Journal of Alloys and Compounds 495 (2010) 481–484

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Tribological property of TiO_2 nanolubricant on piston and cylinder surfaces

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ARTICLE INFO

Article history:
Received 26 June 2009
Received in revised form
10 September 2009
Accepted 4 October 2009
Available online 13 October 2009

Keywords:
TiO_2 nanolubricant
Tribology
Piston ring
Wear rate

ABSTRACT

In this paper, an arc spray nanofluid synthesis system with complex ultrasonic orthogonal vibration and vortex stirring was proposed and developed for TiO_2 nanolubricant, in which TiO_2 nanoparticles were of equal roundness and consistent size. In the proposed nanofluid synthesis system, one of the electrodes and ultrasonic vibrator were assembled to form an orthogonal model with another electrode installed inside the vacuum chamber of arc discharge system, with 10 W/30 lubricant serving as the dielectric liquid. The tribological behavior of the lubricant with TiO_2 nanoparticles at average particle size 25 nm on the surface of piston ring is compared with that of the lubricant without TiO_2 nanoparticles. Experimental results showed that the coefficients of friction between the piston ring and base lubricant was 0.15; between the piston ring and TiO_2 nanolubricant was 0.14. Furthermore, the piston ring's wear rates of the base lubricant and TiO_2 nanolubricant were 0.0055 and 0.0021, respectively. After operating the piston cylinder for 8 consecutive hours in 15 and 30 days, respectively, the diameter of TiO_2 nanoparticles in the lubricant remained 25 nm in average. As observed from the piston ring surface on the 15th and 30th days through scanning electron microscope (SEM), it had less scraping than the piston lubricated without TiO_2 nanoparticles. Therefore, a lubricant added with TiO_2 nanoparticles can better protect the piston ring surface.

1. Introduction

In recent years, the use of different kinds of nanoparticles as oil additives has been extensively investigated in many studies [1–6]. These research results show that nanoparticles deposit on the rubbing surface and improve the tribological properties of the base oil, presenting the good friction and wear reduction characteristics of nanoparticles. Tribology can also be applied to wearing in automotive industry. In general, under the conditions of high speed and low loading, the tribological properties produced are hydrodynamic lubrication and no wear out on contact surface. Nevertheless, under the conditions of heavy loading and boundary lubrication, a chemical thin film generated from the lubricant between machine parts will be intensely squeezed, and may not be able to protect metallic surface. Some studies show that the addition of nanoparticles to lubricant can enhance the supporting force during loading [7]. Therefore, nanoparticles are always added to lubricants, and the goal of wear reduction can be achieved effectively.

When nanomaterials are used to improve lubrication effect, the selection of metal is very important [8]. Today different kinds of nanomaterials have been selected in tribological experiments. Shen and Liu [9,10] used a nanoalloy element to perform the related wear research. Among the various metals, TiO_2 nanoparticle has been extensively applied in different engineering domains due to its easy acquisition and high stability [11].

The paper used the self-developed arc spray nanofluid synthesis system (ASNSS) with complex ultrasonic orthogonal vibration and vortex stirring to fabricate TiO_2 nanofluid, in which TiO_2 nanoparticles could be stably dispersed in the base lubricant. In the experiment of tribological properties of piston ring, a self-assembled universal nanomaterial tester (UNMT) was used to measure the sliding resistance of base lubricant and TiO_2 nanolubricant. In addition, a universal micro-tribometer was employed to measure the coefficients of friction between the piston ring and base lubricant; between the piston ring and TiO_2 nanolubricant. Finally, the paper inspected the surface wear rate of piston ring from the SEM image.

2. Experimental details

Using the basic principles of gas condensation method, the study developed the vacuum arc spray nanofluid synthesis system (ASNSS) with ultrasonic vibration and a vortex stirring device [12]. The experimental devices mainly included an electrical power utility, a servo-positioning system, a vacuum chamber, a vacuum pump, a heating source, a cooling system, an ultrasonic vibrator, a vortex stirring device and a pressure control unit. The ultrasonic system allowed the setting of

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doi:10.1016/j.jallcom.2009.10.017

Table 1
Process variables for preparing TiO_2 nanofluid by the proposed arc spray nanofluid synthesis system.

