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Enhancement of Lubrication Properties of Nano-oil by Controlling the Amount of Fullerene Nanoparticle Additives

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Abstract In this article, the tribological properties of fullerene nanoparticles-added mineral oil were investigated as a function of volume concentration of fullerene nanoparticle additives (e.g., 0.01, 0.05, 0.1, and 0.5 vol.%). The lubrication tests were performed at the disk-on-disk type tester under the various normal forces and fullerene volume concentrations. Tribological properties were evaluated by measuring the friction surface temperature and friction coefficient, and then interpreted in terms of Stribeck curves. At the same time the friction surfaces tested were evaluated by observing their SEM images, surface roughness, and AFM images. The results showed that the nano-oil containing the higher volume concentration of fullerene nanoparticles resulted in the lower friction coefficient and less wear in the fixed plate, indicating that the increase of fullerene nanoparticle additives improved the lubrication properties of regular mineral oil.

Keywords Fullerene nanoparticles · Nano-oil · Lubrication · Volume fraction · Disk-on-disk type tester · Stribeck curve

1 Introduction

Most of contacting surfaces such as gears, bearings, and seals are lubricated with a specific lubricant to control the friction and wear in industry. Mineral oil is generally used in compressors to reduce the scoff and wear of contacting surfaces. Here compressor is a main component in refrigeration cycle and produces refrigeration cycle power. However, the mineral oil provides the poor tribological property so that it should be frequently exchanged to prevent the failure of compressor performance. Therefore it is important to enhance the tribological properties of mineral oils.

As one of the methods to enhance the tribological properties of lubricants, many researchers have added fullerene nanoparticles in the lubricants. For example, Hisakato et al. [1] carried out the friction and wear tests of ceramic disks by using fullerene nanoparticles (1 wt.%)-containing ethanol, and the topographical analysis was performed on the micro-asperities of the wear surfaces to observe the behavior of fullerene particles. They found that the addition of fullerene particles in ethanol decreased the mean friction coefficient and the wear rates of ceramic disks made from Al_2O_3, SiC, and TiC. Ginzburg et al. [2] also investigated antiwear effect of fullerene-added I-40A industrial oil. Fullerene-oil-made film was formed on the copper foil surface of steel roller, which exhibited outstanding antiwear properties. It enhanced the bearing strength of the tribotechnical unit and stabilized its operation at lower friction coefficient. However those previous studies could not provide the effect of volume factions of fullerene additives on the lubrication properties of lubricants. Furthermore their experiments were confined to non-refrigeration conditions so that it was difficult to apply their approaches to the real refrigeration system.

In this article, we investigated the friction and antiwear characteristics of nano-oil as a function of volume fraction of fullerene nanoparticle additives under the various refrigeration conditions. Lubrication properties of both

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nano-oils and raw mineral oil were evaluated by employing a disk-on-disk type tester [3]. The lubrication tests were performed by measuring the friction surface temperature and friction coefficient at the disk-on-disk type tester under the various normal forces and fullerene volume fraction. The Stribeck curves [4], which will be discussed in detail later, were introduced for nano-oils and raw mineral oil to interpret the experimentally determined tribological properties of various oils. The friction surfaces were examined by the 3D topographic features and images of wear.

2 Experimental

Figure 1 shows the schematic view of the disk-on-disk type tester for evaluating the lubrication characteristics in both nano-oils and raw mineral oil (Sun Oil, Japan). It was simply designed with two major plates, which were the rotating plate and the fixed plate, respectively. The disk material was gray cast iron (GC250) without any surface treatment. The surface between rotating plate and fixed plate can be considered as a general friction surface. The disk-on-disk type tester was also consisted of a closed test chamber, an air cylinder, two load cells, a servomotor, oil and refrigerant suppliers, and heaters. The lubricant oil was prepared in an oil bath, where the frictional surface was immersed. The inner space of chamber was kept pressurized by refrigerant gas, R-22 [5], at the pressure of 5 bars for maintaining the equivalent pressure condition of real refrigerant oil. The normal load was operated by the air cylinder system and controlled by the proportional-integrate-derivative (PID) controller, which controls the pressure of air with a high accuracy. The magnitude of normal force was measured by a load cell installed under the air cylinder, and the rotating speed of rotating plate was controlled by the inverter of servomotor. The friction force resulted from the combination of rotating motion and normal load was measured by another load cell located in the closed chamber. Here the friction force made the fixed plate rotate in the same direction of the rotating plate. However the fixed plate was not able to rotate because it was fixed by the load cell, which was also fixed to the wall of the closed chamber. Therefore, the friction force acted on the contacting surface was automatically measured by the load cell mounted. The temperature of frictional surface was also measured by thermocouple installed at the fixed plate. The friction coefficient and surface temperature were measured as the function of normal load and volume fraction of fullerene nanoparticle additive.

