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Synergistic Effect of a Coating and Nano-Oil Lubricant on the Tribological Properties of Friction Surfaces

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In this study, we evaluated the tribological properties of grey cast iron (GC200) surfaces with and without MoS_2 coating that were lubricated with either mineral oil or mineral oil in which fullerene nanoparticles were dispersed (i.e., nano-oil), by using a disk-on-disk type tribotester. A series of friction tests were performed using the disk-on-disk type tribotester under various normal forces, and the friction coefficient and friction surface temperature were monitored simultaneously. First, we observed that the friction coefficient of the GC200 surface that has a MoS_2 coating and is lubricated with mineral oil was 32% lower than that of the GC200 surface without a MoS_2 coating. Second, we found that the friction coefficient of GC200 surfaces lubricated with nano-oil was approximately 74% lower than that of GC200 surfaces lubricated with mineral oil. This suggested that the effectiveness of nano-oil lubrication in reducing the friction between GC200 surfaces is considerably higher than that of MoS_2 coating or mineral-oil lubrication. In order to examine the effects of both the coating and nano-oil lubrication, friction tests for MoS_2-coated GC200 surfaces under nano-oil lubrication was performed. We observed the following: (i) the friction coefficient of MoS_2-coated GC200 surfaces lubricated with nano-oil were approximately 82% lower than that of uncoated GC200 surfaces lubricated with mineral oil; (ii) the nano-oil lubrication even tended to prevent the coating from peeling off, presumably because the fullerene nanoparticles added in the mineral oil acted as ball bearings. These observations suggested that the presence of a coating on friction surfaces and the addition of nanoparticles in mineral oil lubricant have a synergistic effect in significantly reducing the friction between friction surfaces.

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NOMENCLATURE

S = the Sommerfeld number or bearing characteristic number
R = shaft radius
C = the radial clearance
μ = the absolute viscosity of the lubricant
n = the speed of the rotating shaft in revs/s
P = the load per unit of projected bearing area

1. Introduction

Lubrication is a fundamental technique for improving the performance and durability of machines and devices by reducing wear and friction. The surfaces of most devices or machine parts such as gears, bearings, and seals that are in contact with other surfaces are generally lubricated with a specific lubricant in order to reduce the friction and wear. Mineral oil can be used as a lubricant to reduce the wear and friction of the surfaces of tribological machine components. However, to prevent the failure of machine parts, the applied mineral oil has to be frequently changed. Therefore, it is very important to improve the tribological properties of mineral oils.

Numerous research groups have reported that the addition of nanoparticles into lubricants can improve the tribological properties of the lubricants and significantly reduce wear and friction.[1-10] The friction-reduction and anti-wear properties of lubricants with dispersed nanoparticles were attributed to the rolling effect of nanoparticles between the friction surfaces and the protective lubricant film and the formation of a third body between the friction surfaces.[1] Rapoport et al.[2] added inorganic fullerene-like nanoparticles into a lubricant. They observed that the spherical inorganic fullerene-like nanoparticles had the advantages of excellent rolling effect, low affinity to the metal surface, low contact temperatures, high elasticity, and high chemical resilience. Hisakato et al.[3] carried out the friction and wear tests on ceramic disks by using fullerene-added ethanol and then performed topographical analysis of the micro-asperities on the wear surfaces to study the behavior of fullerene nanoparticles. They found that the use of the ethanol solution with fullerene nanoparticles decreased the mean friction coefficient and the wear rates of ceramic disks made from Al_2O_3, SiC, and TiC.

Coating friction surfaces with a lubricant can improve the tribological properties of the lubricant. Bowden and Tabor[11] established a theory of friction of thin solid films based on the adhesion theory of friction. They pointed out that a reduction in friction can be achieved by applying a surface coating with low shear strength on a substrate that has high yield strength. Recently, it was reported that the tribological behavior of such a surface coating is dependent on the following parameters: the ratio of the hardness of the coating material to that of the substrate material, the thickness of the coating, and the roughness of the surface of the substrate.[12,13] MoS_2 is one of the most widely used surface coating materials for lubrication.[14] The wear mechanism of MoS_2 can be significantly affected by the test environments. Most studies on solid coatings were conducted under dry conditions. However, to date, very few studies on the relative effects of solid coating and oil lubrication has been carried out. In order to improve the tribological properties of high speed bearing in a mechanical system, MoS_2 film was chosen and tested in various oil lubrication conditions in this approach.

