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Rheological property of boundary layer formed by oiliness additive evaluated by a new rheometer with narrow clearance

S. Shibata[1], Y. Hashimoto[1], T. Hirayama[1,2,*], T. Matsuoka[1]

[1)] Faculty of Science and Engineering, Doshisha University
1-3 Miyakodani, Tatara, Kyotanabe, Kyoto 610-0394, Japan.
[2)] JST Presto, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan.

[*]Corresponding author: thirayam@mail.doshisha.ac.jp

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ABSTRACT – The recent increase in demand for effective lubricating oils that reduce friction and wear has led to a need for accurate evaluation of oil properties. To meet this need, a rheometer has been developed that can measure rheological properties at various sliding speeds. It has a surface-restricted aerostatic thrust bearing that enables the clearance between the upper and lower disks to be kept constant on the micron or submicron level during shear force measurement. It was used to investigate the rheological properties of lubricating oils with an additive. The experimental results showed that the viscosity of lubricating oils with an additive was lower than that without the additive regardless of sliding speed.

1. INTRODUCTION

Technologies for reducing friction and wear provide great benefits because friction causes many problems such as energy loss and machine degradation. Oils with an additive are commonly used to reduce friction as they form a boundary layer at the interface between sliding surfaces. There is a need to accurately evaluate oil properties as the origins of boundary layers is much increasing, but conventional rheometers cannot accurately evaluate the rheological properties of boundary layers because their clearance for evaluation generally exceeds 0.1 mm. To meet this need, we have developed a rheometer that can provide both micron and submicron order clearance between parallel disks, enabling evaluation of the rheological properties of the oil, including the effect of boundary layers.

2. DESCRIPTION

A schematic diagram of the main part of the rheometer is shown in Fig. 1. The upper and lower disks are attached to the rheometer for testing. The upper disk has an aerostatic thrust bearing face in the center (O.D. = ϕ22 mm) and a simple flat face in the outer toric area surrounding the bearing area (I.D. = ϕ24 mm; O.D. = ϕ30 mm), as shown in Fig. 1. Air is supplied from the center hole (ϕ2 mm) to the aerostatic bearing face having surface restriction. The lower disk has a simple flat face, and is supported by a soft gel at the bottom. The lower disk holder is movable vertically, and the clearance between the upper and lower disks is controlled by adjusting the pressure of the air supplied to the aerostatic bearing through the upper disk or the pushing load applied from the bottom of the lower disk by an air cylinder. The clearance is fixed at a certain value where the force f_s generated in the aerostatic bearing and the pushing load f_b for the upper direction are equal.

In a test, the target oil is first injected into the gap between the upper and lower disks in only the outer toric area. The rheological properties of the target oil are evaluated by measuring the rotational torque of the lower disk by using a load cell operated in the circumferential direction when the upper disk rotates.

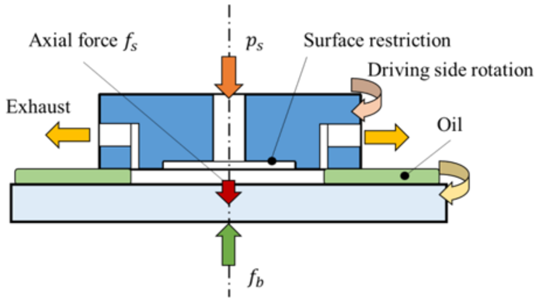

Figure 1 Schematic diagram of developed rheometer.

A photograph of the developed rheometer is shown in Fig. 2. The electric motor on the right rotates a hollow shaft connected to the upper disk through pulleys and a timing belt. Another load cell between the lower disk holder and the air cylinder is used to measure the pushing load in the axial direction.

Figure 2 Photograph of developed rheometer.

3. PERFORMANCE VERIFICATION

To verify the performance of the developed rheometer, we first investigated the relationship between the clearance and pushing load f_b (force f_s generated in aerostatic thrust bearing). Two types of poly-α-olefin, PAO30 and PAO95, were used as sample oils. Their viscosities were 37.9 and 127.7 cP, respectively, at 30ºC. Since PAO molecules are non-polar and stable, PAO oil is widely used as a base oil for sliding parts. The sample oils were injected into the gap in the outer toric area, and the rotational torque of the lower disk was measured when the upper disk rotated. The pressure of the air supplied to the aerostatic bearing was set to 0.27 MPa.

