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Tribological properties of ZnO and WS_2 nanofluids using different surfactants

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ABSTRACT

Previous studies have shown promising tribological performance and thermal properties of nano particles and ionic liquids when they were used separately as oil additives. However, the use of ionic liquid as a nanofluid surfactant has been rarely studied. This work investigates oil based ZnO and WS_2 nanofluid tribological properties using two different surfactants: oleic acid and ionic liquid. ZnO and WS_2 nanofluids were mixed and pin on disk tests were performed using 20MnCr5 carburized axle hypoid gear material. Results showed that phosphinate ionic liquid as surfactant has long term stability when mixed with ceramic nano particles. However, it was found that using phosphinate ionic liquid alone as an oil additive did not improve nanofluid tribological performance. Meanwhile, oleic acid when used as a surfactant showed lower friction and reduced wear for both ZnO nanofluids and WS_2 nanofluids. SEM studies showed a film formed on the disk surface using oleic acid as surfactant which may enhance tribological performance.

1. Introduction

Since the concept of nanofluids was proposed by Choi [1] in 1995, researchers from different fields have been exploring the potential of nanofluids, mainly focusing on their enhanced thermal conductivity, rheological properties, and tribological performance [2–5]. Despite the distinctive potential of nanofluids, the stability, dispersing methods of preparing nanofluids, and operating conditions have been major challenges to the application of nanofluids in industry. In order to utilize the advanced properties of nanofluids, finding an optimal way to produce stabilized nanofluids and analyze their properties in industrial applications is important [6–9].

Ionic liquids as oil additives have some unique properties, such as non-flammability, negligible volatility, low melting point and high thermal conductivity. Because of the molecular structure of ionic liquids, they can produce excellent tribological performance such as reduced friction and wear. Ionic liquids composed of organic cations and organic or inorganic anions, when used as oil additives have been demonstrated to produce a lubricant which can be used over a wide temperature range. A group of phosphonium-phosphate/phosphinate ionic liquids has been developed and some of these ionic liquids have shown excellent miscibility with non-polar hydrocarbon oils. Tribological tests have demonstrated significant friction and wear reductions from adding a small amount (1–5 wt%) of the oil-miscible ionic liquids into base oils [10].

Due to the advanced fluid properties of ionic liquids, several researchers investigated ionic liquid based nanofluids. Yu et al. [11] first introduced ionic liquid as a nanofluid base fluid; room temperature ionic liquid (RTIL) 1-hydroxyethyl-3-hexylimidazolium hexafluorophosphate (HEHImPF6) was synthesized with Multi-Walled Carbon Nanotubes (MWCNTs). The mixture showed excellent dispersibility. The tribological performance of RTIL/MWCNTs was tested on a pin on disk tribo-tester and found to have good friction-reduction and anti-wear properties.

Qu et al. [12] studied phosphonium-based ionic liquids, which are fully miscible with hydrocarbon oils and are thermally stable up to 347 °C. They found that 5% ionic liquid will eliminate scuffing failure when added to neat base mineral oil. Ionic liquid produced a tribo boundary film, which protected the surface and reduced wear.

Tribological properties of nanofluids vary for different nano particles and different base fluids. Some nano particles may act like ball bearings and reduce friction or pack into surface valleys to make the surface smoother [13]. However, some nano particles could be abrasive and increase wear on the sliding surfaces. Also, increasing nano particle concentration does not have a consistent relationship with coefficient of friction or wear. Different surface roughness, load, velocity and temperature make a difference in regard to nanofluid tribological performance [14–16]. Therefore, finding the best concentration of

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nano particles and surfactant at different test conditions are keys to obtaining good performance of nanofluids.

2. Experimental

From the survey of relevant literature, it was found that a well dispersed nanofluid will significantly change the fluid thermophysical properties. Ionic liquids, ZnO nano particles and WS_2 nano particles have shown improved tribological properties when mixed with oil [17,18]. However, previous research did not directly compare the properties of ZnO nanofluid and WS_2 nanofluid. In addition the use of ionic liquid as a nanofluid surfactant has been rarely tested and the performance of ionic liquid and the more traditionally used nanofluid surfactant oleic acid has been seldom compared. This research compares the properties of ZnO and WS_2 nano particles and ionic liquid and oleic acid surfactants. In addition, the use of nanofluids with materials commonly used in production components such as automotive gears has received little attention. In the present work, gear oil without an additive package is selected as the base fluid; ZnO or WS_2 nano particles are mixed with the base oil. To stabilize the nanofluids, two types of surfactant, ionic liquid or oleic acid, are used and different ultrasonic mixing times are studied. The tribological performance of oil based ZnO and WS_2 nanofluids with different concentrations were analyzed using a pin on disk tribo-tester. Carburized gear material 20MnCr5 was selected as the test material, which is the same material used in automotive driveline axle hypoid gears.

2.1. Equipment

A 400 W ultrasonic homogenizer with an output frequency of 20 kHz was used to mix the nanofluids. Full power of 400 W and 70% pulse width modulation were applied to the homogenizer processing tip. A beaker containing cold water (22 °C) was used to maintain the nanofluid temperature during the homogenizing process to prevent the nanofluids from overheating.

