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Wear Characteristics of Diesel Engine Oils with Nano-Diamond Particles on an Al-7075 Alloy

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ABSTRACT
The effects of the friction and wear characteristics upon an addition of ND particles to commercial engine oil are evaluated in an effort to reduce friction and wear. The ball-on-disk contact method was used for the wear test. The friction and wear behaviours of 5W-40 diesel engine oils containing 0, 0.005, 0.0075, 0.01, 0.015 and 0.02% of ND particles were investigated with changes in the wear rate and friction coefficient with surface roughness measurements and surface observations. Wear tests were carried out on an Al-7075 aluminium alloy disc with high-carbon chromium steel ball at a contact load of 10 N with a sliding distance of 500 m. The ND-free oil showed the lowest wear rate, and the oil with 0.02% ND added to it showed an increase in the wear rate of approximately 13% compared to that of the ND-free oil. This was likely caused by the hardness of Al-7075, which is relatively low compared to that of the balls used, while ND is considered to be a type of abrasive. The oils with 0% and 0.0075% ND show superior capabilities in terms of wear and frictional resistance, respectively, according to wear tests with six oils.

Key words: Nano-diamond particles, Wear rate, Friction coefficient, Ball-on-disc method, Al-7075 alloy

INTRODUCTION

Lubrication is intended to improve the efficiency of machine systems by reducing direct contact between parts, reducing wear by supplying the lubricant to machine parts undergoing friction due to contact and movement. Reduced wear by proper lubrication can reduce maintenance and repair costs associated with machine systems by reducing system failures related to machine parts. Proper lubrication also has the effect of reducing energy consumption by reducing friction. The functions of these lubricants are lubrication, cooling, sealing, cleaning, anti-corrosion, stress relief, and noise reduction [1]. In order to improve the performance of these types of lubricants, additives are added to enhance certain properties, such as oxidative stability, anti-friction and anti-wear and anti-corrosion protection properties.

However, most of these additives are mainly heavy metals and are harmful to the environment. Over the past few years, the nano-diamond (ND) material has become one of the most popular additives to base oil given its environmental friendliness [2]. ND is a carbon material that exhibits high hardness, excellent abrasion resistance, scratch resistance, corrosion resistance, alkali resistance, acid resistance and stable chemical properties.

Several studies have reported that adding a small amount of ND to lubricant effectively reduces the friction coefficient, abrasion resistance, and scuffing [3-9]. For example, Elomaa et al. conducted wear tests on a stainless steel (AISI 440B) disc and stainless steel balls (AISI 420) with oils containing up to 3.7% ND in ethylene glycol lubricating oil [3]. The friction coefficient decreased from 0.16 to 0.11 while the ND content was increased from 0% to 1.1%. In addition, the wear rate showed a minimum value at 0.55% ND during the formation of lubricating layers. Lee et al. conducted wear tests using SKD11 steel discs and Al_2O_3 alumina balls with oils containing 0% to 0.005% ND [4]. Experimental results show that the dispersion stability of oil containing ND was excellent and that the friction coefficient was reduced by 23% upon an addition of 0.55% ND to the base oil used. Chou and Lee conducted wear tests on ND-added oil using medium-carbon steel, low-carbon steel, aluminum alloy discs and carbon steel balls [5]. Their experimental results showed that in the carbon steel case, the friction coefficients and the wear rate were reduced in the oil-containing ND particles. However, with regard to aluminum alloys, ND reportedly acts as a type of abrasive and increases wear rates and friction coefficients. Chu et al. evaluated the tribological properties and scuffing resistance of tool steels under various speed and load conditions after an application of oil-containing ND particles [6]. They reported that ND-added oil at rates of 2% to 3% had a friction-reducing effect as compared to the base oil.

In this study, wear tests were carried out using aluminum alloy discs and carbon steel balls and using oil with different ND concentrations. From the experimental results, the effect of the addition of ND on the tribological behavior in terms of the friction and wear rates will be evaluated.

