PREPRINT NO. 01-TC-18
STLE PRESENTATION

Measurement of the Potential of Static Electricity Generated by the Friction of Oil Lubricated Metal on Metal©

AKIRA SASAKI (Member, STLE)
KLEENTEK Ind. Co. Ltd.
Tokyo Japan
SHINYA KAWAI, TOMOMI HONDA and YOSHIRO IWAI
Fukui University
Fukui, Japan

It is known that electricity appears when two bodies contact or cause friction. Although tribology is the science of lubrication, friction and wear, very little has been discussed about the electricity due to friction. One of the authors has studied generation of static electricity during oil filtration and its effects on oil oxidation. This study deals with generation of static electricity while a metallic ball slides on a lubricated metal. The experiment was conducted at various sliding velocities under the lubricated conditions by using a modified pin-on-disc machine. The static electricity, which was accumulated on the insulated pin and ball assembly, was measured. Within the range of the experiment, it was found that both the potential of the static electricity and the frequency of its discharges would increase in proportion to the sliding velocity.

KEY WORDS

Static Electricity; Pin-on-Disc Machine

INTRODUCTION

There have been several studies on triboemission of electrons and ions in the process of friction and wear (Nakayama, et al. (1995) and Katafuchi, et al. (1980)) and the effects of forming lubrication films by applying small current of electricity (Katafuchi, et al. (1980), (1982)). However no study has been seen on the potentials of static electricity generated by metal-to-metal friction, according to the investigation of the authors, although Wood, et al. investigated electric charges by coulombmetrically (Wood, et al. (1997)). Materials have their own work functions and static electricity appears by the difference of two work functions when they contact or cause friction. Almost all machines are made of metals and lubricated with some lubricants, and they sit on the ground. Therefore the authors could not feel any static electricity even when we touch machines during operation. This does not mean that static electricity is not generated at machine elements by friction during machine operation.

When the authors carefully investigate the lubricated parts, there are oil films at the interfaces between the contacting metals whether they are hydrodynamic or elastrohydrodynamic lubrication films. As hydrocarbons are basically dielectric, they will insulate the contacting metals and the electricity will be accumulated as static electricity on the insulated metals, when it is generated by friction. However it is assumed that such insulation will be broken by the static electricity of relatively low voltage, as the lubricating films are very thin.

This study measures the potentials of the static electricity, which is generated by the friction of metal and metal lubricated with polyalphaolefin (PAO) having various viscosities, hydrogenated paraffin oil and grease at various sliding velocities by using a pin-on-disc machine with an insulated pin and ball assembly. A series of experiment indicates that both the potential of the static electricity and the frequency of its discharges increase in proportion to the sliding velocity.

EXPERIMENTAL

Schematic Diagram of Test Device

The schematic diagram of the test device is shown in Fig. 1. The test device consists of a pin-on-disc machine with an insulated pin and ball assembly, a diode, a potentiometer and AD converter assembly and a personal computer. The pin with a ball is inserted into a sleeve made of polytetrafluoroethylene (PTFE) and

**Presented as a Society of Tribologists and Lubrication Engineers Paper at the STLE/ASME Tribology Conference in San Francisco, CA October 21-24, 2001
Final manuscript approved August 18, 2001
Review led by Paul Bessette**

TABLE 1—BLENDING RATIO OF TWO BASE STOCKS FOR TEST OILS

VISCOSITY OF BASE STOCK	28.8 mm^2/s TEST OIL	150 mm^2/s TEST OIL	320 mm^2/s TEST OIL	420 mm^2/s TEST OIL
28.8 mm^2/s	100%	35%	9%	0%
420 mm^2/s	0%	65%	91%	100%

