Effect of Externally Applied Electric Field on Friction and Wear Characteristics*

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The effect of an electric field applied between rubbing surfaces on friction and wear characteristics was examined using a ball-on-disc testing apparatus under a mixed lubrication condition. The ball and disc were made of bearing steel with high hardness and plain carbon steel annealed with low hardness, respectively. The frictional characteristics were improved in an electric field where the disc was the anode, but with application of an electric field in which the disc was the cathode, the frictional characteristics were deteriorated. Improvement resulted from the formation of a passive-state film on the disc surface of the anode. The lowest limiting values of voltage and electric current possible to form a passive-state surface film were found. Applying an electric field below the limiting values did not result in an effective passive-state film. The limiting values were also influenced by oxygen content in the oils tested.

Key Words: Tribology, Lubrication, Friction, Wear, Voltage, Electric Field, Passive State, Surface Film

1. Introduction

The application of an electric field between rubbing surfaces acting under mixed or boundary lubrication conditions was known to influence the state of the surface films formed, the running-in process, and the friction and wear characteristics⁽¹⁾. Endo et al.⁽²⁾ found in sliding tests using a machine oil without additives that wear rate increased with an increase in the electric voltage applied, and with dissimilar metal combinations, the application of an electric field which canceled out the contact potential differences between the rubbing metals could reduce the wear rate. Katafuchi^{(3),(4)} discussed the effect of applied electric current on wear characteristics by taking into account the state of the surface film formed and the self-generated voltage proposed by Goldblatt⁽⁵⁾. Takeuchi et al.⁽⁶⁾ pointed out that running-in process in journal

bearing testing was significantly affected by an externally applied electric field.

An electric field also affects the chemical reaction at rubbing surfaces. Morizur and Briant⁽⁷⁾ showed the influence of the magnitude and direction of an electric field on the extent of the formation of surface films and wear rate using a lubricant containing ZnDTP. One of the present authors also confirmed that scuffing loads could be changed by applying electric fields.⁽⁸⁾

The research mentioned above suggested that lubrication performance could be improved by applying or generating an electric field during a run. However, the effect of an electric field still requires elucidation. To investigate the influence of an electric field in detail, the authors carried out sliding tests under boundary lubrication conditions with a paraffinic base oil containing little polar substance and sulfur. The tests were conducted with and without an external electric field.

2. Experimental Method

The apparatus used was a ball-on-disc-type sliding tester. The main part of the tester is shown in Fig. 1. Three balls of 19.05 mm diameter slid on the disc

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surfaces at a constant load of 19.6 N and a constant sliding speed of 523 mm/s. The balls were made of bearing steel (SUJ 2, hardness: about HV 786, surface roughness: about $0.02 \mu\text{mRa}$), and discs, made of 0.45% plain carbon steel (S 45 C, about HV 180, about $0.2 \mu\text{mRa}$), were used except in a few tests where discs made of bearing steel of about HV 780 were used. That is, most tests were carried out with the combination of hard balls and a soft disc.

The electric field to be tested was applied using an electric circuit shown in Fig. 2, where the oil reservoir was electrically insulated from the other parts of the apparatus. The applied voltage (open circuit potential difference) ranged from -8 V to $+8 \text{ V}$, the electric current flowing at short circuit (short current) ranging from 0 to 40 mA. The positive sign of the voltage indicates that the electric potential of the disc is higher than that of the balls, the current thus flowing from the disc to the balls through the oil. The circuit in Fig. 2 was also used to monitor the contact condition between the rubbing surfaces. The degree of

separation⁽⁹⁾ was defined by the measured voltage between the balls and disc divided by the applied voltage.

The oil used was paraffinic base oil P 150. The properties of the oil are shown in Table 1. To investigate the effect of oxygen content in the oil, additional tests were carried out with oil blown in by a dry gas of oxygen, air or argon at a rate of 100 mL/min during a run.

The minimum oil film thickness calculated⁽¹⁰⁾ under the present test conditions being at most $0.04 \mu\text{m}$, the oil film formed during a run seems to be considerably smaller than the composite surface roughness of the rubbing surfaces. The separation between the rubbing surfaces due to the oil film was hence not expected, and thus if a degree of separation was observed during a run, it appears to be caused by surface films formed on the rubbing surfaces and/or wear particles generated. In the present investigation, the electrical separation of the rubbing surfaces was detected in tests with little wear debris, and the surface film formed on the rubbing surfaces appears to be responsible for this separation. Therefore, the magnitude of the degree of separation observed during a run could be regarded as a measure of the extent of the insulating surface film formation.