EXPERIMENTAL DETAILS

In this study, the ball-on-disk contact wear test was utilized for the wear tests. In these tests, ring-shaped specimens immersed in a lubricant are rotated and the friction coefficient between the ball and disc used is measured. This system, as shown in Fig. 1, is composed of a load train system that transfers the vertical load to the test specimen, a rotary motion system that rotates the disc specimen, and a load measuring system to monitor the friction coefficient. The disc specimens used in this study were made of a heat-treated Al-7075 alloy with hardness of 92 HRB and an inner diameter of 24 mm, an outer diameter of 40 mm and a thickness of 5 mm. The wear tests were carried out using SUJ-2 balls having a hardness of 511.4 Hv (= 49.90 HRC) and a diameter of 4 mm. With a contact load of 10 N, the wear tests were carried out up to a distance of 500 m at a sliding speed of 0.25 m/s.

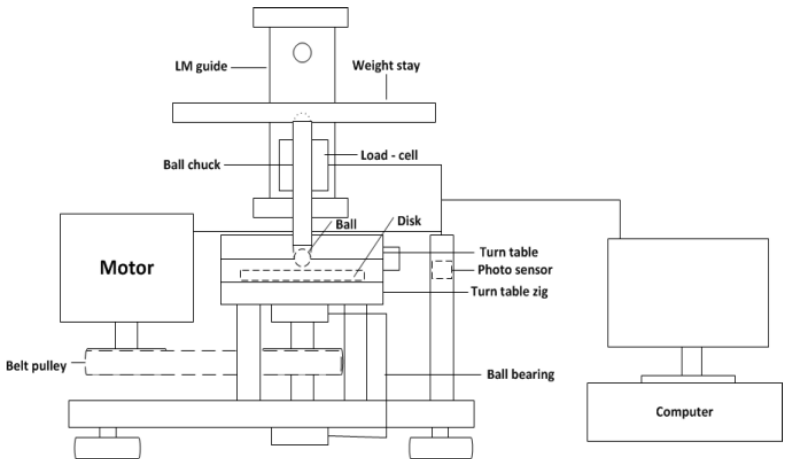


Fig. 1 Schematics of the ball-on-disc type of wear testing machine system

The surfaces of all disc specimens were polished with 0.3 μm alumina abrasive before the wear test. The oil solutions used in the experiment were prepared by adding 0.005, 0.0075, 0.01, 0.015, and 0.02% of ND to diesel engine oil (5W-40). These five types of oil containing ND as well as a base oil without ND were used. As shown in Fig.2, ND particles 4 to 6 nm in diameter were clustered, reaching a size of approximately 30 nm after a surface treatment of the ND particles to ensure high dispersion stability. The wear rate, friction coefficient, and surface roughness of the specimens were evaluated with varying concentrations of ND in the oil solutions.

The maximum contact pressure and the contact radius during the wear tests can be derived from the Hertz elastic contact theory [10]. The contact radius (a) between the ball and the disc is calculated by the following equation.

$$a = \sqrt[3]{\frac{3\pi}{4} \frac{P(k_1 + k_2)R_1 R_2}{R_1 + R_2}} \quad (1)$$

Here, R_1 (= ∞) and R_2 (= 2 mm) are disc radius and ball radius, respectively; P is the contact force and $k_1 = (1-\nu_1^2)/\pi E_1$, $k_2 = (1-\nu^2)/\pi E_2$. Poisson's ratios of aluminum (ν_1) and steel (ν_2) are 0.3 and the elastic moduli of aluminum and steel are E_1 = 70 GPa and E_2 =200 GPa, respectively. The contact radius was determined to be 63.8 μm. The maximum contact pressure can be calculated by the following equation.

$$p_{\max} = \frac{3P}{2\pi a^2} = 1{,}174 MPa \quad (2)$$

The maximum contact pressure of 1,174 MPa is considered to cause plastic deformation during contact with the ball due to stresses far exceeding the tensile strength of the disc material (= Al-7075).