TABLE 2—BREAKDOWN STRENGTH OF THE BASE STOCKS

VISCOSITY OF BASE STOCK	BREAKDOWN STRENGTH
28.8 mm^2/s	31.6 kV
420 mm^2/s	43.5 kV

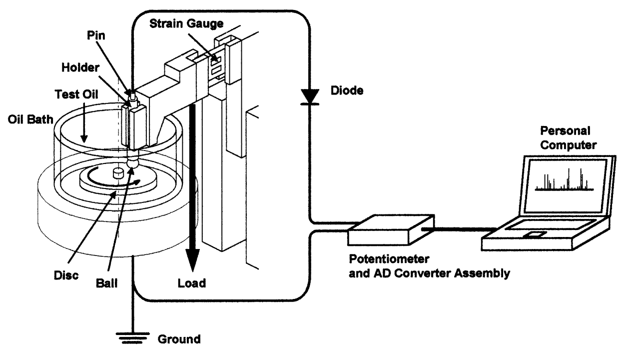

Fig. 1—Schematic diagram of test device.

the balancing arm holds the pin sleeve to insulate. The diode was connected between the pin and the potentiometer and AD converter assembly in the direction of the potentiometer assembly in order to know the polarity of the static electricity accumulated on the pin and ball assembly.

Experimental Conditions

The ball was a commercial bearing ball with 10 mm diameter, which was made by bearing steel (composition (wt.%): 0.10%C; 1.5%Cr; 0.25%Si; Fe, bal.). It was fixed to 0.45% carbon steel pin of 4 mm diameter by soldering. The disc was made of 0.45% carbon steel and the dimension was 5 mm in thickness and 60 mm in diameter. The test surface of disc was finished with No. 1200 emery paper. The surface roughness of ball and disc were 0.05 and 0.03 µmRa, respectively.

The lubricants used for the experiments are shown below:

Polyalphaolefin (PAO): 28.8, 150, 320 and 420 mm^2/s.

The viscosity of PAO was adjusted by blending two base stocks as shown in Table 1.

The breakdown strengths of the base stocks, which were exposed to the atmosphere, were measured as shown in Table 2.

Hydrogenated paraffin base oil: 32 mm^2/s.

Grease: Grease having 150N mineral oil (Viscosity is about 30 mm^2/s)

The temperature was 20 ± 2˚C.

The moisture was not specifically controlled.

The sliding velocity was in the range from 0.1 m/s to 0.5 m/s and the load on the ball was 1N. Table 3 shows the experimental condition in each test. Table 3 shows the order of a series of tests. A new test specimen and oil were prepared for each series of tests. For example, the first test was carried out under a sliding velocity of 0.10 m/s until the sliding distance reaches 100 m, and the sliding velocity was changed into 0.2 m/s and the test was conducted until 200 m. Likewise the velocity of 0.3 m/s, 0.35 m/s, 0.4 m/s and 0.5 m/s with each 100 m distance until he total distance reaches 600 m. The test specimens and test oil were exchanged when the sliding distance reached 600 m. When a series of tests were completed, the next series of tests were carried out by the order shown in Table 3.

RESULTS AND DISCUSSION

Preliminary Measurement

When the preliminary measurement was made without diode, both positive and negative potentials appeared almost equivalent as shown in Fig. 2. The potentiometer has an internal condenser and measures the potential by collecting the electric charge in the condenser in accordance with the following equation (Sasaki, et al. (1999)).

$$Q = CV = \frac{\varepsilon S}{d} V \qquad [1]$$

where Q : Electric charge (Coulomb)
C : Capacitance (F)
V : Potential (Volt)
ε: Dielectric Constant (F/s)
S : Area (m^2)
d : Distance (m)

When the electric charge accumulated on the pin and ball assembly discharges to the disc by breakdown of the oil film, the counter current having the opposite polarity fills into the condenser. This counter current will be measured and shown on the display. The diode works to shut off such a counter current. An example of the measured potential pattern with a diode is shown in Fig. 3. With the diode, the polarity of the static electricity due to friction was confirmed positive.

Potentials of PAO

The potentials were measured 20 times at each sliding velocity in the range from 0.1 m/s to 0.5 m/s. The average values of the potentials *vs*. sliding velocities are collectively shown in Fig. 4. The measured potential must be understood as the breakdown potential of the oil film by the electric charge accumulated on the pin and ball assembly.

The potentials *vs*. oil viscosity are also shown in Fig. 5, collectively. The Fig 5 indicates that the potentials are not influenced by oil viscosity when the sliding velocity is as low as 0.1 m/s and 0.2 m/s but that the potentials decrease in inverse proportion to oil viscosity at same sliding velocity when it exceeds 0.3 m/s.