In this study, the friction-reduction and anti-wear properties of MoS_2-coated GC200 surface lubricated with mineral oil and with mineral oil with dispersed fullerene nanoparticles (hereafter referred to as nano-oil) were examined under various normal load conditions by using a disk-on-disk type friction tester,[15] which continuously monitored the temperatures and friction coefficients of friction surfaces while the friction tests were being performed. The Stribeck curves,[16] which will be discussed in detail later, for various lubrication zones were used to interpret the experimentally-determined tribological properties of the MoS_2 surface coating and nano-oil. The wearing of friction surfaces were also investigated by employing the scanning electron microscope (SEM) and thin film measuring device (Dektak3, Sloan Technology).

2. Experimental

2.1 Friction disk specimen and lubricating oil preparation

The mechanically machined disk specimens for friction tests were made of grey cast iron (GC200) with a Vickers hardness of 100 Hv and an mean roughness of $R_q = 0.059$ μm, which was taken as average value out of 10 times measurements. The roughness and hardness of GC200 surfaces (Rotating plate) without MoS_2 coating were measured by using a surface roughness tester (SJ-401, Mitutoyo) and a micro hardness tester (MVK-H10, Akashi), respectively.

The mineral oil for lubrication employed in this approach had a density of 0.88 g/cm^3, viscosity of 10.2 mm^2/s at 40 °C, and flash point of 165 °C. Nano-oils were prepared by adding fullerene nanoparticles into the mineral oil with a total volume fraction of 0.1 vol%[17] and subsequently sonicating for 24 h. There was no appreciable change in transparency of nano-oils for 600 hours evaluated using a dispersion photometer (2100AN, Hach). The kinematic viscosity of mineral oil and nano-oil was measured by using a capillary viscometer (Schott, Germany), according to ISO/DIS 3105, ASTM D 2515, and ASTM D 446.

2.2 Experimental setup

Figure 1 shows the schematic view of a disk-on-disk type friction tester for evaluating the lubrication characteristics of friction surfaces. This friction tester has a simple structure with two main plates—the rotating plate and fixed plate. The surface between the rotating and fixed plates can be considered to be a general friction surface. The disk-on-disk type tester also consisted of a closed test chamber, an air cylinder, two load cells, a servomotor, oil, refrigerant suppliers, and heaters. The lubricant oil was prepared in an oil bath, and the friction surface was immersed in the lubricant oil. The normal load was exerted by the air cylinder system and controlled by a proportional-integrate-derivative 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 the rotating plate was controlled by the inverter of a servomotor. The friction force resulting due of both the rotating motion and the normal load was measured by another load cell located in the closed chamber. This friction force made the fixed plate rotate in the same direction as the rotating plate. However, the fixed plate could not rotate because it was fixed by the load cell, which was also fixed to the wall of the closed chamber. Therefore, the friction force acting on the friction surface was automatically measured by the mounted load cell. Further, the temperature of the friction surface was

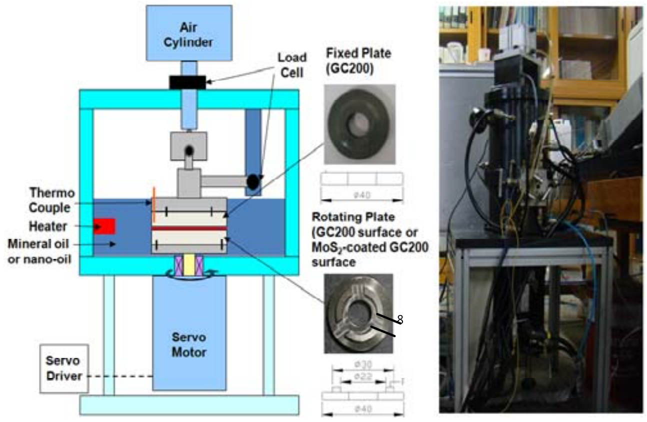

Fig. 1 Schematic of disk-on-disk type friction tester

measured by a thermocouple installed on the fixed plate. The friction coefficient and surface temperature were measured as functions of the normal load. The total uncertainty of the friction coefficient was calculated to be approximately 4.9 %.

2.3 Experimental procedure

Table 1 shows the test conditions under which the lubrication characteristics were evaluated in this study. The disk-on-disk tester was first operated for 10 min under a load of 100 N and rotating speed of 500 rpm; this was considered the period of running-in. After that time, the rotating speed was fixed to 1000 rpm and the applied load was increased by 100 N from 1,000 N to 1,500 N. After each increment of 100 N, the applied load was maintained constant for 30 min. These friction tests were performed for various friction surfaces immersed in mineral oil and nano-oil.