Working condition	Description
Peak current (A)	1, 1.5, 2.5, 3
Breakdown voltage (V)	250
Work atmosphere (Torr)	20
Pulse duration (μs)	2
Off time (μs)	2
Electrode size (mm)	5
Dielectric fluid base lubricant oil temperature of dielectric fluid (°C)	0 ± 2

different frequencies and amplitudes. In the ASNSS, a bulk metal serving as an electrode was submerged in a dielectric liquid (base lubricant No. LB21046 provided by Chinese Petroleum Corporation) held in a vacuum chamber. The applied electrical energy was the heating source that generates adequate arc under high temperature ranging from 6000 to 12,000 °C. The vaporized metal powder was then rapidly quenched by the designed cooling system, nucleating and forming nanocrystalline powder. The nanoparticles thus produced were dispersed in the dielectric liquid, which helped reduce aggregation during particle collection and avoided spraying of particles and powder. During discharge, the dielectric liquid was disturbed by the orthogonal vibration of the ultrasonic vibrator. Thus, the vaporized metal could leave a high-temperature gap zone easily, and could be rapidly condensed by the low-temperature insulating liquid. At the same time, it could suppress the growth of material after nucleation, making nanograins spread throughout the insulating liquid. In addition, a vortex generator was placed under the nanofluid collector, enabling the nanoparticles to be stirred evenly by the vortex. In this way, nanoparticles could be evenly dispersed in the insulating liquid, giving high degree of suspension stability to nanofluid.

Table 1 shows the process parameters, with the peak currents of 1, 1.5, 2.5 and 3 A selected for making comparison. After analysis of the results of several experiments, a TiO_2 nanofluid with high suspension stability was prepared. The main process parameters were peak current 2.5 A, on-time pulse duration 2 μs, and off-time pulse duration 2 μs. In addition, the weight fraction of the prepared TiO_2 nanolubricant was 0.01%.

To have deeper understanding of the wear property of the developed lubricant in a cylinder piston ring and cylinder wall, the study used the self-assembled piston-cylinder tester (Fig. 1) for testing. The piston-cylinder assembly being used was Kymco Motors' cylinder No. 12100-KHE7-900, with cylinder diameter 72.42 mm. Besides, a pneumatic cylinder was used to push the piston. The stroke length for driving the pneumatic cylinder was 5 cm, and the sliding velocity was 37.2 cm/s. The average contact pressure and load of the piston ring and cylinder wall were 1.2 kg/cm^2 and 53 N, respectively. The test temperature was 25 °C, and the humidity was 40–65% RH. In addition, the air pressure driving the piston was 2 kg/cm^2, and the time of each stroke was 0.16 s.

During the actual test, the piston performed reciprocating motion inside the cylinder for 8 consecutive hours per day, and this operation lasted for 30 days. After operation for 15 and 30 days, electron microscopy was used to inspect the surface of piston ring. Furthermore, a comparison with the surface of piston ring was made after the cylinder piston ring caused friction with the cylinder wall, where the lubricant was added with no nanoparticles.