Generally, when a ball runs on a disc, oil film will become thick in proportion to the sliding velocity and oil viscosity. The authors did not actually measured the oil film thickness but calculated the oil film thickness based on the two dimensional EHL the-

TABLE 3—THE EXPERIMENTAL CONDITION IN EACH TEST

	Sliding Distance (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
Test 1	①	②	③	④	⑤	⑥
Test 2	⑥	①	②	③	④	⑤
Test 3	⑤	⑥	①	②	③	④
Test 4	④	⑤	⑥	①	②	③
Test 5	③	④	⑤	⑥	①	②
Test 6	②	③	④	⑤	⑥	①

① 0.10 (m/s) ④ 0.35 (m/s)
② 0.20 (m/s) ⑤ 0.40 (m/s)
③ 0.30 (m/s) ⑥ 0.50 (m/s)

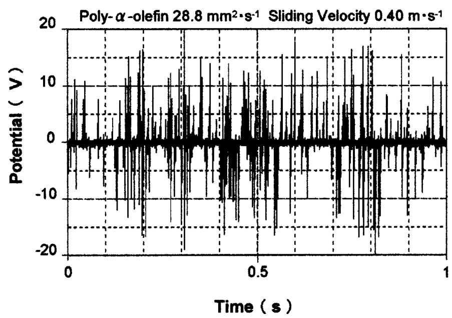

Fig. 2—The measured potential pattern without diode.

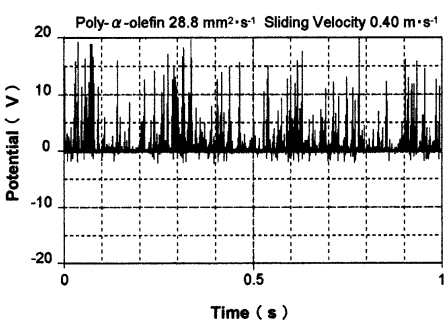

Fig. 3—The measured potential pattern without diode.

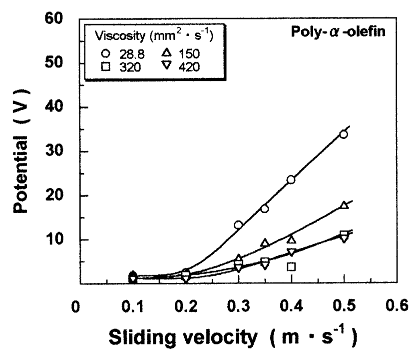

Fig. 4—The summary of the measured potentials *vs.* sliding velocity (PAO).

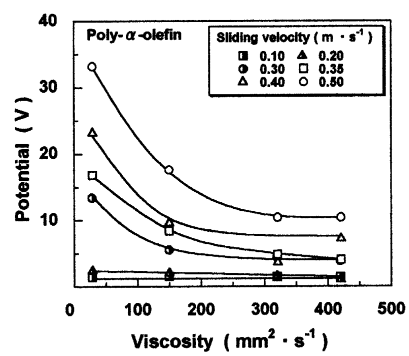

Fig. 5—The summary of potentials *vs.* oil viscosity (PAO).

ory. Figure 6 shows the result. The oil film thickness of 420 mm^2/s oil was about seven times as large as that of 28.8 mm^2/s one. The measured breakdown strength of 420 mm^2/s oil was larger than 28.8 mm^2/s one as shown in Table 2. These facts indicate that the insulating capability and the breakdown strength of the oil film of 420 mm^2/s oil are greater than those of 28.8 mm^2/s one. If the breakdown strength of the oil film governs the potential, the potential of 420 mm^2/s oil must be higher than that of 28.8 mm^2/s one but the potential of the 420 mm^2/s oil was lower than that of 28.8 mm^2/s one as shown in Fig. 4. In order to understand this contradiction, it is important to consider the mechanism of generation of static electricity.