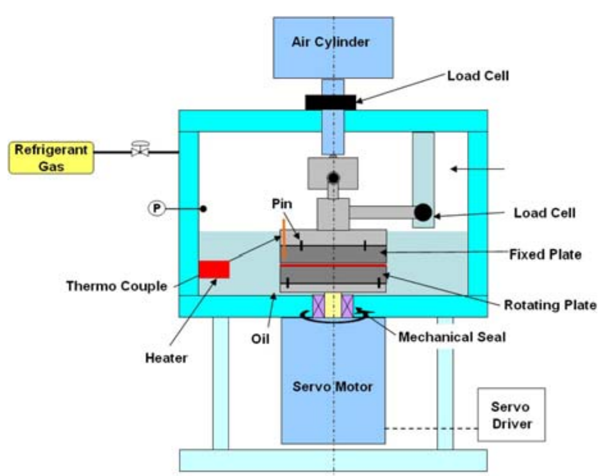

Fig. 1 Schematics of a disk-on-disk type tester for evaluating the characteristics of friction of raw oil and nano-oils

Table 1 shows the major specification of lubrication tests performed in this study. Before each lubrication test, the initial temperature of lubrication oils was maintained at 40 °C. The friction coefficient and friction surface temperature between two friction plates were measured as a function of normal force ranging from 50 N to 1,000 N under the fixed rotating speed of 1,000 rpm. These friction tests were performed for both raw mineral oil and nano-oils (i.e., fullerene-added mineral oil). The physical properties of the raw mineral oil used in this study were the density of 0.915 g/cm^3, the kinematic viscosity of 54.6 mm^2/s at the 40 °C and of 6.06 mm^2/s at the 100 °C.

Table 2 shows the lubrication test conditions performed in this study. Fullerene nanoparticles (C_{60}, purity >∼99.5%) with average size of ∼0.7 nm were added to mineral oil with different volume fractions up to 0.50 vol.%. Nano-oil I, II,

Table 1 Major specifications of lubrication tests in this study

Axial force (N)	0∼1,000
Rotating speed (rpm)	1,000
Refrigerant oil	Mineral oil (raw oil), nano-oil
Refrigerant	R-22
Nanoparticle	Fullerene (C_{60})
Average size of nanopaticle (nm)	∼10
Specific gravity of nanopaticle and raw oil	1.6, 0.915

Table 2 List of lubrication tested materials

Oil type	Solvent	Fullerene fraction (vol.%)
Raw oil	Mineral oil	0
Nano-oil I	Mineral oil	0.01
Nano-oil II	Mineral oil	0.05
Nano-oil III	Mineral oil	0.1
Nano-oil IV	Mineral oil	0.5

III, and IV were the mixture of mineral oil and fullerene at the volume fraction of 0.01, 0.05, 0.10, and 0.50 vol.%, respectively, prepared by sonication for 5 h.

3 Results and Discussion

3.1 Physical Properties of Nano-oil

Figure 2 shows the kinematic viscosity of nano-oils as a function of volume fraction of fullerene nanoparticles in suspension for temperature ranging from 40 °C to 80 °C. The kinematic viscosity of nano-oils was measured by capillary visocometer [ViscoClock, Ubbelohde]. There was no considerable change in the kinematic viscosity of nano-oil at the various volume fractions of nanoparticles, indicating that the kinematic viscosity of nano-oils is a weak function of oil temperature considered.

3.2 Lubrication Test of Nano-oils

Figure 3 shows the lubrication test results for nano-oils and raw mineral oil. The friction coefficients as a function of normal force were measured under the fixed rotating speed of 1,000 rpm. The friction coefficient of nano-oils and raw mineral oil were increased with increasing the normal force. As one can see that the friction coefficients for all nano-oils was less than that of raw mineral oil. It indicates that less metal contacts appear to be occurred in the presence of fullerene nanoparticles in the mineral oil. The friction coefficient of nano-oil IV shows ∼0.02, which is the lowest friction coefficient among various nano-oils in this study. It was clearly observed that nano-oil with more fullerene nanoparticle additives shows enhanced lubrication property.