3. Results and Discussion

Figure 3 shows the effect of applied voltage on the coefficient of friction and the degree of separation. Voltage was applied after a 3-minute running-in process was carried out with no applied voltage. As soon as $+4 \text{ V}$ was applied, the coefficient of friction decreased. Terminating the application of $+4 \text{ V}$ elicited an increase in the coefficient of friction, and the application of -4 V further increased it. A similar change in the coefficient of friction with applied voltage was observed throughout the run. The degree of separation was greater with $+4 \text{ V}$ than with -4 V .

To investigate the effect of applied voltage in detail, tests at a constant applied voltage of $+4 \text{ V}$ or -4 V were conducted for 60 minutes. Here, voltage was done after a 5-minute running-in process with no applied voltage. The results are shown in Fig. 4.

Fig. 1 Main part of test apparatus

Fig. 2 Electric circuit for measuring the degree of separation

Table 1 Properties of oil P 150

Viscosity	40°C	30.98
	cSt 100°C	5.486
Viscosity index		105
Specific gravity	15/4°C	0.8630
Sulfur content	ppm	5>
Ring analysis	%CA	0.0
	%CN	32.9
	%CP	67.1

With +4 V the coefficient of friction rapidly fell to 0.02 to 0.04 immediately after the application. After 13 to 18 minutes the degree of separation began to decrease with a subsequent significant rise in the coefficient of friction. Once the coefficient of friction increased, it remained at a high value of 0.08 to 0.09 throughout the run. In contrast, the application of -4 V resulted in a significant increase in the coefficient of friction up to 0.08 to 0.09, and this high

Fig. 3 Change in the coefficient of friction and the degree of separation with applied voltage (0: no application of voltage, +: application of +4 V, -: application of -4 V)

Fig. 4 Effect of applied voltage on frictional characteristics (●: without applied voltage, ○□: with applied voltage) The arrows in the figures indicate the time of the application of voltage

value was maintained throughout the run. The degree of separation was greater with +4 V than with -4 V.

The appearances of rubbing surfaces after runs for 15 minutes are shown in Fig. 5. In the test with +4 V, where the coefficient of friction remained as low as 0.04 until the end of the test, the rubbing surface of the ball was worn in a circle, but the rubbing track of the mating disc was only slightly worn. In addition to the slight wear, a large part of the rubbing track was metallically lustered. This suggested that the hard ball was worn by the soft disc and that the surface film on the disc was harder than the ball and thinner than the wavelength of visible light. By contrast, with -4 V and without application, the ball surfaces were only slightly worn, and debris transferred from the disc

Fig. 5 Appearance of rubbing surfaces after a run (SUJ 2 ball/S 45 C disc)

was observed. On the other hand, the wear track of the disc was considerably worn and covered with a brown film. The disc surface with +4 V after the coefficient of friction increased was also covered with a brown film similar to that with -4 V shown in Fig. 5.

Figure 6 shows the EPMA (electron probe microanalysis) line analysis of the disc tracks shown in Fig. 5. The scanning direction was perpendicular to the sliding direction. At the rubbing track with +4 V, oxygen concentration was not increased, and Cr which was contained only in the ball material was not detected. In contrast, the rubbing track with -4 V was significantly increased in oxygen concentration, although no Cr was detected. This indicates that an oxide film was formed at the rubbing surface of the disc, and that the oxide originated not from the ball material but from the disc material. The surface film was therefore considered to be produced as a result of the oxidation of the rubbing track itself and the accumulation of the oxidized wear debris generated from the disc surface.

Since oxidation and reduction reactions are generally promoted at the anode and cathode, respectively, the oxidation of rubbing surfaces is enhanced on the anode side, and suppressed on the cathode side. On the cathode surface even reduction of the oxide film formed in advance could occur. It is known that an electrochemical passive-state film can be produced on an anode surface, and that this passive-state film is very compact, as thin as a few nm.⁽¹¹⁾ Therefore a surface covered with a passive film retains a metallic luster. The results discussed above suggest that a passive-state thin film composed of oxide was formed on the disc rubbing surface with +4 V. Interruption of

Fig. 6 Distributions of oxygen and chromium on disc surfaces after a run

the application of the electric field ceased formation of the passive film, and diminished the ability of the passive film produced in advance to protect the rubbing surface. Consequently, the coefficient of friction increased. Application of -4 V even lead to the disappearance of the passive film as a result of the reduction reaction, thus, the coefficient of friction increased further. The oxide film formed with -4 V was not thin and compact as was to the passive-state film, however, it was instead composed mainly of oxidized wear debris from the disc material. The oxide film was sparse and thick compared with the passive-state film and the surface roughness was greater; hence, the coefficient of friction was higher due to the greater ease of the destruction of the surface film and lubrication film by rubbing.

In the case of a hard ball rubbing on a soft disc, the formation of a passive-state film on the soft disc surface is effective in reducing friction. When a passive film is being formed on the hard ball, improvement in friction characteristics cannot be expected because the mating disc surface is worn and adhesion of the wear debris to the ball surface occurs.

