ナノ隙間における潤滑油のインピーダンス計測法の確立

Impedance measurement methods for lubricating oils sheared in nanogaps

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1. Introduction

In the development of electric vehicles, there is a need to improve the performance of electric drive unit fluid (E-Axle fluid), which is mainly composed of oil and is used to lubricate reduction gears and cool motors. To further reduce viscous friction and improve cooling efficiency, the oil must have a lower viscosity. However, if the viscosity is too low, the oil film cannot be maintained in the sliding gaps and the lubrication condition tends to shift to boundary lubrication. Therefore, the addition of polymers to oil has been attracting attention. Polymers are conventionally used to increase the viscosity index, and it has recently been reported that an adsorption layer of polymers contributes to the low friction in boundary lubrication[1)]. Lubrication performance can be improved by controlling the structure and mechanical properties of the polymer adsorption layer.

On the other hand, when the sliding surfaces are charged by the effects of motors or electric circuit systems, electrical discharges due to dielectric breakdown occur, causing damage to the sliding surfaces (electric corrosion) and oil degradation. In particular, under boundary lubrication conditions, the gap between the sliding surfaces is narrowed to the nanometer order, and the electric field is concentrated, increasing the possibility of dielectric breakdown. In addition, polymer additives have been reported to affect the conductivity of lubricants[2)]. However, a method for evaluating the conductivity of lubricating oil in a nanoscale sliding gap has not yet been established. Conductivity evaluation of oil in nanoscale gaps is indispensable for safe design. In this study, we developed a method to quantify the mechanical properties (shear viscoelasticity) and conductivity of lubricating oil in nanoscale gaps by developing an original nano-rheological measurement method, the fiber wobbling method (FWM)[3)]. Furthermore, we aimed to clarify the influence of the adsorbed layer of polymer additives on conductivity and dielectric breakdown.

2. Simultaneous measurement of shear viscoelasticity and impedance of lubricating oils in nano-gaps

An overview of the fiber wobbling method (FWM), a nano-rheological measurement method, is shown in Fig. 1.An optical fiber with a spherical tip of approximately 200 µm in diameter was sinusoidally vibrated by a piezoelectric actuator to shear lubricant oil on a substrate with a tip sphere. The amplitude and phase changes of the probe tip were optically detected, and the shear viscoelasticity of the lubricating oil sheared in the nanogap between the probe tip and the substrate was quantified. The gap between the lubricant and the substrate was controlled with an accuracy of 0.1 nm using a piezo stage, and the shear force was detected with an accuracy of 0.1 nN. The impedance measurement function, shown in Fig. 2, was added to the FWM measurement system. The FWM probe and substrate were coated with a conductive film (Cr), and both were used as the electrodes. An AC electric field was applied to the lubricating oil in the nanogap, and shear viscoelasticity and impedance were measured simultaneously. The frequency and voltage of the AC electric field were 10 kHz and 15 V, respectively. The small current was converted to a voltage value using an I-V converter, and the amplitude and phase of the voltage signal were measured by synchronous detection using a lock-in amplifier. The resistance of the lubricant was calculated from these results. The circuit model of the lubricant was an RC parallel circuit consisting of a resistor and capacitor.

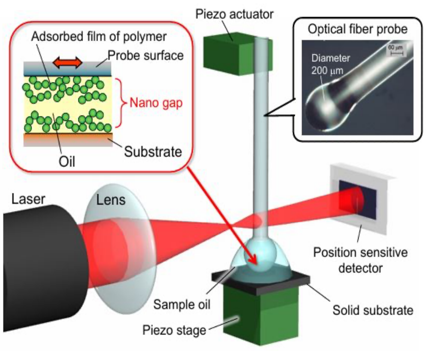

Fig. 1 Schematic of fiber wobbling method (FWM)

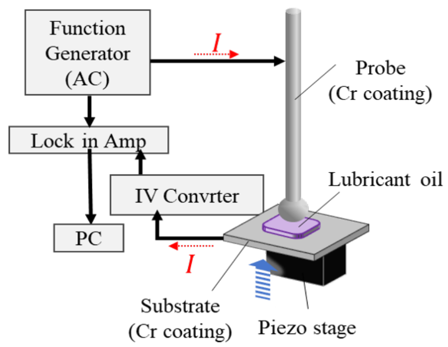

Fig. 2 Schematic of fiber wobbling method equipped with impedance measurement.