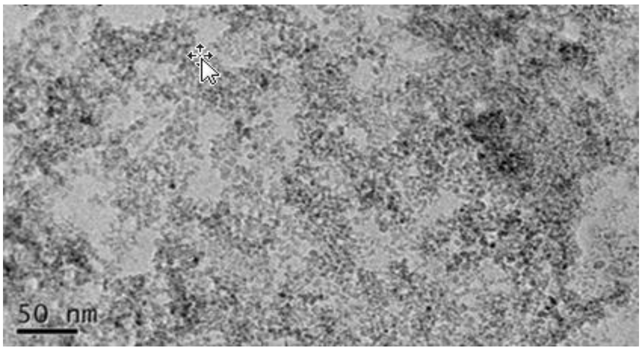


Fig. 2 TEM of ND powders in the lubricant

The wear rate was determined by the surface roughness test of the worn disc specimens. The total wear volume was calculated by multiplying the wear area on the bottom of a reference plane by the average circumference of the worn trajectory of the disc. The wear rate was then determined by dividing the total wear volume by the contact load (= 10 N) and the total moving distance (= 500 m). Fig. 3 shows the wear rate of the lubricant to which various amounts of ND were added. This figure shows that the wear rate of ND-added oil exhibits a sharp increase past a concentration of 0.01% compared to the ND-free base oil. That is, for the aluminum Al-7075 alloy, the addition of ND to the oil has no effect of reducing the wear rate. Conversely, the wear rate is increased. Fig. 3 shows the ND-free oil has lowest wear rate within a concentration range of 0 ~ 0.02% of ND. The wear rate with the oil containing 0.02% of ND increased by approximately 13% compared to that of the ND-free base oil. There are reports of similar results. According to a study by Hwang [11], ND-containing oil showed an increased wear rate when ND-added oil was applied to an Al-6061 alloy disc with a relatively low hardness. As the ND concentration was increased, the wear rate increased continuously, reaching maximum value when 0.015% of ND was added. This occurred because the hardness of Al-6061 is low compared to that of the ball and because the ND particles acted as a type of abrasive. In contrast, other studies have shown a reduction of the wear rate when ND-added oil was used [3,5,6,9]. ND particles reportedly intervene between surface protrusions of test specimens, serving as a type of rolling bearing to reduce wear. Therefore, it is considered that when the hardness difference with reference to the contact material is small, the ND particles serve as rolling bearings, and ND particles added to a lubricant efficiently improve the wear and friction performance

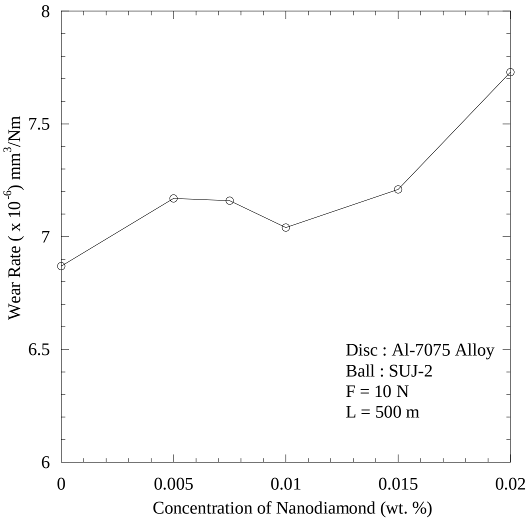
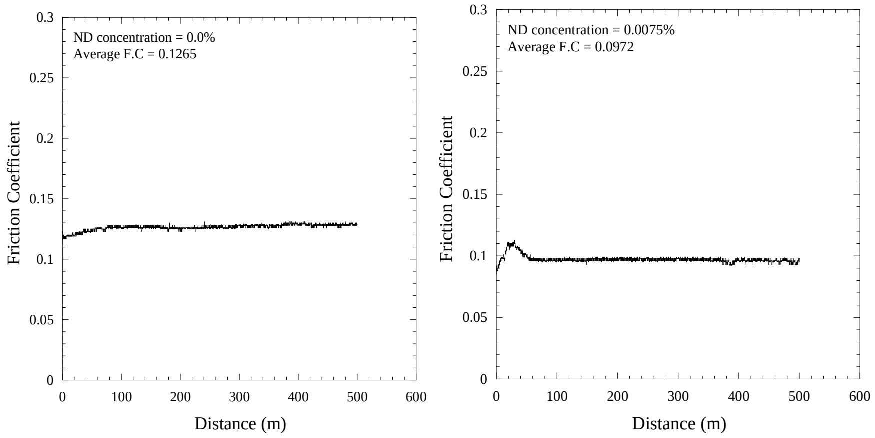


