaller contribution of EHD lubrication and a slower rate of the formation of the protective oxide film in the test of low sliding speed. However, the mechanism is not clear. Much efforts must be needed to clarify how the sliding speed affects the running-in process.

Comparison between Mineral Oil and Commercially Available Engine Oil

The test using a commercially available synthetic automobile engine oil, as a lubricant produced different results than did those using mineral oil. Since the commercial oil has a viscosity of 2.5 times that of the mineral oil, the speed was reduced to 1/2.5 times that used with

mineral oil. In this test, no black-colored surface film was observed throughout the test. Additives apparently inhibit the formation of Fe_3O_4 film⁹⁾. The coefficient of friction during the test is shown in Figure 13. The value of μ was more constant, a little higher than that using mineral oil, and almost constant over the full range of loads applied during the test.

The electrical contact resistance was very different from that using mineral oil. Figure 14 shows schematically this difference observed in oscilloscope. In the case of mineral oil, the resistance was of medium value and the variations were synchronized with rotation as shown Figure 14(a). However in the case of engine oil, the electrical resistance had only two values, extremely high resistance and nearly 0Ω , as shown in Figure 14(b), throughout the test. The latter behavior of electric resistance seems to be the same as that described by Furey¹¹⁾. The extremely high value of electric resistance does not mean the surface was separated by a fluid film,

Fig. 13 Envelop of Value of Coefficient of Friction; With engine oil, load step; 4N every 10 min, test time; 200 min (Max 80N)

because the load was the same when using either oil. To check this, the electric resistance after a sliding test was measured after stopping the machine. With engine oil, R in the static condition was of the order of 10Ω at a load of 40N , while for mineral oil it was less than 1Ω even at a load of 4N . This shows that the film formed by engine oil is more electrically insulating film than is the Fe_3O_4 film. Unfortunately it has not been possible to measure the thickness of the film formed by the additives in the engine oil. The wear of the disk and cylinder in engine oil were about $1/80$ and $1/24$ of those values obtained in mineral oil, respectively, as shown in Figure 9. The surface of disk in the sliding direction was apparently rougher than that in test using mineral oil as shown in Figure 15, although the value of R_a was the same for both oils. (Recall, when

using equation 1, roughness in the sliding direction is relevant to estimate the effectiveness of lubricant films to separate surfaces.) In the measurements of roughness in the sliding direction, a component of the roughness across the wear path was partly included because the stylus pass was straight whereas the wear path is curved, as shown in Figure 15. When using mineral oil, the ridge-like shape across the rubbing path seemed to affect the R_a value in the sliding direction.

CONCLUSION

There are four conclusions from the experiments performed, They are:

- a. The reduction in friction during the running-in stage of sliding is not primarily due to surface smoothing. Rather, in mineral oil at

Fig. 14 Sketch of Change of Electrical Contact Resistance Observed in Oscilloscope

Fig. 15 Comparison of Surface Roughness between with Mineral Oil and With Engine Oil

least, the Fe_3O_4 film that forms appears to behave in the manner of a soft and ductile material, thus preventing the formation of local high shear stresses which could produce plastic flow and low cycle fatigue in the sliding surfaces.

- b. The sliding of lubricated pairs of steel in mineral oil involves the formation and progressive dislodging of Fe_3O_4 . During repeat pass sliding some of the oxide gathers in the entrance region, probably in clumps. These clumps abrade oxide from the steel surface in narrow paths. This action appears to enlarge the clumps which causes a set of conforming grooves in contacting bodies that are considerably deeper than the original processing marks on surfaces.
- c. The accumulated oxide can be dislodged by wiping the contact surfaces or simply by separation of the sliding bodies. This shows that the accumulated oxides are not firmly attached. This also suggests that vibration, poor tracking in repeat pass sliding, slide-roll combination, and entrance region geometry could strongly affect the formation of grooves, and therefore could strongly affect the type and amount of wear of otherwise similar systems. When using a commercially available engine oil, the formation of Fe_3O_4 film was inhibited, but an electrically insulating surface film was formed between the asperities, which had a good load carrying capacity. The wear rate was very small in this case, but this may retard the running-in process.
- d. A thin oxide film of about $0.03\ \mu\text{m}$ thick also exists and it may be firmly attached to the disk. Clearly, the oxide film has a moderate electrical resistance and apparently also prevents adhesion.

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APPENDIX

The Basic Principle of Ellipsometry

A technique of Ellipsometry is concerned with the measurement of changes in the state of polarization of light upon reflection from a surface. From these changes, thicknesses and refractive indexes of thin film on solid surfaces and optical constants of reflecting surfaces can be calculated.

Figure A1 shows schematically how an incident light is reflected by a surface of a sample with a thin film. The state of polarization, that is, the amplitude ratio and the phase difference between the component of the light parallel to the incident plane (S direction in the figure) and that of perpendicular to the incident plane (P direction in the figure), may be changed in the process of reflection. So that, the reflected light

Fig. A1 Process of Reflection by a Sample with Thin Film; Linearly polarized light is generally reflected as an elliptically polarized light. Note that the refractive index is complex for an absorbing medium.

is generally elliptically polarized, as shown in Figure A1.

Figure A2 shows the arrangement for null ellipsometry used in this study. The system consists of a laser light source (monochromatic light source), a polarizer (prism), a compensator (quarter wave plate), an analyzer (prism), a photocell and a photometer. The monochromatic light emitted by the source is linearly polarized by the polarizer, then converted into elliptically polarized light by the compensator. The reflected light from the sample, changed the state of the polarization, goes through the analyzer, then into photocell. The intensity of the light is monitored by the photometer.

In the technique of null ellipsometry, the polarizer and the analyzer are rotated alternatively to obtain extinction of the light. When this occurs, the light reflected from the sample is plane polarized and can be extinguished by the analyzer. Thus the change in the state of the polarization of the light between before and after the reflection can be determined from the angles of rotation of the polarizer and the analyzer.

For the evaluation of the oxide film thickness, refractive index of the substrate are measured ($n = 2.29$, $k = 1.23$), and the known value of refractive index for Fe_3O_4 ($n = 2.60$, $k = 0.3$) is used.

Fig. A2 Arrangement for Null Ellipsometry

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