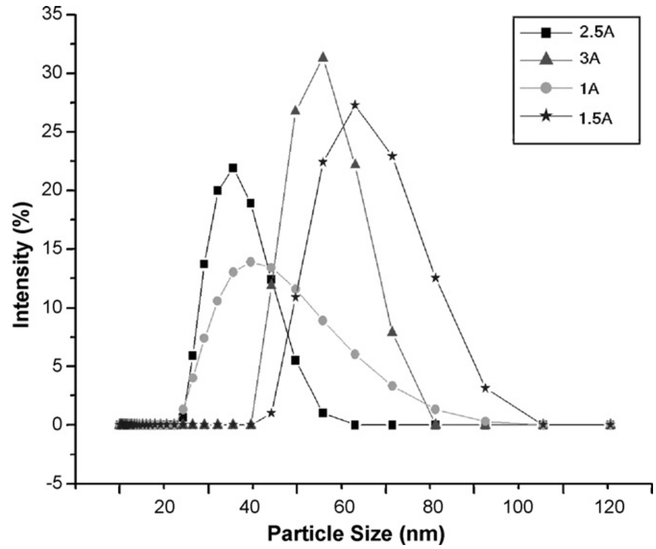

Fig. 2. Particle size distribution of the prepared TiO_2 nanoparticles at different peak currents.

3. Results and discussion

A particle size analyzer (MALVERN Nanao-ZS90) was used to measure the particle size distribution of the prepared nanoparticles. As known from Fig. 2, when the peak current was 2.5 A, the prepared TiO_2 nanoparticles had the smallest average particle size 25 nm. Therefore, the peak current 2.5 A was taken as the process parameter of the prepared TiO_2 nanolubricant. Seven days after TiO_2 nanolubricant was fabricated, the fabricated nanofluid still had high suspension stability. Besides, it had Zeta potential 35 mV, and pH value 7. The pH value was far higher than the pH 4 of isoelectric point, at which particles conglomerated easily [13].

One of the important challenges to nanolubricant is industrial application. The attractive force between particles can make them aggregate since the size is too small. The simply mixed TiO_2 nanoparticles are not satisfactory, so the suspension stability of TiO_2 nanofluid is not high. Therefore, its value has to be reduced for industrial applications [14]. Between the prepared nanolubricant and the one previously reported by another author, the greatest difference is on the process, where the high temperature of arc discharge can rapidly melt and vaporize the electrode. In this way, when metallic droplets are scattered over the base lubricant, they

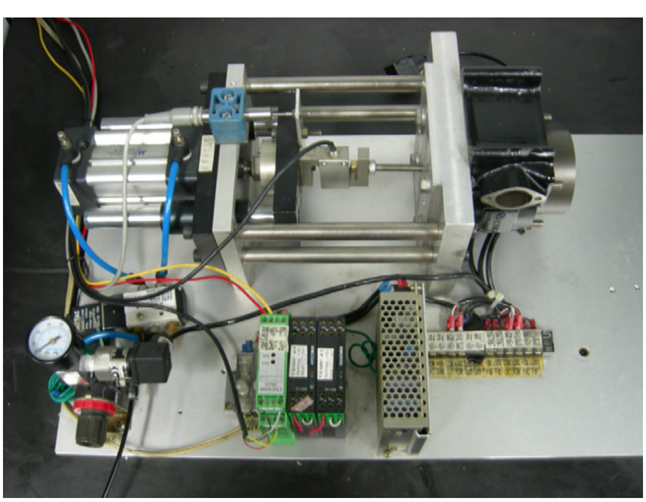

Fig. 1. A generally used and assembled universal nanomaterial tester (UNMT).

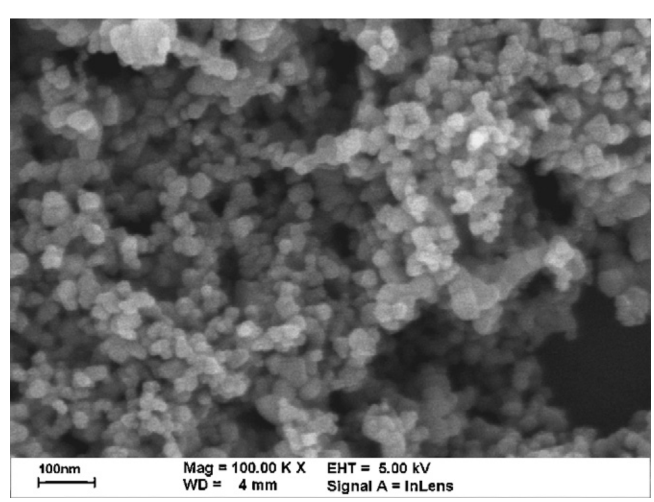

Fig. 3. FE-SEM images of the produced TiO_2 nanoparticles.