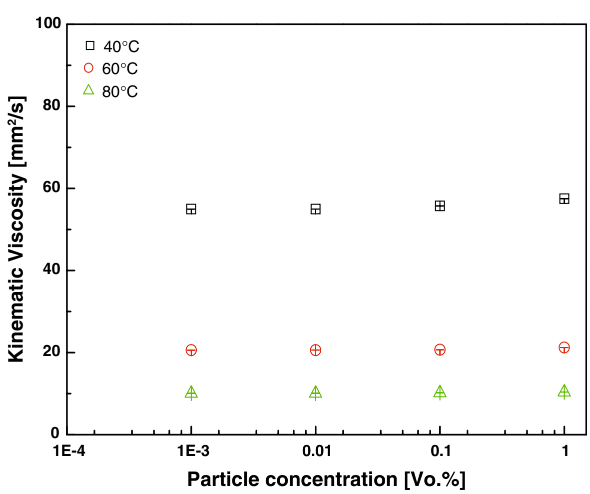

Fig. 2 Kinematic viscosity of nano-oils as a function of fullerene nanoparticle concentration and oil temperature ranging from 40 °C to 80 °C

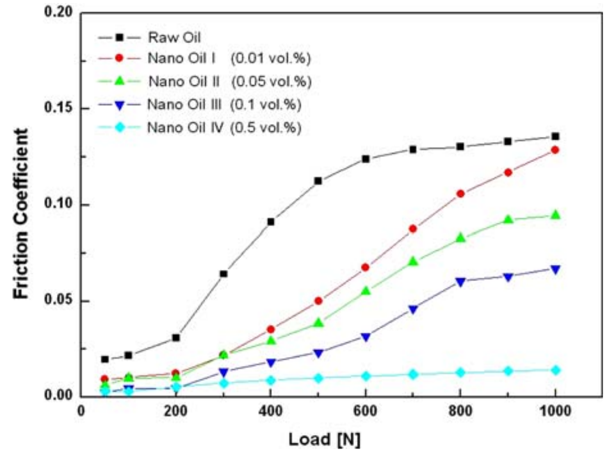

Fig. 3 Lubrication test results on the friction coefficient as a function of the fullerene volume fraction of nano-oil using the disk-on-disk type tester at the rotating speed of 1,000 rpm

The friction behavior can also be analyzed by considering the Stribeck curves [6, 7], which are the friction coefficient as a function of rotation speed, normal force and viscosity of oil. Briefly, the Stribeck curve presents the relationship between friction coefficient and lubrication conditions as seen in Fig. 4. Generally the friction coefficient of lubricants is a function of rotating speed (V), normal force (P), and kinematic viscosity (η). The region to the right of the minimum friction coefficient in the Stribeck curve corresponds to a 'hydrodynamic lubrication', while the region to the left of the minimum friction coefficient corresponds to a 'boundary lubrication'. The region of the minimum friction coefficient in the Stribeck curve corresponds to the 'mixed lubrication' (see Fig. 5). It is known that the hydrodynamic lubrication regime is mainly influenced by the properties of the lubricant film, whereas the boundary lubrication regime is influenced by the material properties and the surface interactions of the contacting surfaces. And the mixed lubrication regime is complicated by the combination effects of boundary lubrication and hydrodynamic lubrication.

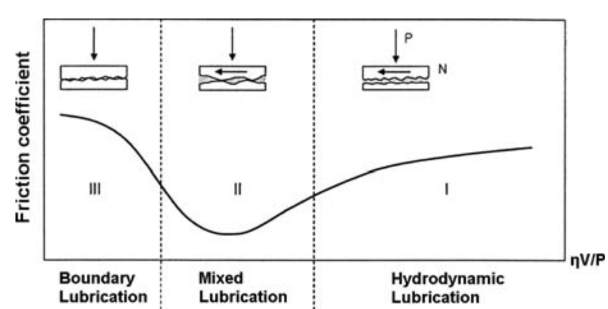

Fig. 4 Stribeck curve and categorization of lubrication [8]

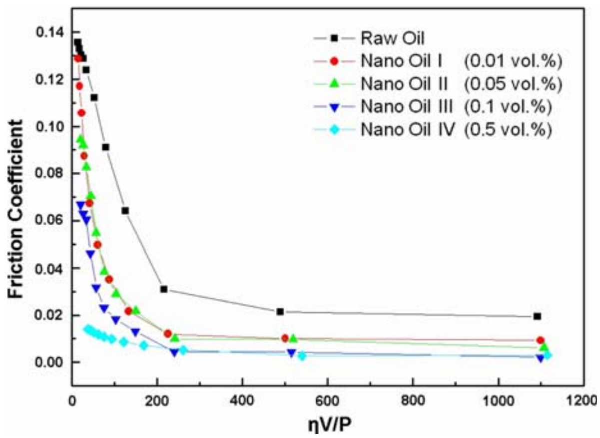

Fig. 5 Relationship between and the friction coefficients as a function of the fullerene volume fraction of nano-oils