The tribo-tests were conducted using a Bruker UMT 3 pin on disk tester. As shown in Fig. 1, a normal load Fz was applied to a fixed ball that is attached to the test specimen. The test specimen was fixed to the spindle on the bottom of the tribometer. The wear tracks were analyzed using a Bruker Optical Profiler and Scanning Electron Microscope.

2.2. Test specimens

20MnCr5 gear material was used in the study. A round steel bar was cut and machined to a diameter of 70mm and thickness of 10mm, then carburized to obtain a surface hardness of 61HRC. The carburized specimens were then ground to Ra roughness of approximately 0.36um.

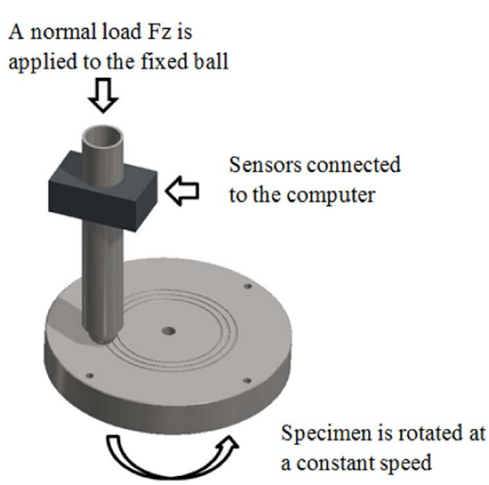

Fig. 1. Pin on disk tribo-test schematic.

The ball used in this study is E52100 alloy steel with a hardness of HRC60. The diameter of the ball is 7.9375mm and the average surface roughness for the ball is approximately 18.2 nm.

Group III gear oil without an additive package was used as baseline oil. The base line gear oil is a mineral oil with a viscosity of 18 cSt at 40 °C. The ZnO nano particles used in this study are from US Research Nanomaterials Inc. They have 99 + % purity and the particles sizes ranged from 10–30 nm in diameter. The surface area is 20–60 m^2/g and the molecular weight is 81.37 g/mol. True density is 5.606 g/cm^3. The crystal structure is single crystal and the morphology is near spherical. The WS_2 nano particles used in this study are from US Research Nanomaterials Inc. They have 99.9% purity. The WS_2 nano particles are amorphous structured with particle size 40–80 nm. The surface area is 80 m^2/g, the true density is 7.5 g/cm^3 and bulk density is 0.25 g/cm^3.

The ionic liquid used in this study is phosphonium ionic liquid, i.e., Trihexyltetradecylphosphonium bis (2, 4, 4-trimethylpentyl) phosphinate. The density is 0.895 g/ml at 20 °C. The molecular formula is $C_{48}H_{102}O_2P_2$ with a molecular weight of 773.27 g/mol. Oleic acid was used to compare with ionic liquid as the nanofluid surfactant. The molecular formula of the oleic acid used in this study is $C_{18}H_{34}O_2$; it has a linear formula of CH_3 $(CH_2)_7CH$: CH $(CH_2)_7CO_2H$ and molecular weight of 284.62 g/mol.

2.3. Test procedure

Lubricant volume for mixing a nanofluid was 35 mL. This produced sufficient nanofluid so that test specimens could be submerged into the nanofluid when running tribotests. Surfactant is applied in the nanofluids, the surfactant and nano particles weight ratio is controlled to be 1:1. Baseline oils with only ionic liquid or oleic acid were mixed and tested as well to investigate the surfactant properties. Four different concentrations by weight were mixed, which are 0%, 0.5%, 1%, and 2%. Ten minutes shaking was applied using a wrist action shaker to premix the mixture. Five minutes of ultrasonic homogenizing process was applied after the shaking process. After the ultrasonic mixing process, the water bath temperature is 23 °C, and the nanofluid temperature is approximately 28 °C. The mixed nanofluid were tested 10–15 minutes after the mixing process; the test starting temperature of the nanofluid mixture is approximately 24 °C.

For the baseline tribo-test, the sliding velocity is held constant at 2 m/s, which is experienced by several tribological components in driveline axle systems. This sliding velocity produced mixed lubrication. The normal load was held constant at 22 N. Based on the materials elastic moduli and Poisson's ratios, the maximum Hertzian contact stress was calculated to be 1538 MPa. Each test duration is 30 minutes; each test case was repeated three times using different specimens.

The coefficient of friction was recorded every 10 ms during each test. The coefficient of friction value produced for each test was found by averaging the stabilized coefficient of friction data. The average coefficient of friction for each oil mixture was found by averaging the values from the 3 tests. The standard deviation for the three tests was also calculated. For the wear performance, since the disk in this study is carburized and slightly harder than the balls and the surface finish is relatively rough, most of the wear tracks are not obvious and deep enough to accurately calculate the wear volume of the disk. Therefore, ball wear diameter was measured and ball wear volume V was calculated based on the ball radius r, the radius of the ball wear scar a, and the height of the wear scar h. See Eqs. (1) and (2). The ball wear volume for each oil mixture was then calculated by averaging the ball wear volume and the standard deviation for three ball volumes was also calculated.

$$h = r - \sqrt{r^2 - a^2} \quad (1)$$

$$V = \frac{\pi h}{6}(3a^2 + h^2) \quad (2)$$