The measured potential of each oil sample increases in proportion to the sliding velocity as shown in Fig. 4 but in inverse proportion to the oil viscosity in Fig. 5. This suggests that generation of electric charge increases in proportion to the sliding velocity and that the potential becomes high in accordance with the equation (Nakayama, et al. (1995)). In the case of this experimental, a ball slides on a lubricated disc with oil in between. Although the oil film is very thin, the oil will form a strong meniscus on the ball surface, as the surface energy of a ball, which is made of steel, is very large in comparison with that of oil. When the ball slides on the disc, the oil film will be sheared at the part where the diameter of the oil meniscus is the smallest and the influence of the metal is weak. However the majority of the oil film forming the meniscus will stay on the ball when the oil film is sheared. When the oil film is thick, the shearing line will be far from the ball surface and when it is thin, it will be near the ball surface. It is also known that oil is dielectric and the electric double layer thickness of oil is large. In this case, the positive charge

TABLE 4—THE RELATION OF THE COUNT OF ELECTRIC DISCHARGES AND OIL VISCOSITY AT 0.5 m/s

Oil Viscosity (mm^2/s)	28.8	150	320	420
The Reverse Ratio of Viscosity to 420 mm^2/s	14.6	2.8	1.3	1
Count of Discharges in 1.3 second	450	6	3	2
Distance per Discharge (mm)	1.4	108	217	325
Count of Discharges in a Round	107	1.4	0.7	0.5

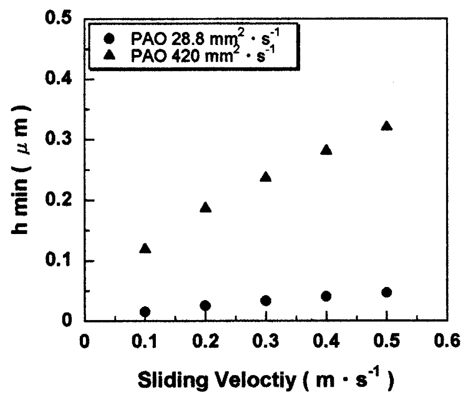

Fig. 6—The oil film thickness based on the two dimensional EHL theory *vs.* sliding velocity (PAO).

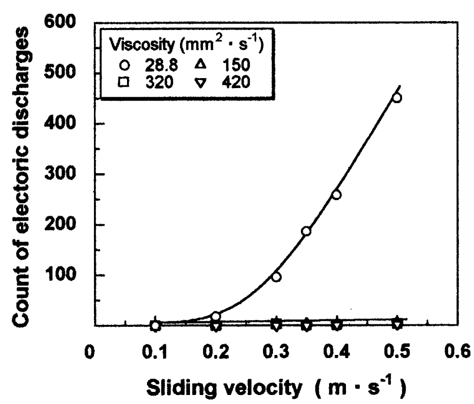

Fig. 7—The count of electric discharges *vs.* sliding velocity (PAO).

appeared on the ball and the negative one in the oil. When oil carries away the negative charge, the equivalent amount of positive charge will remain on the insulated ball and be accumulated there. The farther the distance from the ball surface is, the lower the density of the negative charge will be. Therefore when the shear happens far from the ball with high viscosity oils, the amount of charge, which is carried away by sheared the oil film, will be less. It is the reason why the potential with 420 mm^2/s oil was low, while that with 28.8 mm^2/s one was high. The potential with 28.8 mm^2/s oil was 34V and that with 420 mm^2/s one was 10V in Fig. 4. The ratio of the potential with 28.8 mm^2/s oil to that with 420 mm^2/s one was about 7 to 2, while the reverse number of the ration of the viscosities of 28.8 mm^2/s oil to 420 mm^2/s one was 15 to 1 and that of the oil film thickness of 28.8 mm^2/s oil to 420 mm^2/s

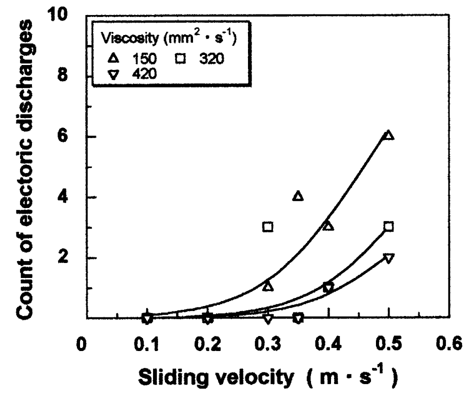

Fig. 8—The count of electric discharges *vs.* sliding velocity for high viscosity oil (PAO).

