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Short Communication

Effects of two sliding motions on the superlubricity and wear of self-mated bearing steel lubricated by aqueous glycerol with and without nanodiamonds

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ABSTRACT

Comparative experiments were performed to demonstrate how the lubricated sliding friction and wear behavior of a bearing steel can be affected by the type of relative motion. Data from rotary motion (ball-on-disk tests) were compared to that for reciprocating motion (high frequency ball-on-flat tests) using the same contact pressure, average velocity, temperature and humidity. Two lubricants were compared. The first was aqueous glycerol and the second was aqueous glycerol containing 0.1% w nanodiamonds. The aqueous glycerol solution showed superlubricity effects in rotary testing because its friction coefficient was lower than 0.01. This effect was attributed to a stable protective matrix comprised of free and bound water layers in aqueous glycerol and a thick film lubrication condition. Under reciprocating conditions, it is proposed that the protective matrix was damaged due to the repetitive application of compressive stress and boundary lubrication condition. As a result, there was no superlubricity behavior observed in reciprocating tests. In the rotary test method, the nanodiamond additives (dispersed in glycerol) and wear debris accumulate at the contact zone. That mixture grows into a large abrasive particle mix. However, during reciprocation there are fewer nanodiamonds and wear debris particles in the contact zone. They polish and smooth the surface, as indicated by the post wear surface images. The abrasive nature of nanodiamonds increases the micro polishing effect and thus decreases friction, significantly. It is shown that the lubricity behavior of a lubricant and additive can be influenced by the direction of motion used in the test method.

1. Introduction

The most common set of test methods used in the lubricant test labs consist of ball-on-disk, high frequency reciprocating rig, four ball test and block on ring. Although these test methods do not simulate the field conditions however it can be used for screening of novel lubricants and additives for the field test. Field tests are expensive compared to the lab test. Therefore, a good use of lab scale screening test of lubricants is important to reduce the cost of lubricant product development. However, it is not clear how these test methods influence the friction and wear behavior of lubricants. For example the ball-on-disk (rotation) test an reciprocating test due to can produce different results due to difference in its motion type [1–3]. Although the common knowledge is that these test methods could yield different lubrication mechanism however there are no relevant literatures with a systematic study. Therefore, it is important to look into the role of type of motion in the lubrication mechanism.

Engine lubricants are important in reducing the friction and improving the fuel economy [4]. Main ingredient in a lubricant is the base oil (semisynthetic or mineral) which is produced from the depleting crude oil reserves. Moreover, there are two environmental issues associated with using a mineral oil based lubricants, (1) disposal of these lubricants is dangerous for the aquatic life [5], (2) possible health hazards from the particulate matters consisting of metal nanoparticles released during the combustion [6,7]. Therefore, a general consensus is to reduce the use of mineral base oils and look for an alternative, for example the biodegradable lubricants. Biodegradable lubricants derived from the vegetable oils have shown better lubrication behavior than mineral based oils [8]. And, aqueous glycerol solution can reduce the friction by a fold compared to the lubricants derived from the vegetable oil [9]. Glycerol is a byproduct from biodiesel production and it is abundantly available at low cost. However, glycerol has a poor wear resistant property because of its shorter hydrocarbon chains [9].

Nanoparticles from metals, metal oxides, nanocomposites, sulfides and carbon based materials are used as additives to improve the friction and wear resistant behavior of lubricants [10]. Carbon based additive

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like nanodiamond is particularly interesting because of its properties like biocompatibility, high thermal conductivity, hardness and the ease of surface modification [11]. Use of nanodiamonds in the commercially available oils have improved the friction and wear resistance of steel surfaces [12]. Such behavior can be attributed to any of the following mechanism induced by adding nanodiamonds, that is, ball bearing, micro-polishing and improved hardness by embedding into the surface [11–13]. We consider that nanodiamond additive could be a potential candidate to further improve the friction and wear resistant behavior of glycerol.

In this study, we have used the high frequency reciprocating rig and ball-on-disk rotary test method to measure the friction coefficient of aqueous glycerol with and without nanodiamond particles. Optical microscopy is used to scan the ball and disk wear tracks in the post test analysis. The friction coefficient, ball wear scar diameter and surface topography is used to determine the role of reciprocation and rotary type testing methods in lubrication by aqueous glycerol and nanodiamond additive.

2. Materials and methods

2.1. Lubricants

Glycerol (99.9% pure, Sigma Aldrich, Germany) was diluted in demi water to have a final concentration of 10% w/w of water. This mixture is called as aqueous glycerol.

Polycrystalline synthetic diamonds (99.5% pure DP micron diamond powder, Microdiamant GmbH, Germany) was mixed in aqueous glycerol to have a final concentration of 0.1% w/w of aqueous glycerol. The hydrodynamic diameter of polycrystalline diamonds in ultrapure water was measured using the dynamic light scattering technique (Zeta sizer nano system, Malvern Instruments Ltd., United Kingdom). The diameter of the diamonds was 125 nm (spectra not shown in the results). Hereafter, these polycrystalline synthetic diamonds are addressed as nanodiamonds or ND.

