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ORIGINAL PAPER

Understanding the Role of Nanoparticles in Nano-oil Lubrication

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Abstract A disc-on-disc type tester was used to examine the role of fullerene nanoparticles dispersed in a mineral oil-based lubricant. In the friction test, the friction coefficient of the disc specimen immersed in the nano-oil was significantly lower than that of the disc specimen immersed in the mineral oil. This suggests that the nanoparticles dispersed in mineral oil played the important role in the lubrication enhancement of nano-oil. A series of experiments in this study were carried out to delineate the two effects [i.e., direct effect (e.g., rolling/sliding/filming) and surface enhancement effect (e.g., mending/polishing)] of nanoparticles for nano-oil-based lubrication enhancement. The disc specimens immersed in the nano-oils during the friction test was removed, and then they were re-immersed in new mineral oil for an additional friction test. The direct and surface enhancement effect of nanoparticles was then visualised by the evolution of the friction coefficient of the disc specimen immersed in the mineral- and nano-oil. The results showed that the direct effect of nanoparticles was much more dependent on the magnitude of the applied normal load than the surface enhancement effect.

Keywords Nanoparticles · Nano-oil · Fullerene · Disc-on-disc type tester · Lubrication

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1 Introduction

The addition of nanoparticles into a lubricating oil significantly reduces the friction coefficient and increases the load-bearing capacity of the friction parts in mechanical systems. A variety of mechanisms have been proposed to explain the lubrication enhancement of the nanoparticle-suspended lubricating oil (i.e., nano-oil), including the ball bearing effect [1–3], protective film [4–8], mending effect [9] and polishing effect [10]. These mechanisms can be mainly classified into two groups, as shown in Fig. 1. The first is the direct effect of the nanoparticles on lubrication enhancement. The nanoparticles suspended in lubricating oil play the role of ball bearings between the friction surfaces. In addition, they also make a protective film to some extent by coating the rough friction surfaces. The other is the secondary effect of the presence of nanoparticles on surface enhancement. The nanoparticles deposit on the friction surface and compensate for the loss of mass, which is known as mending effect [9]. And also the roughness of the lubricating surface is reduced by nanoparticle-assisted abrasion, which is known as a polishing effect [10].

Various analysis techniques, such as scanning electron microscopy/energy dispersive spectrometer (SEM/EDS), atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), glow discharge spectroscopy (GDS) and X-ray diffraction (XRD), have been used to verify the lubrication mechanisms by examining the friction surfaces after a series of standard friction test [1–22]. However, it is difficult to distinguish the role of nanoparticles amongst the various lubrication mechanisms only using these surface analysis tools. This poses two major questions: (i) Can one simply demonstrate the role of nanoparticles in lubricating oil using a general disc-on-disc type tester without using any surface analysis tools? (ii) Based on the results of a

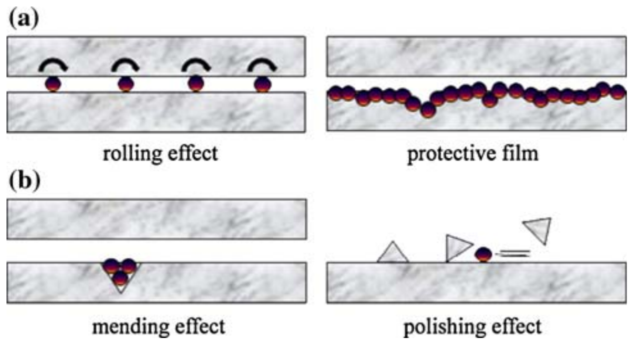

Fig. 1 Possible lubrication mechanisms by the application of nano-oil between the frictional surfaces

friction test (i.e., friction coefficient measurement), how can one separate the direct effect of nanoparticles on the lubrication properties from the surface enhancement effect (e.g., mending and polishing effect)?

This study addressed these issues using a disc-on-disc type tester, in which the friction coefficient of a disc specimen was recorded continuously as a function of the normal load and elapsed time. A fullerene nano-oil and pure mineral oil were prepared and tested repeatedly with various specimens in the disc-on-disc type tester to examine the direct effect and surface enhancement effect of nanoparticles in lubricating oil.