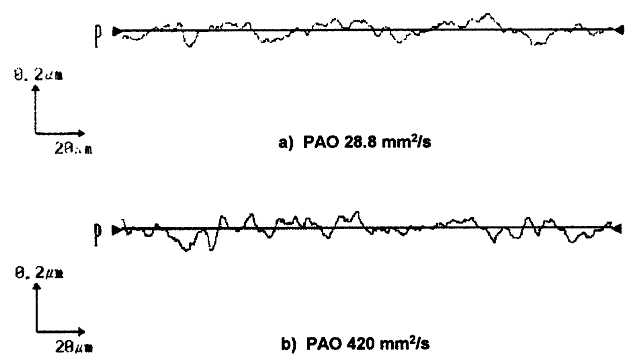

Fig. 9—The surface roughness of the sliding track (PAO).

oil was 7 to 1 in Fig. 6. If the electric charge, which is carried away by the sheared oil film, reduces in inverse proportion to the distance from the surface of the ball, the potential with 420 mm^2/s oil must be inverse proportional to the oil film thickness. However it was a little bit higher than that in inverse proportion. This must be discussed in relation with the count of electric discharges.

The average number of electrical discharges in the scale, which was equivalent to 1.3 second, was counted at each sliding velocity and the result is shown in Figs. 7 and 8. As the diameter of the sliding track on a disc is 50 mm, the sliding distance of a round track is about 150 mm. When a sliding velocity is 0.5 m/s, the sliding distance in 1.3 second is about 650 mm. The relation of the count of electric discharges and oil viscosity is shown in Table 4.

The count of electric discharges *vs.* the reverse ratio of viscosity to 420 mm^2/s shows an interesting relation. The count of electric discharges with 28.8 mm^2/s oil was 450 in 1.3 second and 107 in a round slide, while that of the heavy oil was substantially low. The surface roughness of the sliding track was examined as shown in Figs. 9(a) and 9(b). There was almost no difference with the viscosity of oil. These may suggest that the count of electric discharges was high due to the thin oil film thickness and the weak breakdown strength of 28.8 mm^2/s oil. The counts of electric discharges with 150, 320 and 420 mm^2/s oils were proportional to the reverse ratio of the viscosity to 420 mm^2/s. This suggests that the 420 mm^2/s oil governs the viscosity of the 150 and 320 mm^2/s oils as shown in Table 1.

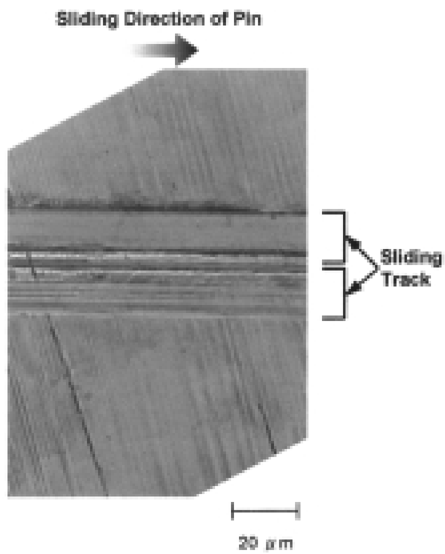

Fig. 10—The sliding track of the ball on the disc lubricated with 28.8 mm^2/s PAO at the sliding velocity of 0.4 m/s.

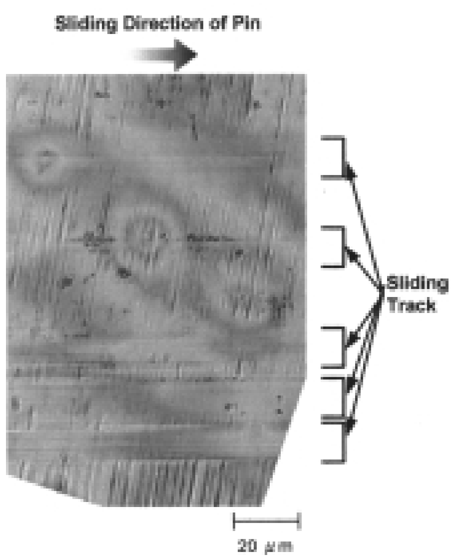

Fig. 11—The sliding track of the ball on the disc lubricated with 420 mm^2/s PAO at the sliding velocity of 0.4 m/s.