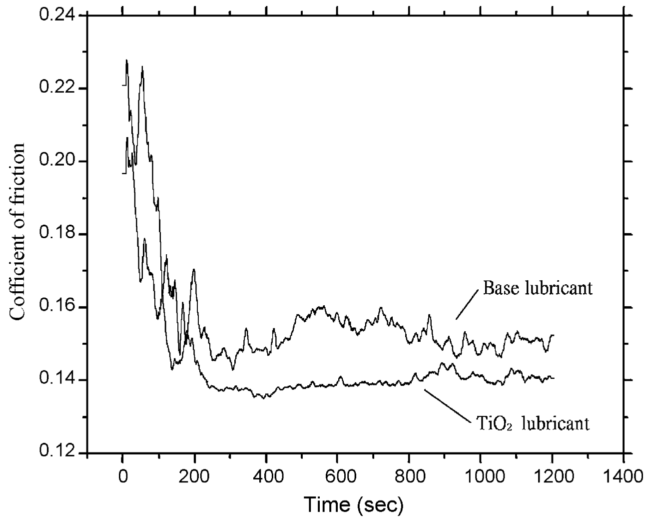

Fig. 4. Friction coefficients of base lubricant and TiO_2 nanolubricant.

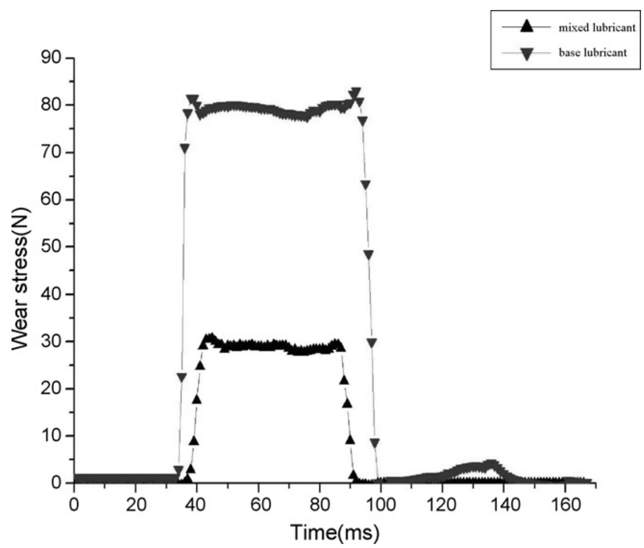

Fig. 5. Dynamic friction force of lubricants added with and without TiO_2 nanoparticles measured in wear test.

rapidly condense into nanoparticles, which are then dispersed and suspended in the lubricant. According to Stokes' law, the sedimentation speed of suspended particles can be known, as shown in Eq. (1). Since both density and viscosity of lubricant are higher than those of deionized water, the particle suspension stability of the prepared nanolubricant is better than that of nanofluid prepared by deionized water, which serves as dielectric liquid:

$$v_0 = 54.5d^2 \frac{\delta - \rho}{\mu} \quad (1)$$

where δ is the density (g/cm^3) of nanoparticle; d is the diameter (cm) of nanoparticle; ρ is the density (g/cm^3) of medium; and μ is the viscosity (Pa s) of medium.

Fig. 3 shows the FE-SEM image of TiO_2 nanoparticle suspension prepared with the process variables shown in Table 1. As shown in Fig. 2, the TiO_2 nanofluid prepared by the proposed ASNSS has good dispersion of nanoparticles with average particle size below 30 nm.

A micro-tribological tester (Universal Micro-Tribometer, UMT) was used testing the friction coefficient of the prepared nanolubricant. A stainless steel sample was installed to cause friction with a stainless steel ball by ball-on-disc way in 4 ml of test lubricant. Nanolubricant was dropped on the surface between two friction materials. After running for 20 min, the coefficients of friction between the piston ring and base lubricant was 0.15; between the piston ring and TiO_2 nanolubricant was 0.14. As known from the experimental results, when base lubricant is added with TiO_2 nanolubricant, the coefficient of friction can effectively decrease (as shown in Fig. 4).