2 Experimental

Figure 2 shows a schematic of the disc-on-disc type tester used to evaluate the lubrication characteristics in both nano-oil and mineral oil. The tester was simply designed with two major plates, a rotating plate and a fixed plate. The discs were made from grey cast iron (GC200) without any surface treatment. The contact surfaces between the rotating and fixed plates can be considered as general frictional surfaces. The disc-on-disc testing machine 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 normal load was operated by an air cylinder system and controlled by a proportional-integrate-derivative (PID) controller, which controls the air pressure with high accuracy. The magnitude of the normal force was measured using a load cell installed under the air cylinder, and the rotating speed of the rotating plate was controlled by the inverter drive of the servomotor.

The friction force resulting from a combination of the rotating motion and normal load was measured using another load cell located in the closed chamber. Here, the friction force would impart a rotational force to the fixed plate in the same direction as the rotating plate. However, the fixed plate was unable 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 acting on the contacting surface is measured automatically by the mounted load cell. The uncertainty of disc-on-disc type tester can be calculated using 'standard single sample uncertainty analysis' that was suggested by Kline and McClintock [23]. There are two uncertainty sources in the load cell for measuring the normal load ($\sim 1.2 \times 10^{-5}$) and the friction force ($\sim 1.5 \times 10^{-4}$). Therefore, the total bias uncertainty of the disc-on-disc type tester used in this study is $\sim 1.505 \times 10^{-4}$.

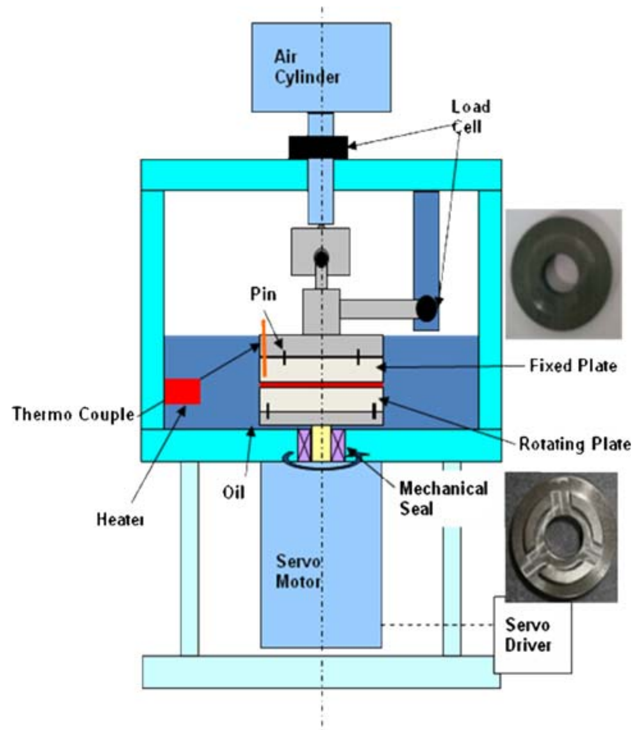

Fig. 2 Schematic of a disc-on-disc type tester

The temperature of the friction surface was also measured by a thermocouple installed at the fixed plate. The friction coefficient and surface temperature were measured as a function of normal load. Before performing each lubrication test, the initial temperature of the lubrication oils was maintained at 40 °C. The friction coefficient and friction surface temperature between the two frictional plates were measured as a function of the normal force ranging from 200 N to 800 N under a fixed rotating speed of 1,000 rpm. These friction tests were carried out in both mineral oil and nano-oils. The nano-oils were prepared by adding fullerene nanoparticles (0.1 vol.%) with an average size of $\sim$10 nm to the mineral oil followed by sonication (250 W, 44 kHZ) for 24 h. After the series of friction tests, the specimens were analysed by SEM and AFM to corroborate the results of the friction test based on the disc-on-disc tester.

3 Results and Discussion

In the series of lubrication tests, bimodal normal loads (i.e., solid line in Fig. 3) were applied to the disc specimens to observe the evolution of the friction coefficient as a function of the elapsed time, as shown in Fig. 3. The normal load was increased from 200 N to 800 N in 200 N increments during the friction test. Each applied normal load of 200 N was maintained for 30 min. After the normal load had reached the maximum of 800 N, it was decreased from 800 N to 200 N in 200 N decrements. Hence, a single friction test cycle took 210 min. Two consecutive friction test cycles (i.e., bimodal load) were applied to a specimen during each friction test. The evolution of the friction coefficient of a new specimen in mineral oil (i.e., solid square in Fig. 3, Test-1) and nano-oil (i.e., open square in Fig. 3, Test-3) was monitored to determine the direct effect of the nanoparticles in the mineral oil. The friction coefficient of the specimen immersed in mineral oil was strongly dependent on the magnitude of the normal load. On the other hand, the friction coefficient of the specimen immersed in the nano-oil showed a very weak dependence on the magnitude of the normal load applied. This suggests that there were more collisions between the frictional surfaces of the disc specimens immersed in the mineral oil with increasing normal loads and less with decreasing normal loads. The nanoparticles in the nano-oil acted as the combination of rolling and sliding bearings between the