There may be other factors to be considered. One is the temperature of the oil film, which may reduce the breakdown strength, and the other was deep groove of the track with 28.8 mm^2/s oil. The temperature of oil film at the nearest point between the ball and the disc was not possible to measure during sliding. The sliding track of the ball on the disc with 28.8 mm^2/s oil is shown in Fig. 10 and that with 420 mm^2/s one in Fig. 11. The tracks of Fig. 10 are deep but those of Fig. 11 shallow. It was found that the width of each sliding track was about 10 μm. The tracks of Fig. 10 suggest that the ball contacts with the disc at the edges of the grooves, as the disc swings during rotation.

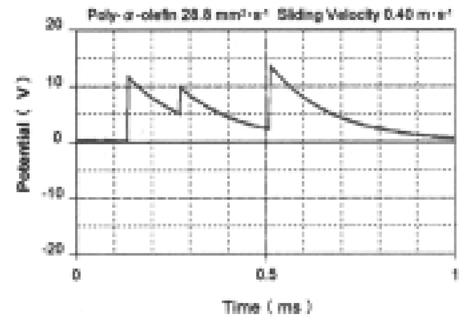

Fig. 12—The pattern of electric discharge measured at microsecond range.

The pattern of the electrical discharges appeared on the display as shown in Fig. 3 at the millisecond range. This picture gives us an impression that electricity is immediately generated and instantly released by breakdown of the insulating oil film. For further investigation, the measurement was made at the microsecond. The pattern appeared on the display is shown in Fig. 12. This pattern suggests that electricity is immediately generated but that it takes time for the charge to be released, because electricity is continuously generated while discharges happen.

Potentials of Hydrogenated Paraffin Oil and Grease

The potentials of hydrogenated paraffin base oil having the viscosity of ISO VG 32 and the grease having 150N mineral base oil (about 30 mm^2/s) were also measured as shown in Figs. 13 and 14. The potential increases in proportion to sliding velocity for both the paraffin base oil and the grease.

The potentials of three oil samples of 28.8 mm^2/s PAO, hydrogenated paraffin base oil and the grease are shown in Fig. 15, collectively. The average potentials of the three samples were almost equivalent at every sliding velocity. This suggests that the potential of the frictional electricity may depend on the viscosity of oil.

The counts of electrical discharges of three samples of 28.8 mm^2/s PAO, the hydrogenated paraffin base oil and the grease were incorporated in one figure as shown in Fig. 16. The number of electrical discharges in a unit time of the grease was larger than those of PAO and hydrogenated paraffin base oil.

Different from the oil samples, only the grease had some additives. However it is not clear why the number of electrical discharges of the grease is larger than those of the other oils, in view that the potentials of all three samples are similar. Further study must be made to this matter.

SUMMARY AND CONCLUSION

1. The static electricity generated by metal-to-metal friction was positive charge.
2. The potentials of 28.8 mm^2/s PAO were higher than those of the other PAO having the viscosity of 150 mm^2/s, 320 mm^2/s and 420 mm^2/s.
3. The count of electrical discharges of 28.8 mm^2/s PAO were substantially larger than those of the other PAO having the viscosity of 150 mm^2/s, 320 mm^2/s and 420 mm^2/s.

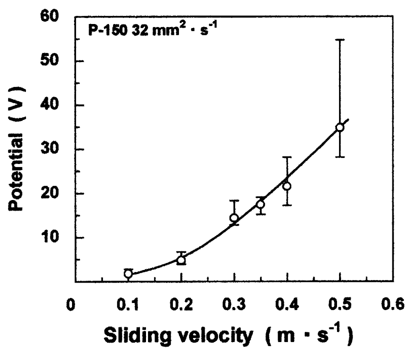

Fig. 13—The potential of hydrogenated paraffin base oil *vs*. sliding velocity.