3. Results and discussion

3.1 Friction-reduction properties

In order to compare the friction characteristics of GC200 surface and those of MoS_2-coated GC200 surface, the friction coefficients of both surfaces were measured by the disk-on-disk friction tester. Figure 2 shows the friction coefficients of both GC200 and MoS_2-coated GC200 surfaces immersed in mineral oil. The friction coefficients increased with the normal force. The friction coefficient of the MoS_2-coated GC200 surface was approximately 32% lower than that of the GC200 surface. This is because the stratiform crystal structure of MoS_2 coating film consisted of hexagonal layers that could produce a sliding effect when shear force was applied on the surface.[14] This explanation was corroborated by measuring the shear stress (i.e., shear stress measurement test (Scratch tester, J&L)) for both GC200 and MoS_2-coated GS200 surfaces. The shear stress on GC200 and MoS_2-coated GC200 surfaces ware found to be approximately 10.8 and 9.3 MPa, respectively. The shear stress on the MoS_2-coated GC200 surface was observed to be about 14% lower than that on the GC200 surface. The friction coefficients of the friction surfaces immersed in nano-oil were considerably lesser than those of friction surfaces immersed in mineral oil. This is presumably because the fullerene nanoparticles dispersed in the mineral oil acted as ball bearings between the friction surfaces and formed a protective film on the friction surfaces.[18]

Table 1 Experimental conditions of the disk-on-disk type tribotester in the friction tests

Test conditions	Ranges
Normal load	1000-1500 N
Rotating speed	1000 rpm
Lubrication oil	Mineral oil & Nano-oil (C_{60})
Surface coating	MoS_2
Ambient temperature	26-28 °C
Relative humidity	50-70 %

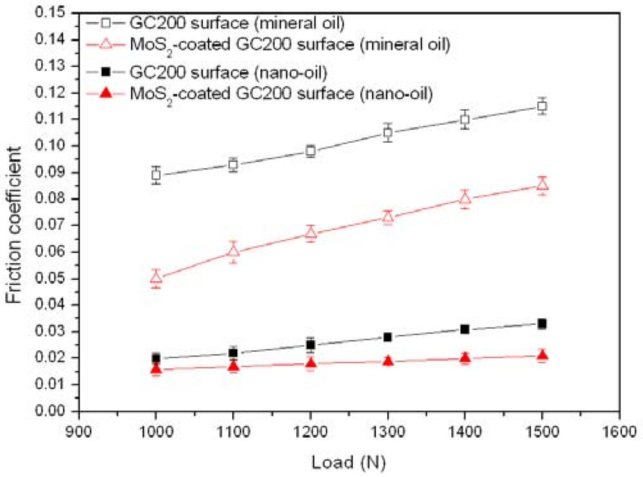

Fig. 2 Evolution of friction coefficients of GC200 surfaces with or without MoS_2 coating as a function of normal load and lubricant oil type (i.e., mineral oil or nano-oil)

To analyze the friction-reduction properties of mineral oil and nano-oil, both GC200 and MoS_2-coated GC200 surfaces immersed in either mineral oil or nano-oil were tested. The friction coefficient of MoS_2-coated GC200 surface immersed in mineral oil was first found to be approximately 32% lower than that of the GC200 surface in mineral oil. The friction coefficients of GC200 and MoS_2-coated GC200 surface immersed in nano-oil were about 74% and 82% lower than that of GC200 surface in mineral oil, respectively. This indicates that nano-oil is more effective than MoS_2 coating in reducing the friction between GC200 surfaces and that the synergistic effect of the MoS_2 coating and the nano-oil lubricant significantly reduces the friction. The change in the temperature of the fixed MoS_2-coated disk that was made of GC200 and immersed in nano-oil, during the friction tests is shown in Figure 3 From the results, the temperature of the fixed disk that was immersed in nano-oil and that was subjected to considerable friction when in contact with the rotating disk was substantially lower than the temperature of the fixed disk immersed in mineral oil; this indirectly suggests that the fullerene nanoparticles added in mineral oil acted as ball bearings and formed a protective film so