The bearing clearance estimated by applying Newton's viscous law to the obtained rotational torque for each pushing load is shown in Fig. 3. The bearing clearance could be kept constant for each load regardless of the rotational speed of the upper disk. Moreover, the minimum clearance achieved (with a pushing load of 70 N) was about 1 µm. This means that the developed rheometer can be used to accurately evaluate the rheological properties of a sample liquid with a change in the rotational speed in a narrow gap, which can be set from several micrometers to sub-micrometer.

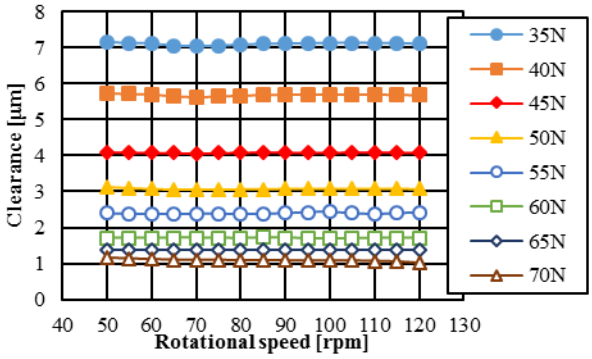

Figure 3 Estimated bearing clearance based on pushing load.

Fig. 4 shows the relationship between the pushing load (load capacity of aerostatic bearing) and the clearance for PAO30 and PAO95. The load capacity plots are on a common curve, meaning that the load capacity did not depend on the viscosity of the sample liquid. This means that the load was supported in only the aerostatic bearing and that the sample oil in the outer toric area did not generate a significant amount of hydrodynamic pressure. The theoretical curves calculated using the Reynolds equation considering the effects of surface restriction and inherent restriction are also shown. The experimental values agreed well with the theoretical load capacity curve when contraction coefficient *C* was set to 0.35.

This performance verification demonstrated that the clearance can be set regardless of the viscosity of the sample liquid and sliding speed and can be varied from sub-micrometer to several micrometers by changing the pushing load.

4. EVALUATION

For our evaluation, we used PAO95 with palmitic acid, a typical oil additive that forms a boundary layer at a solid-liquid interface. The concentration of acid was 0.3 mass%, and the pushing loads and air supply pressure were set to 55, 60, and 65 N and 0.27 MPa, respectively. The expected clearances were 2.0, 1.5, and 1.2 µm, respectively.

The apparent viscosities calculated from the rotational torque are shown in Fig. 5. The viscosities of the oil with an additive were lower than those of the oil without an additive. The reduction ratio of the apparent viscosities became larger, meaning that the effect of the additive became larger, as the clearance became narrower. However, this tendency was not seen for a pushing load of 65 N because of occasional contact between the upper and lower disks. Since an additive forms a boundary layer at the interface, there may have been interfacial slip of the flow due to the existence of a boundary layer.

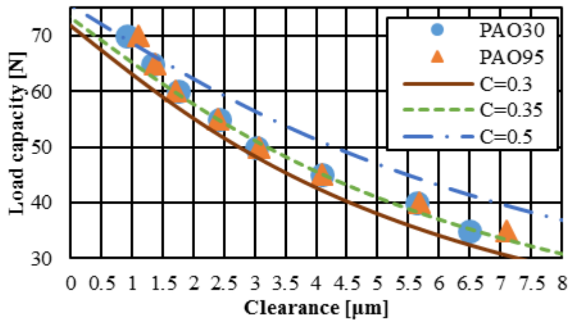

Figure 4 Load capacity of bearing (pushing load) versus estimated clearance.

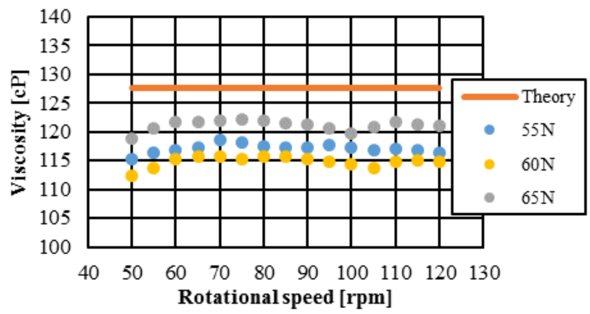

Figure 5 Apparent viscosities of PAO95 with palmitic acid for each pushing load.

5. CONCLUSION

A rheometer has been developed that can keep a constant clearance regardless of the viscosity of the sample liquid and sliding speed. The clearance can be adjusted from sub-micrometer to several micrometers by changing the pushing load. The apparent viscosity was lower for an oil with an additive than for one without the additive due to the formation of a boundary layer.

6. ACKNOWLEDGMENTS

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