Fig. 3 Wear rate of disc after a 500-m wear test

The average friction coefficients during the wear test were in the range of 0.097 to 0.127. Fig. 4 shows the changes in the coefficient of friction in the 500-m wear test for various ND concentrations. In the case of the ND-free oil, as shown in Fig. 4(a), the average friction coefficient is 0.116, which is the second highest among the six types oil tested. It can also be seen that the variation of the friction coefficient is relatively stable in this case compared to other lubricating oils. The oil with 0.0075% ND exhibits the lowest average friction coefficient, and the coefficient was very stable as wear progressed, as shown in Fig. 4(b). For all of ND-added oils apart from the ND-free oil, the friction coefficient increased once before a sliding distance of 100 m, and then decreased and remained constant. For SK3 tool steels with high hardness levels, variation of the friction coefficient was found to be very stable with an increase in the ND concentration [12]. However, such a trend was not observed with the current Al-7075 alloy disc. The average friction coefficient and wear rate with various ND concentrations are plotted in Fig. 5. This figure shows that there is no correlation between the average friction coefficient and the wear rate for the Al-7075 alloy disc with oil added at various ND concentrations.

Surface roughness analysis



(a) (b)

Fig. 4 Variation of the friction coefficient for oil samples with ND concentrations of (a) 0% and (b) 0.0075% during a 500-m wear test

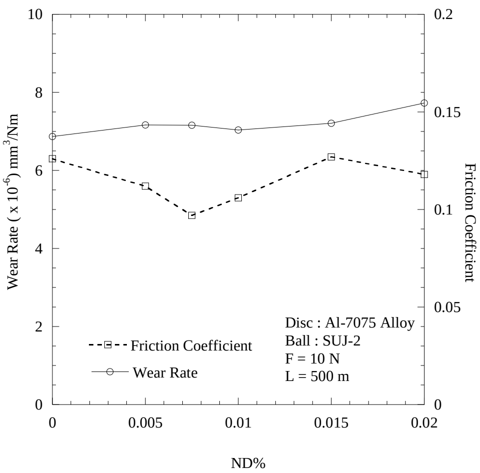
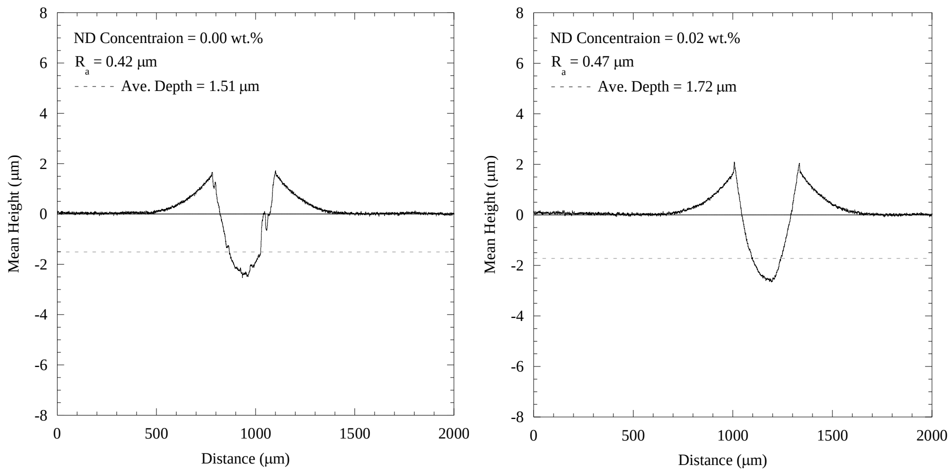


Fig. 5 Relation between the wear rate and average friction coefficient for oils with different ND concentrations



(a) (b)

Fig. 6 Surface profiles of the specimens with (a) 0% and (b) 0.02% ND concentrations

The roughness levels of the surfaces of the disc specimens with wear scarring were measured after a 500-m wear test. The results of these roughness measurements are shown in Fig. 6. Figs. 6(a) and (b) show the wear-damaged surfaces for the 0% and 0.02% ND concentration oils. It can be seen that the damaged surface for these two specimens are relatively smooth with rounded puddling. Fig. 7 shows the wear rate and average depths for oils with various ND concentrations. This figure shows that there is a similar trend between the wear rate and the average depth as a function of the ND concentration. This tendency shows a slight decrease at around 0.01% of ND and then an increase as the ND concentration increases.