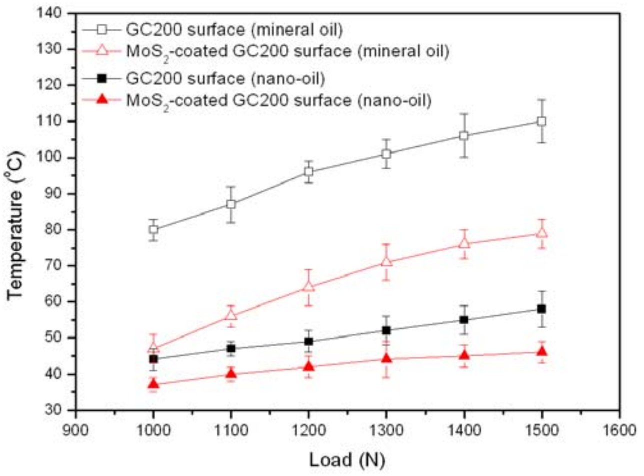

Fig. 3 Evolution of temperatures of GC200 surfaces with or without MoS_2 coating as a function of normal load and lubricant oil type (i.e., mineral oil or nano-oil)

that the friction between the friction surfaces was reduced.

The friction coefficient of lubricants is generally dependent on rotating speed (n), normal force (P), and kinematic viscosity (η). The relationship between the friction coefficient and lubrication conditions can be represented by Stribeck curves.[18]

These curves indicate three lubrication regimes. In the Stribeck curve, the region to the right of the minimum friction coefficient corresponds to hydrodynamic lubrication, while the region to the left of the minimum friction coefficient corresponds to boundary lubrication and the region at the minimum friction coefficient corresponds to mixed lubrication.

In the hydrodynamic lubrication regime, the friction coefficient linearly increases as a result of fluid film lubrication, and friction is proportional to the viscous drag force in the oil film. In the mixed lubrication regime, the fluid film thickness reduces considerably and the metal surfaces come in to contact with each other. In the boundary lubrication regime, contact between the surfaces becomes stronger as a result of a reduction in the Sommerfeld number (ηn/P). The thickness of the oil film becomes lower than the height of the surface asperities. 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 between the contacting surfaces. The mixed lubrication regime is somewhat complicated because of the combined effects of boundary and hydrodynamic lubrication regimes.

Figure 4 shows the Stribeck curves for the GC200 and MoS_2-coated GC200 surfaces immersed in mineral and nano-oil, respectively. In a series of friction tests of both the surfaces lubricated by mineral oils, the characteristics of their respective hydrodynamic lubrication regimes were observed when low normal force was applied. However, as the applied normal load increased, it was observed that the lubrication regime changed from hydrodynamic lubrication regime to mixed lubrication regime. Unlike the Stribeck curves for the friction surfaces lubricated with mineral oils, the Stribeck curves of friction surfaces lubricated with nano-oils exhibited only the hydrodynamic lubrication regime; this indicates that lubrication of friction surfaces using nano-oils is better than that using mineral oils. This could be attributed to fullerene-induced self-restoration of the polymeric tribofilm, which was damaged during the course of mechanochemical degradation. It can also be attributed to the action of the spherical fullerene nanoparticles that act as ball bearings between the friction surfaces.[19-21]

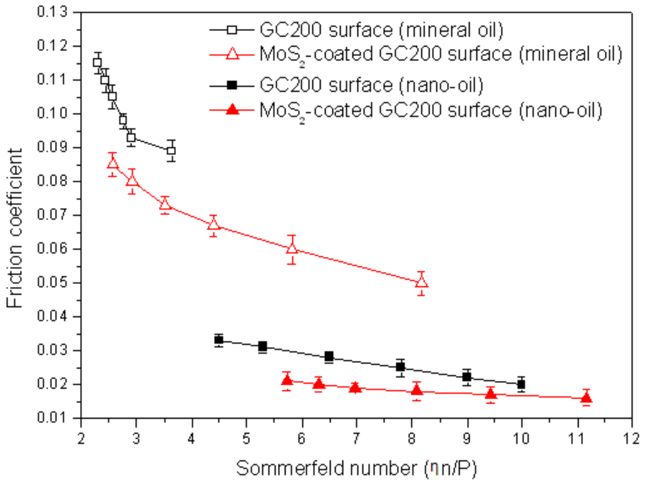

Fig. 4 Stribeck curves for GC200 surfaces with or without a MoS_2 coating as a function of Sommerfeld number and lubricant oil type (i.e., mineral oil or nano-oil)

The typical Sommerfeld number is shown in Eq. (1).

$$S=\left(\frac{r}{c}\right)^2\frac{\mu n}{P} \tag{1}$$

This study used relation factors (μ, n, P) in Eq. (1) to evaluate the friction regimes by excluding the stationary factors (r, c). Since the four sets of lubrication tests have different absolute viscosity, we can see different abscissa ranges. And, absolute viscosity depends on the temperature of lubricant. The absolute viscosity of the lubricant has a negative association with temperature of the lubricant, which indicate that range of low temperatures is in the right of the abscissa range.