The experimental results showed that the lubricant with TiO_2 nanoparticles added brought more obvious scraping than the lubricant without TiO_2 nanoparticles added. The wear test machine was a generally used and assembled universal nanomaterial tester (UNMT), which measured a stroke of dynamic friction. A cycle took 0.16 s, and the actual motion took 0.06 s, with a stroke interval of 0.1 s. Fig. 5 shows the dynamic friction forces of two lubricants, respectively, added with and without TiO_2 nanoparticles, and the dynamic friction forces were measured in one stroke of wear test. As shown from the figure, the dynamic friction force of the lubricant with nanoparticles added is 30 N, whereas the dynamic friction force of the lubricant without nanoparticles is 80 N.

As to the measurement of wear rate, after friction running for 30 days, a microbalance was used measuring the weight of piston ring before and after wear. As observed from the measured results, when TiO_2 nanolubricant was used, the weight of piston ring before wear was 0.5623 g, and after wear was 0.5611 g. Therefore, the weight of piston ring decreased by 0.0012 g, and the wear rate was 0.0021. Relatively, when merely using base lubricant without any TiO_2 nanoparticles added, the weight of piston ring before wear was 0.5645 g, and after wear was 0.5614 g. Hence, the weight of piston ring decreased by 0.0031 g, and the wear rate was 0.0055. From the above comparison, it is known that using TiO_2 nanolubricant can effectively decrease wear rate.

The FE-SEM used by the study was Hitachi S4800, which was able to magnify images by 2000 times and 50,000 times for obser-

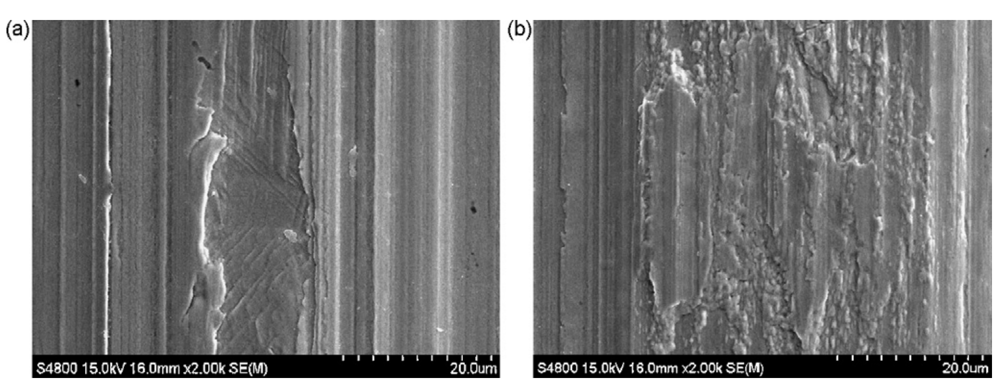

Fig. 6. FE-SEM image of surface wear of piston ring after wear test has lasted for (a) 15 days and (b) 30 days, without TiO_2 nanoparticles added to base lubricant.