Figure 5 shows the Stribeck curve measured for raw mineral oil, nano-oil I, II, III, and IV. It was noted that the friction coefficients of all oils was not appreciably changed up to the normal force of 200 N (i.e., ηN/P > 200). However, when the normal force increased higher than 200 N (i.e., ηN/P < 200), the viscosity was decreased by increasing oil temperature due to local metal-to-metal contact between the plates. It indicates the significant increase of normal load results in the boundary lubrication regime so that metal surface contacts must be frequently occurred [9]. One can see that the maximum friction coefficients were decreased as the fullerene volume fraction was increased. This is presumably attributed to (i) the added fullerene molecules accelerate self-restoration of the polymeric tribofilm damaged in the course of mechano-chemical degradation, and also (ii) the fullerene particles with a spherical structure play a role of ball bearing in the friction surfaces [2, 10].

3.3 Wear Analysis of Frictional Surfaces

Figure 6 shows the image of wear of the fixed plate at the orbiting speed of 1,000 rpm and the normal force up to 1,000 N for 100-min test period. Scratched circle in the image of the fixed plate shows the mark of wear. The amount of scratched circles was decreased with increasing the volume concentration of the fullerene suspension. It indirectly indicates that the nano-oil IV, which has the highest volume concentration (~0.5 vol.%) in nano-oils employed in this study, performs the best lubrication than raw mineral oil and nano-oil I, II, and III at the same friction conditions.

We also employed surface measuring instrument [Model SV 414, Mititoyo, Inc.] to measure the surface roughness of fixed plate. Briefly, the surface roughness was measured electronically by tracing a very sensitive needle-shaped stylus over the test surfaces. This method assesses the finish of surfaces by means of stylus type devices. The stylus motion perpendicular to the surface is recorded, and then this recorded profile is used to calculate the roughness parameters. Table 3 shows the surface roughness of fixed plate operated at the orbiting speed of 1,000 rpm and the normal force up to 1,000 N for 100-min test period. The surface roughness of the fixed plate for raw mineral oil was distinctively high 0.106 μm in depth at the scratched circle, while those of nano-oil I, II, III, and IV were 0.077, 0.067, 0.052, and 0.048 μm, respectively. In a related previous work [10], the extreme pressure was found to be increased when the fullerene nanoparticles were added in pure oil. The extreme pressure is one of the means to evaluate the level of resistance against metal-to-metal contact between the friction surfaces. Thus, the scratch resistance must be increased by increasing both the extreme pressure and the coating of fullerene nanoparticles on the friction surfaces. It was also corroborated by observing the microstructure of

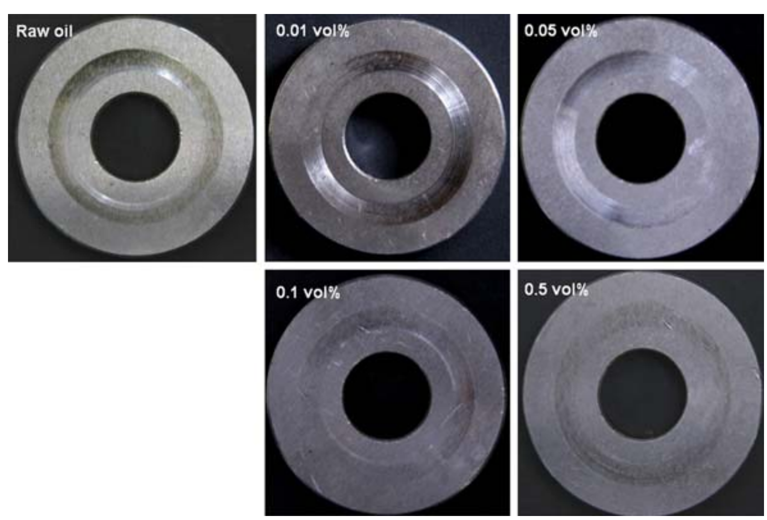

Fig. 6 Images of wear of the rotating plate at the rotating speed of 1,000 rpm and the normal force up to 1,000 N for 100-min test period

Table 3 Surface roughness of the fixed plate measured by alpha-step at the rotating speed of 1,000 rpm and the normal force up to 1,000 N for 100-min test period

Lubricant	Surface roughness (μm)
Raw oil	0.106
Nano-oil I	0.077
Nano-oil II	0.067
Nano-oil III	0.052
Nano-oil IV	0.048

the coated area, which was finer and more compact with increasing the volume fraction of fullerene nanoparticles [11].