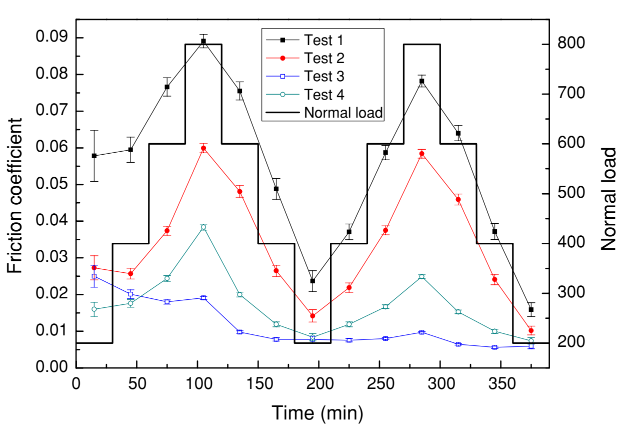

Fig. 3 The evolution of the friction coefficient as a function of the normal load and time (where, Test-1, disc specimen immersed in mineral oil for 1st friction test; Test-2, disc specimen immersed in the mineral oil for 2nd friction test; Test-3, disc specimen immersed in nano-oil for 1st friction test; Test-4, the disc specimen (previously tested in nano-oil for 1st friction test) immersed in new mineral oil for 2nd friction test)

frictional surfaces, leading to a significant decrease in friction coefficient; approximately ~67% and ~88% at 200 N and 800 N, respectively, compared to the mineral oil.

In order to observe the surface enhancement effect by both the mineral oil and nano-oil, each specimen used in the first bimodal friction test in either mineral oil or nano-oil was reused in a subsequent bimodal friction test with new mineral oil. First, the specimen previously immersed in mineral oil underwent a second bimodal friction test with new mineral oil (i.e., solid circle in Fig. 3, Test-2). The friction coefficient of the reused specimen was ~33% lower than that of the specimen used in the first friction test (i.e., Test-1). This suggests that the frictional surfaces in the mineral oil were worn to some extent during the course of the repeated friction test. Secondly, the specimen previously immersed in the nano-oil underwent a second bimodal friction test in new mineral oil (i.e., open circle in Fig. 3, Test-4). Here, the nano-oil was fully replaced with the new mineral oil. The friction coefficient of the specimen increased slightly with increasing normal load. It finally reached double the friction coefficient of the disc specimen immersed in the nano-oil at a maximum load of ~800 N. However, it was still 30% lower than the friction coefficient of the specimen tested twice in the mineral oil. This suggests that the surface enhancement effect of the nanoparticles comprises a significant portion of nano-oil-based lubrication, particularly a higher normal load.

The frictional surfaces were examined by SEM and AFM analyses, as shown in Fig. 4. The width and depth of the scratches made on the disc specimens (i.e., Fig. 4a) immersed in the mineral oil (i.e., average roughness = ~0.183 μm) were much larger than those of the specimen (i.e., Fig. 4b) immersed in the nano-oil (i.e., average roughness = ~0.107 μm). This suggests that the nano-oil-assisted lubrication properties are enhanced significantly by modification of friction surfaces. Interestingly, the modified frictional surfaces using the nano-oil were not changed appreciably after the second frictional test with the new mineral oil, as shown in Fig. 4c. It should be noted that the friction coefficients of both specimens in Fig. 4b and c were similar at a medium normal load (200–600 N). This indicates that the enhanced lubrication properties of the nano-oil are due to the presence of nanoparticles, which play the role of an abrasive material.