2.2. Friction coefficient measurements

Friction coefficient of the lubricants was determined using the ball-on-disk instrument (TR 20, Ducom Instruments Pvt. Ltd., India) and the high frequency reciprocating rig or HFRR instrument (TR-282, Ducom Instruments Pvt. Ltd., India). Friction force was measured by a button type load cell and a piezo transducer in ball-on-disk and HFRR, respectively. The data acquisition and analysis was through a labview based Winducom 2010 software (Ducom Instruments Pvt. Ltd., India). The ball and disk are made of steel grade EN 52100. The ball diameter was fixed at 6 mm. The disk used in ball-on-disk and HFRR was of diameter 60 mm and 10 mm, respectively. As shown in the Fig. 1 the operating parameters were kept the same for both the test methods, that is, contact pressure was fixed at 0.7 GPa, sliding velocity at 100 mm/s, humidity at 45% RH, lubricant temperature at 60 °C and the volume of the lubricant was 2 mL. The operating parameters complied with the diesel lubricity test standard ISO 12156-1: 2006. The sample preparation and cleaning was also in accordance with this ISO standard. The only difference between the ball-on-disk and HFRR was the relative motion that can reproduce different lubrication mechanism. The relative motion in the case of ball-on-disk was rotary (see Fig. 1a) and for HFRR it was reciprocation at 1 mm stroke length (see Fig. 1b). Hereafter, we address the ball-on-disk as rotary test and HFRR as reciprocation test. Note: All the friction measurements were repeated for three times.

2.3. Wear analysis

Two-dimensional images of the wear track on ball and disk surfaces were captured using an optical microscope (Olympus Vanox-T, Leica Microsystems B.V., Netherlands). All the samples were cleaned according to the standard ISO 12156-1: 2006 before imaging the wear track. The mean wear scar diameter (MWSD) on the ball was calculated by the Eq. (1),

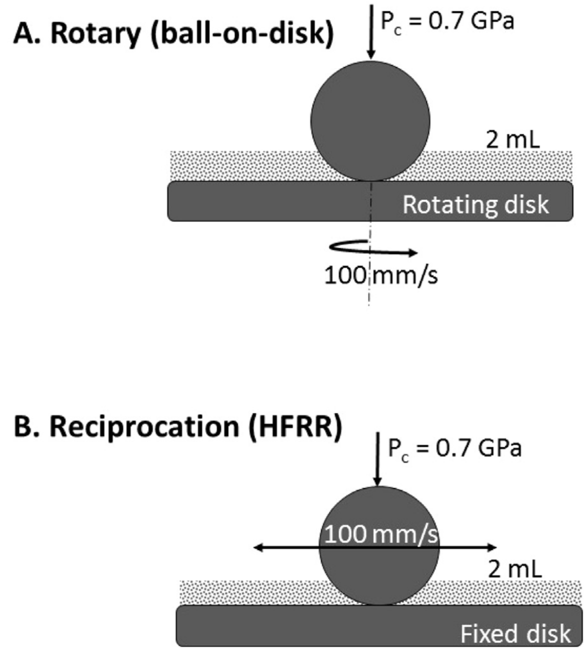

Fig. 1. Schematics that represent the similarity in operating variables and difference in the relative motion. A. rotary type ball-on-disk test method and. B. reciprocating type high frequency reciprocating rig (HFRR).

$$\text{MWSD} = (x + y)/2 \tag{1}$$

where x is the scar dimension perpendicular to the oscillation direction (in µm) and y is the scar dimension parallel to the oscillation direction (in µm).

2.4. Statistical analysis

The friction coefficient and MWSD of aqueous glycerol and aqueous glycerol with 0.1% w ND was compared pairwise using the student *t*-test. Similar comparison was made for the results from the rotary and reciprocation test method.

3. Results

Fig. 2 represents the friction profiles and average friction coefficient values for rotary and reciprocation test methods. As shown in Fig. 2a, for the aqueous glycerol the run-in friction coefficient during the reciprocation is a factor of 5 higher compared with the rotary test. After the run-in, there is a stable friction coefficient established during the reciprocation. In the case of rotary test, after run-in the friction coefficient drops by a factor of 100 and it reaches below 0.01. Later the friction coefficient increases and it represents an unstable and chaotic profile. As shown in Fig. 2b, for the aqueous glycerol with 0.1% w ND the friction profile during the reciprocation is unstable because the friction decreases over an increase in the sliding distance. During the rotary test the friction coefficient is lower than the reciprocation test and it reaches a stable zone after 250 m of sliding. The friction coefficient is below 0.0 l and its profile is chaotic.

Error bars represent the standard deviation over three independent measurements of friction coefficient. * Statistically significant ($p < 0.05$, student *t*-test) differences between the rotary and reciprocation test method. # Statistically significant ($p < 0.05$, student *t*-test) differences between the aqueous glycerol and aqueous glycerol