Once substantial breakdown of the passive film occurs, the metallic contact between the rubbing surfaces increases considerably and the rubbing surfaces become rougher. Therefore, complete repair of the film over the rubbing surface is nearly impossible. As shown with +4 V application in Fig. 4, the coefficient of friction, once increased, did not decrease again. The wear of the disc, however, was effectively suppressed owing to the promotion of oxidation or the formation of an oxide film harder than the mating hard ball, which consequently was considerably worn in a circle. The disc surface profiles after 60-minute runs shown in Fig. 7 confirmed that the amount of wear of the discs was small with +4 V and large with -4 V and without application.

The results of the SUJ 2 ball on SUJ 2 disc are shown in Fig. 8. The wear characteristics of SUJ 2/SUJ 2 were similar to those of SUJ 2/S 45 C. With +4 V the amount of wear of the disc was so small that the grinding mark on the surface finish still remained after the test, and the mating ball was considerably worn in a circle.

It is necessary for producing and sustaining an

Fig. 7 Surface profiles of disc surfaces

electrochemical passive-state surface film that the externally applied electric field has an open circuit voltage and short current larger than certain values. Therefore, the frictional characteristics are considered to change with the magnitudes of applied voltage and short current. The effects of the applied voltage and short current are shown in Fig. 9. Cases where the coefficient of friction was kept low for more than 6 minutes and for less than 5 minutes after the application of prescribed electric fields are denoted by open circles and triangles, respectively. The black circles show the cases of no improvement in frictional characteristics with the application of an electric field.

Application of an electric field of voltage higher than +2 V and short current larger than 1 mA considerably improved the frictional characteristics. The application of an electric field less than these values resulted in little or no improvement in frictional characteristics. It was confirmed that these values were the lowest limiting voltage and short current of the externally applied electric field which lead to the formation and maintenance of a passive film effective in reducing friction.

Fig. 8 Appearance of the rubbing surfaces after a run (SUJ 2 ball/SUJ 2 disc)

Fig. 9 Effects of applied voltage and short current on frictional characteristics (Frictional characteristics ○: improved, △: slightly improved, ●: not improved)

The oxygen content in oil also is considered to affect the formation of oxide film⁽¹²⁾. The results with oils blown-in by a dry gas of air, oxygen or argon are shown in Fig. 10. The external field of +4 V/5 mA was applied. The friction was decreased by applying the electric field irrespective of the kinds of blown-in gases, but the duration of low friction showed a different response. The duration was the longest with dry air. By contrast, with dry oxygen where the oil tested seemed to be the highest in oxygen content the low friction duration was the shortest, and with dry argon, with the lowest oxygen content, it was also short compared with the case where no blown-in gas was used. These results indicate that the oxygen content in oil has a considerable effect on the extent of the oxide formation and the properties of the oxide film.

Since blowing dry air into the oil to be tested improved the friction characteristics significantly, a test under +1 V/1 mA conditions, which did not improve the friction performance without blown-in, was conducted with blown-in dry air (Fig. 11). The friction rapidly decreased just after application of the electric field. With dry air blown-in, the effect of an external electric field on the friction characteristics is shown in Fig. 12. The friction characteristics were

Fig. 10 Effect of blown-in gases on frictional characteristics (Blown-in gas ●: no gas, ○: oxygen, △: air, □: argon) The arrow in the figure indicates the time of the application of voltage

Fig. 11 Changes in the coefficient of friction with applied voltage with and without dry air blown-in (+1 V/1 mA) (○: with blown-in, ●: without blown-in)

Fig. 12 Effects of applied voltage and short current on the frictional characteristics with dry air blown-in. Open circles indicate improvements in the frictional characteristics with the application of voltage

improved by the application of electric fields with which the improvement in friction characteristics was not attainable without blowing-in of gases as shown in Fig.9. These results indicate that to improve friction characteristics by externally applying an electric field the lowest limiting voltage and short current must be used, and that their lowest values change with the oxygen content in the oil.

4. Conclusions

The effect of an electric field applied between rubbing surfaces on friction and wear characteristics was examined using a ball-on-disc testing apparatus under a mixed lubrication condition. The ball and disc were made of bearing steel with high hardness and plain carbon steel annealed with low hardness, respectively.

The frictional characteristics were improved by applying an electric field where the disc was the anode; however, when the disc was used as the cathode, the frictional characteristics deteriorated. Improvement resulted from the formation of a passive-state film on the disc surface of the anode. The lowest limiting values of voltage and short current possible to form the passive-state surface film were found. Application of an electric field below the limit values did not result in the formation of an effective passive-state film. The limiting values were also influenced by the oxygen content in the oils tested.

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