3. Materials and methods

Two types of lubricants were used: base oil only and polymer-added lubricant. The base oil was a Gr. III mineral oil. The polymer-added lubricant was a base oil, to which polyalkyl methacrylate (PAMA, molecular weight 20,000) was added at 2.0 wt%. PAMA is a random copolymer of adsorbable and non-adsorbable side chains that can improve lubricity by forming a polymer adsorption film on a sliding surface[4]. The mechanical properties and impedance characteristics of these two lubricants were simultaneously measured in a nanogap using FWM. The formation of the polymer adsorption film was verified by measuring its mechanical properties. From the impedance characteristics, the effect of polymer addition on conductivity was evaluated. Both properties were measured while the gap between the probe and substrate was narrowed at a constant rate, and the gap dependence was obtained for each.

4. Results and discussion

The shear gap dependence of the viscosity and elasticity measured by FWM is shown in Fig. 3(a) and 3(b), respectively. As the gap narrowed, the viscosity and elasticity of both the base oil and PAMA increased below a gap of approximately 10 nm. However, the lubricant containing the polymer additive showed a more pronounced increase, which is thought to be due to the formation of a polymer adsorption film on the surface[5]. The increase in viscoelasticity of the base oil alone is considered to be due to the effect of confinement in nanogaps[3], and its effect on viscoelasticity was smaller than that of polymer addition. These results indicate that PAMA forms an adsorption film with a thickness of approximately 10 nm on the surface.

The impedance characteristics measured simultaneously by the FWM are shown in Fig. 4 for the base oil and for the PAMA-added lubricant. Both results show the resistance values in the RC circuit model. When the gap was narrowed, the impedance of the base oil decreased sharply at a gap of approximately 10 nm, immediately before contact with the substrate. The decrease in resistance before contact suggests that the base oil alone caused a discharge due to dielectric breakdown. In the case of the PAMA-added lubricant, the resistance did not change until the gap was zero, where contact occurred, and then suddenly decreased when the probe was pushed at approximately 20 nm after contact. This is attributed to a decrease in resistance due to the direct contact between the probe and the substrate after the PAMA adsorption film was removed from the gap. In other words, the presence of the PAMA adsorption film prevented dielectric breakdown and direct contact between the probe tip and the substrate.

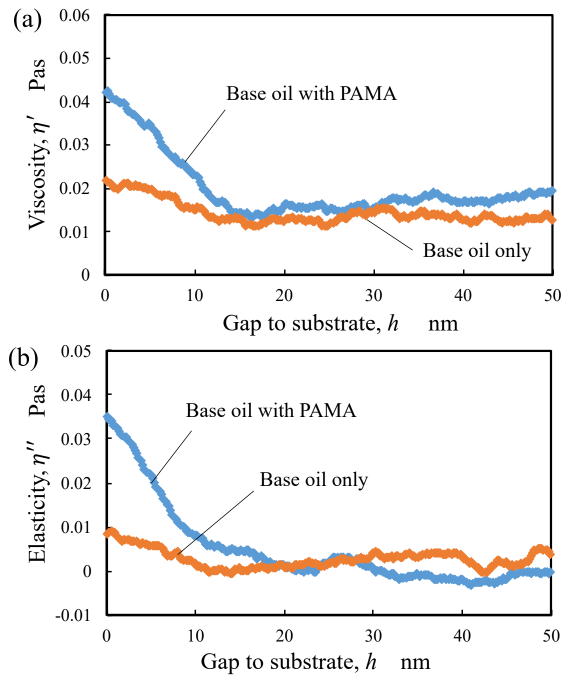

Fig. 3 Gap dependence of (a)viscosity and (b)elasticity measured by FWM with base oil with PAMA and base oil only

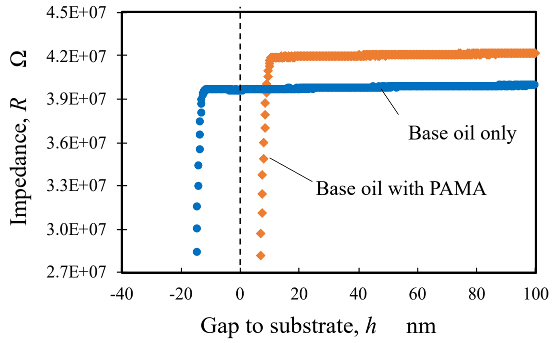

Fig. 4 Gap dependence of impedance of base oil only and base oil with PAMA measured by FWM.

5. Summary

The objective of this study was to establish a method for simultaneously measuring the shear viscoelasticity and impedance of lubricants in nanogaps, and to determine the effect of polymer addition on the electrical conductivity and dielectric breakdown properties. It was suggested that the presence of an adsorbed film of a polymeric additive (PAMA) suppresses dielectric breakdown and solid contact in nanogaps.

References

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