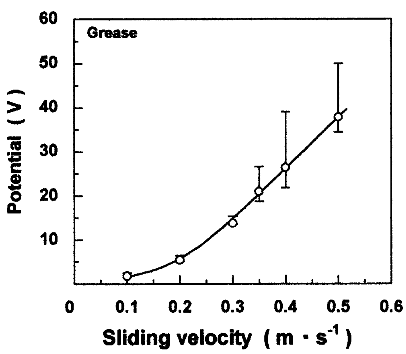

Fig. 14—The potential of grease *vs*. sliding velocity.

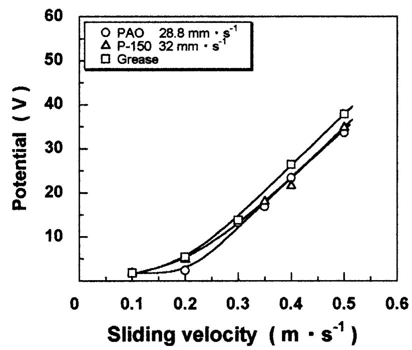

Fig. 15—The potentials of two low viscosity oils and grease *vs*. sliding velocity.

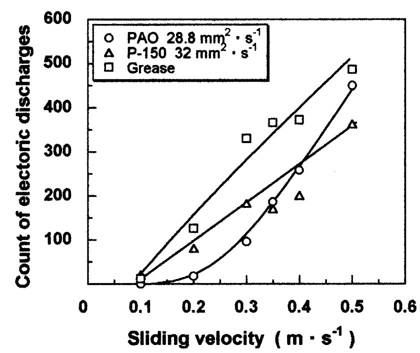

Fig. 16—The counts of electric discharges of two low viscous oils and grease *vs*. sliding velocity.

4. The tracks of 28.8 mm^2/s PAO were smooth but deep, although that of 420 mm^2/s was smooth and shallow. The 28.8 mm^2/s oil might have caused more metal-to-metal contact of the ball and the disc at the edges of the grooves and generated more electricity than the 420 mm^2/s one.
5. The potential of frictional electricity may depend on the sliding velocity and the oil viscosity, in view that the potentials of 28.8 mm^2/s PAO, hydrogenated paraffin base oil and grease are almost equivalent.

REFERENCES

(1) Katafuchi, T. and Takano, N. (1980), "Electrical Characteristics between Lubricated Frictional Surfaces (I)," *Jour. of Japan Soc. of Lubr. Eng*., **25**, 6, pp 395-399.

(2) Katafuchi, T. and Takano, N. (1980), "Electrical Characteristics between Lubricated Frictional Surfaces (II)," *Jour. of Japan Soc. of Lubr. Eng*., **25**, 6, pp 400-404.

(3) Katafuchi, T. and Takano, N. (1980), "Electrical Characteristics between Lubricated Frictional Surfaces (III)," *Jour. of Japan Soc. of Lubr. Eng*., **25**, 7, pp 444-449.

(4) Katafuchi, T. and Takano, N. (1982), "Electrical Characteristics between Lubricated Frictional Surfaces (IV)," *Jour. of Japan Soc. of Lubr. Eng.*, **27**, 2, pp 129-134.

(5) Nakayama, K. and Hashimoto, H. (1995), "Triboemmision of Electrons and Ions During Wear of Solids under Boundary Lubrication with Saturated Hydrocarbon Liquids," *Trib. Trans.*, **38**, 3, pp 541-548.

(6) Sasaki, A., et al. (1999), "Generation of Static Electricity During Oil Filtration," *Lubr. Eng*., **55**, 9, pp 14-21.

(7) Wood, R. J. K., et al. (1997), "Electrostatic Charging Precursor to Scuffing in Lubricated Contacts," *Abstract of World Tribology Congress*, p 102.

Presented at the STLE/ASME Tribology Conference in San Francisco, California, October 21-24, 2001: This paper is the literary property of the Society of Tribologists and Lubrication Engineers. The Press may summarize freely from this manuscript after presentation, citing source; however, publication of material constituting more than 20 percent of the manuscript shall be considered a violation of the Society's rights and subject to appropriate legal action. Manuscripts not to be published by the Society will be released in writing for publication by other sources. Statements and opinions advanced are understood to be individual expressions of the author(s) and not those of the Society of Tribologists and Lubrication Engineers. Discussions of this paper will be accepted at STLE Headquarters until December 4, 2001.