4 Conclusions

We have demonstrated a simple method to identify the role of nanoparticles in lubrication using a general disc-on-disc tester. The friction coefficient of specimen in the disc-on-disc tester was significantly reduced by the presence of

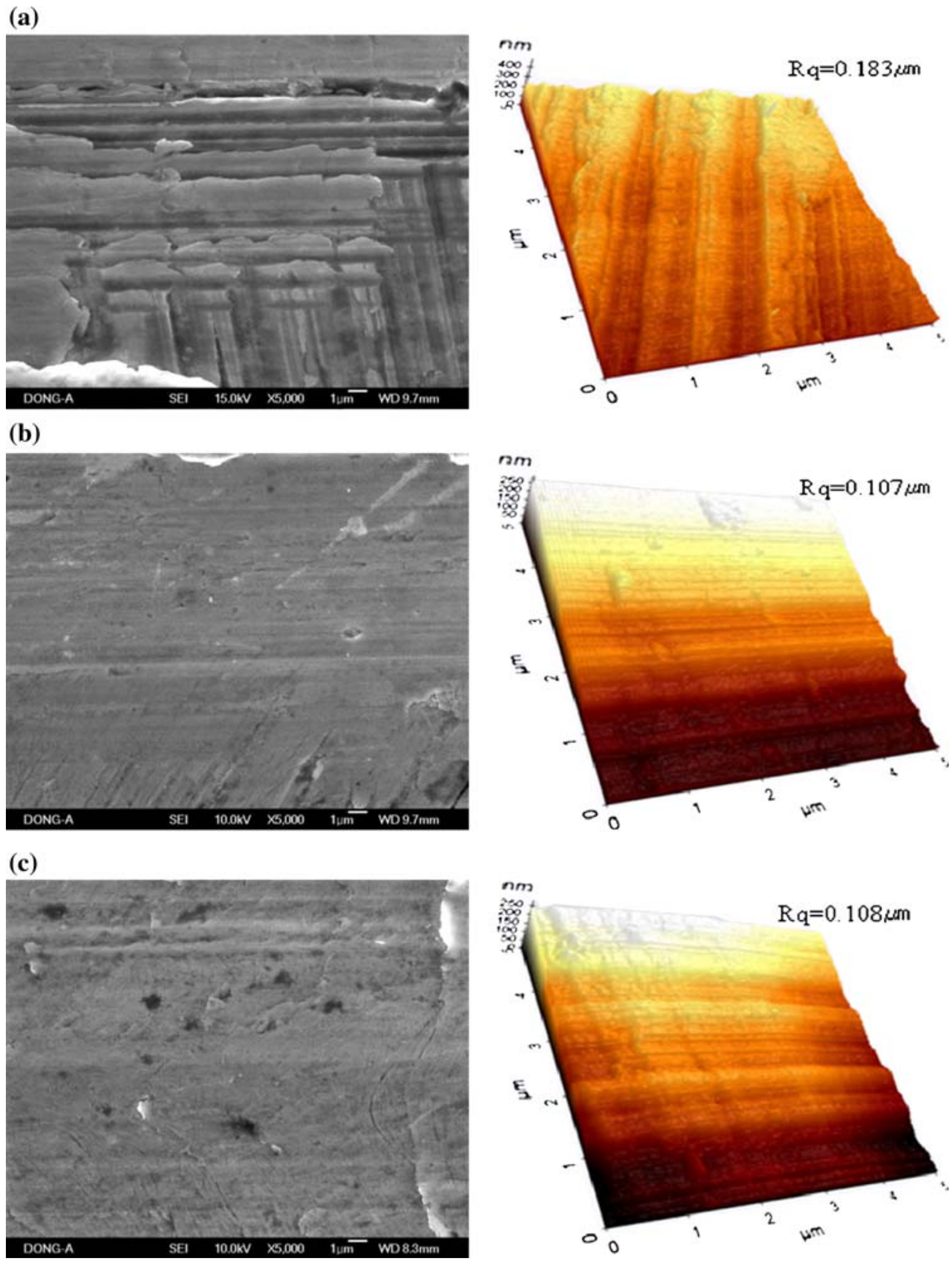

Fig. 4 SEM and AFM images of the surfaces of the disc specimens frictional tested in the mineral and nano-oils (R_q = average roughness). **a** Surface of a new disc specimen lubricated with mineral oil, **b** nano-oil; **c** Surface of the nano-oil-assisted surface modified disc specimen lubricated with new mineral oil

nanoparticles in lubrication oil between friction surfaces. This was easily verified by comparing the evolution of friction coefficient of the disc specimens immersed in both mineral oil and nano-oil. However, the enhancement of lubrication property in the nano-oils is also resulted from the surface modification by the presence of abrasive nanoparticles to some extent. In order to separate the surface enhancement effect, the specimen employed in the nano-oil friction test was reused in new mineral oil-based friction test. After severe surface modification was occurred by the prior nano-oil lubrication, the friction coefficient of the specimen was rarely changed even without nanoparticles in the new lubrication oil, indicating that the surface modification occurred by nanoparticle abrasion significantly enhances lubrication property.

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