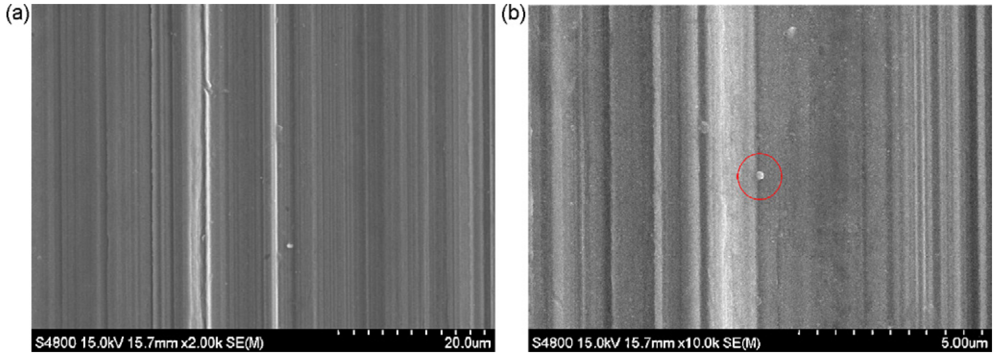

Fig. 7. FE-SEM image of surface wear of piston ring after wear test has lasted for (a) 15 days and (b) 30 days, with TiO_2 nanoparticles added to base lubricant.

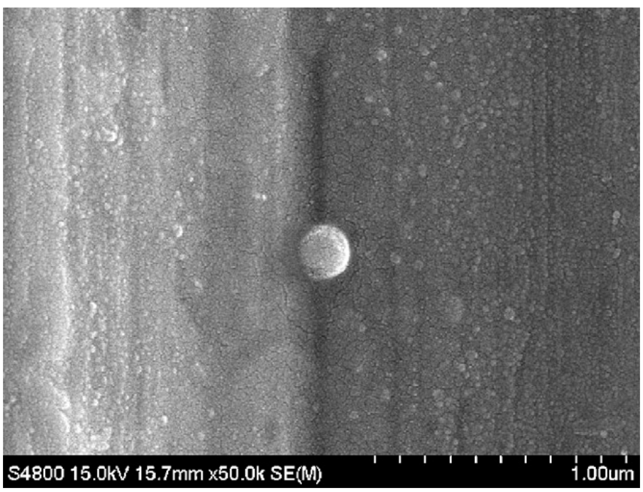

Fig. 8. FE-SEM image of surface wear of piston ring magnified from Fig. 7(b).

vation. As observed from the surface of piston ring (as shown in Figs. 6 and 7), scraping was produced by metallic friction between piston and cylinder. After the continuous contact motions, the surface of piston ring started to wear. As the contact motion sustained for 15 days, tiny scrapes were found (Fig. 6(a)). On the 30th day, obvious scraping damage was found on the surface (Fig. 6(b)). As observed from the FE-SEM image in Fig. 7(a), since TiO_2 nanofluid was used, scrapes were not obviously found on the surface of piston ring. However, after the friction test lasted for 30 days, some regular scrapes appeared on the surface of piston ring, as shown in Fig. 7(b). And the FE-SEM image of Fig. 7(b) was magnified in Fig. 8. Nanoparticles were inlaid in the ditch of piston ring. It refers that nanoparticles not only can enhance the lubrication effect, but also can fill the ditch formed by wear.

4. Conclusions

According to the above results and discussion, the following conclusions are made:

1. When TiO_2 nanoparticles were fabricated by ASNSS, and the parameters were set with peak current at 2.5 A and off-time pulse duration at 2 μs, the analytical measurement by FE-SEM showed that the average particle size was around 25 nm, and the weight fraction of the prepared TiO_2 nanolubricant was 0.01%.
2. As known from the test and comparative analysis of dynamical friction force made by UNMT, the surface wear caused by TiO_2 nanolubricant was 50 N less than base lubricant. The coefficients of friction of base lubricant and TiO_2 nanolubricant were 0.15 and 0.14, respectively. In addition, as observed from the measured result of wear rate, when using TiO_2 nanolubricant as the lubricant, the wear amount of piston ring was less than that of base lubricant. Therefore, the base lubricant with TiO_2 nanoparticles added has better tribological efficiency than general base lubricants.
3. The pH value of the prepared TiO_2 lubricant was 7, which is a value far greater than the pH value 4 at isoelectric point, at which particles conglomerate easily. Therefore, the suspension stability of TiO_2 nanoparticles in lubricant is better.

Acknowledgement

The study is supported by the National Science Council of Taiwan, Republic of China under the project grant: NSC 96-2221-E-027-093.

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