To evaluate the changes in topography during lubrication tests, the atomic force microscope (AFM), which is able for us to observe 3D topographic features, was employed. Figure 7 shows the AFM image of the fixed plates at the rotating speed of 1,000 rpm and the normal force up to 1,000 N for 100-min test period. The maximum roughness of original fixed plate was less than ∼300 nm, and it shows slightly irregular shape. However, the 3D topographic image of fixed plate lubricated by raw mineral oil looked like peaks and valleys repeated along the friction direction. After the raw mineral oil lubrication test, we also observed that the scoffing phenomena were occurred to the fixed plate, and then the maximum roughness of the fixed plate was found to be increased up to ∼1,000 nm. However, after the nano-oil-based lubrication tests, it was clearly observed that the 3D topographic images were changed as a function of volume concentrations of fullerene nanoparticles in the nano-oils. More smooth and shallow peaks and valleys were observed for nano-oils having higher volume concentration of fullerene nanoparticles. It indicates that the significant portion of the peaks and valleys of the fixed plate was removed so that it looks like plain with little irregular scoffing phenomena. Especially the 3D topographic image of nano-oil IV was changed into a totally new topography, which showed the maximum roughness of fixed plate was much less than ∼300 nm.

4 Conclusion

In this work, the lubrication tests of nano-oils and raw mineral oil were conducted in the closed chamber with the refrigerant gas (R-22), focusing on the effect of volume concentration of fullerene nanoparticle additive on the lubrication properties of lubricants. The friction coefficient and friction surface temperature for both nano-oils and raw mineral oil were evaluated by varying the operating parameters, including the normal force and additive fullerene volume fraction. As the results of various friction tests under the refrigerant condition, the presence of fullerene nanoparticles in the lubrication oil was observed to improve the lubrication performance in the friction surfaces by reducing the metal surface contacts. We also found that the volume fraction of fullerene nanoparticles in nano-oils was a key factor to control the fraction coefficient and the magnitude of wear of frictional surfaces.

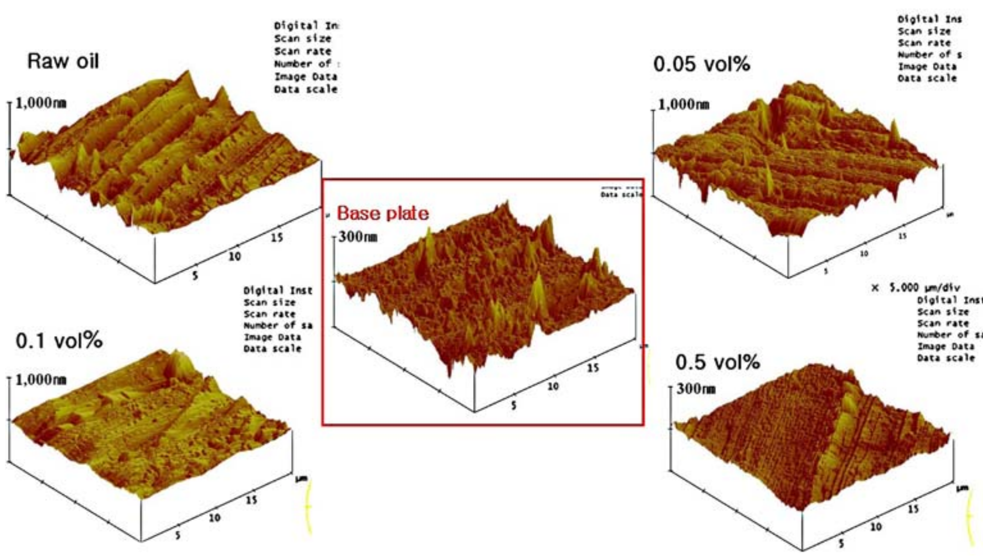

Fig. 7 AFM images of the fixed plate at the rotating speed of 1,000 rpm and the normal force up to 1,000 N the normal force up to 1,000 N for 100-min test period

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