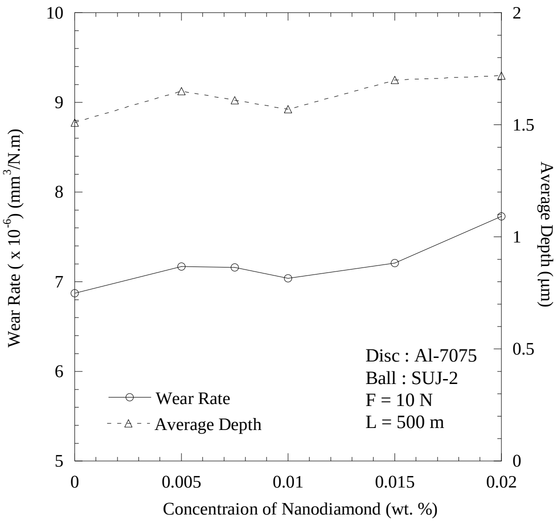
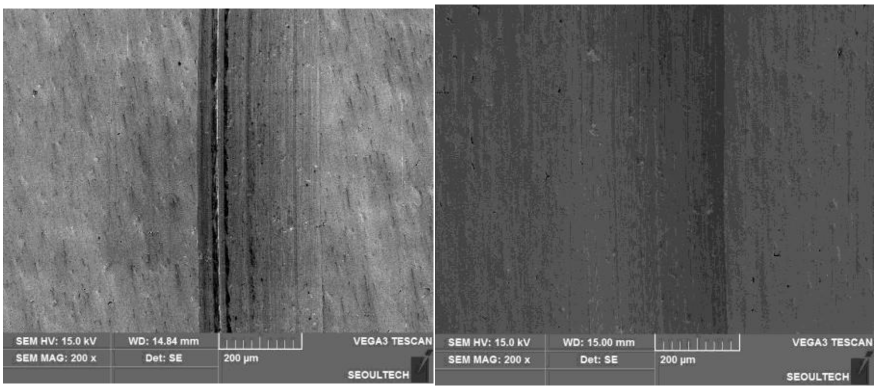


Fig. 7 Wear rate and average depth as a function of the ND concentration

The wear-damaged surfaces of the disc specimens were observed using a scanning electron microscope (SEM). Figs. 8(a) and (b) show the shapes of the worn surfaces of the discs tested with oil without ND and with a 0.02% ND concentration, respectively. Fig. 8(a) shows that the damaged surfaces of the specimen are slightly rougher than the specimens with oil added at an ND concentration of 0.02% (Fig. 8(b)).

Finally, as a result of wear tests on six types of oil, oil without ND and oil with a 0.0075% ND concentration are found to be superior in terms of wear resistance and frictional resistance, respectively. However, this study was carried out under only a constant load and at a single speed. Therefore, it is necessary to study the optimal ND concentration considering various loads, sliding speeds, and sliding distances in order to apply these results to industrial applications.



(a) (b)

Fig. 8 SEM micrographs of the wear tracks on discs after wear tests using oil with ND concentrations of (a) 0% and (b) 0.02%

CONCLUSION

The effect of ND on lubrication performance outcomes was evaluated through wear tests with ND added to diesel engine oil (5W-40). Experiments were carried out on oil samples containing 0, 0.005, 0.0075, 0.01, 0.015, and 0.02% of ND. Wear tests were performed up to a sliding distance of 500 m using Al-7075 alloy discs and high-carbon chromium steel balls with a contact load of 10 N. The friction and wear outcomes due to the addition of ND into the oil were investigated. The experimental results are as follows.

1. It was found that after the 500-m wear test, the wear rate of the ND-added oil increased sharply with more than 0.01% of ND compared to the ND-free oil. ND-free oil showed the lowest wear rate, and the oil with 0.02% of ND added showed a 13% increase in the wear rate compared to the oil without ND. This resulted from the hardness of Al-7075, which is relatively low compared to that of the ball. Moreover, ND is considered to serve as a type of abrasive.
2. The average friction coefficient shows the highest value at an ND concentration of 0.015% and the lowest value at 0.0075% of ND. It was also found in the wear tests with oils with varying ND concentrations that the average friction coefficient and wear rate were not correlated with each other.

3. After the 500-m wear test, there is a similar tendency between the wear rate and mean depth of wear scarring of disc specimen with different ND concentration. This tendency shows a slight decrease at around 0.01% of ND, though it then increases again with an increment in the ND concentration.
4. The oil with 0% and 0.0075% ND were found to be superior in terms of wear and friction resistance, respectively, after wear tests with six types of oil.

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