3.2 Anti-wear properties

The anti-wear properties of friction surfaces lubricated with mineral oil and nano-oil were analyzed by SEM and atomic force microscopy (AFM). Figure 5 shows the SEM images of GC200 and MoS_2-coated GC200 surfaces lubricated with mineral oil and nano-oil, respectively, after the friction tests were performed. Before the friction test of the GC200 surface, the wear trace of GC200 (see Figure 5(a) average roughness = 0.059 μm) showed various vertical directions. However, after the friction test of GC200 surface, it was found that the nano-oil was considerably more effective than mineral oil in reducing friction, as shown in Figures 5(b) and 5(c).

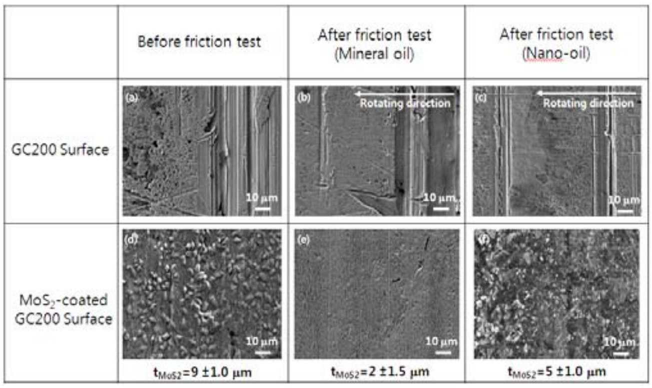

Fig. 5 SEM images of GC200 and MoS_2-coated GC200 surfaces before and after the friction tests when they were lubricated with either mineral oil or nano-oil. (a) GC200 surface before friction test, and GC200 surface after friction test when it was lubricated with either (b) mineral oil or (c) nano-oil. (d) MoS_2-coated GC200 surface before friction test, and MoS_2-coated GC200 surface after friction test when it was lubricated with either (e) mineral oil or (f) nano-oil (Here, t_{MoS2} is the thickness of the MoS_2 coating on the GC200 surface)

The horizontal trace of abrasion wear in Figure 5(c) appeared little compared with the sliding surface in Figure 5(b). This indicates that higher magnitude of friction between friction surfaces must be occurred at mineral oil-based lubrication in Figure 5(b) than nano-oil-based lubrication in Figure 5(c). This suggests that applying C_{60} nanoparticles in mineral oil can be much more effective in reducing the severe friction between the friction surfaces. This was corroborated by AFM analysis that the average approximately 0.073 μm, while the average roughness of GC200 surface lubricated with mineral oil was approximately 0.147 μm.

In the case of the MoS_2-coated GC200 surface, the original thickness of the MoS_2-layer was measured using a thin-film measuring instrument (Dektak3, Sloan Technology) and found to be approximately 9 ± 1.0 μm, as shown in Figure 5(d). However, after the friction test, the thickness of MoS_2-layer when lubricated with mineral oil and nano-oil reduced to 2 ± 1.5 μm and 5 ± 1.0 μm, respectively, as shown in Figures 5(e) and 5(f). This indicates that the friction between the friction surfaces lubricated with mineral oil was considerably higher than that between the friction surfaces lubricated with nano-oil, and as a result, the MoS_2 coating was severely damaged and the thickness of the MoS_2 layer reduced significantly in the case of lubrication with mineral oil. Therefore, it is noted that the synergistic effects of the MoS_2 coating and nano-oil lubricant result in a significant reduction in high friction between friction surfaces.

4. Conclusions

We demonstrated the effect of the MoS_2 coating and nano-oil lubricant on the tribological properties of the surfaces of GC200 specimens. A disk-on-disk tribotester was employed to evaluate the reduction in the friction between GC200 surfaces with and without a MoS_2 coating. As the results, we found that the magnitude of reduction in the friction coefficient as a result of lubricating the friction surfaces with nano-oil was almost two times higher than the magnitude of reduction in the friction coefficient as a result of coating the friction surfaces with MoS_2-layer. This suggests that effectiveness of mineral oil with dispersed fullerene nanoparticles in reducing the high friction between the friction surfaces is significantly higher than that of a simple coating of protective film layers. Furthermore, when a MoS_2-coated GC200 surface was lubricated with nano-oil, the friction coefficient was found to be approximately 82% lower than that of GC200 surface without a MoS_2 coating lubricated with mineral oil. This suggests that the synergistic effects of the MoS_2 coating and nano-oil significantly reduce the friction between the friction surfaces.

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