Tribological properties of self-mated SUS304 lubricated by palm methyl ester mixed lubricant at boundary lubrication

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Abstract. Due to environment and sustainability issues, it is important to reduce the use of petroleum based products in automotive and industrial application. One of the efforts is to use bio oils as base oil for lubricants. This paper presents the experimental results on the effects of palm methyl ester mixing in a conventional lubricant on the friction and wear characteristics of stainless steel SUS304. The friction tests were conducted using a ball-on-disk tribometer at boundary lubrication condition. Three kind of lubricants were prepared, i.e. commercial SAE40, and the mixture of 0.5% and 1% palm methyl ester into SAE40 lubricant. The prepared lubricants were designated as PME0, PME5, and PME10, in reference to 0%, 0.5%, and 1% palm methyl ester mixture in the SAE40 oil. Results shows that the addition of palm methyl ester in the lubricant has reduced the value of coefficient of friction from 0.7 to 0.55 with the addition of 1% palm methyl ester in the base lubricant. As for the wear, 10% reduction of the wear scar was achieved at the condition of PME10 compared to that at PME0. One of possible explanation for this reduction is the formation of oxidative layer on the contact interface due to the existence of the methyl ester in the lubricant. This result indicates the positive impact of the palm methyl ester as additive for enhancing the performance of conventional lubricant thus requiring further analysis and investigation.

1. Introduction

Automotive and industrial machineries have been heavily relying on petroleum based products in their operation, causing pollution and environment health hazards. Lubricants, among others, vital to those machines in maintaining good and reliable operation, have also caused serious problems to environments due enormous amount of waste products, especially when not properly disposed. Therefore, it becomes very important to reduce the use of petroleum based products and replace them with a more environmentally friendly ones. Here, bio-based oils have received significant attentions, particularly due to their exhibiting good lubricity comparable to mineral and synthetic oils suitable for various engineering applications [1].

Bio oils have many advantages to be developed for base lubricants due to their low toxicity and biodegradability [2], ability to provide low wear and friction characteristics [3] and improved surface* To whom any correspondence should be addressed.
finished [4]. Although they have low thermal and oxidative stability, their properties can be improved chemically by transesterification [4]. Natural triglycerides in bio oils could promote the formation of protective layer on the contact interface and provide anti wear characteristic to the mineral based oils [5]. Inclusion of 5% modified soybean oil in hexadecane-based oil has improved the wear up to 50% [6]. The viscosity index of mineral-based lubricant also increased by addition of 5% palm methyl esters [7]. Castor oil methyl ester can also enhance the lubricity due to its unique fatty acid content [8].

Significant reduction in wear and friction can be achieved by mixing bio oils derived ester with mineral based oils without additional conventional additives [9]. Trimethylolpropane and pentaerythritol ester derived from palm oil match the properties of a full formulated lubricants in terms of friction coefficient [10]. Addition of 3% palm oil based trimethylolpropane in an ordinary lubricant resulted in wear scar diameter reduction up to 30% in boundary lubrication condition [11].

In this research, palm methyl ester were mixed with mineral lubricant to find out its effect on the friction and wear characteristics of stainless steel SUS304. Previously, it is reported that palm methyl ester has an ability to form a protective tribolayer on the contact interface of SUS304 [12]. Thus, in this investigation, the palm methyl ester has been applied as an additive to the base lubricant to find out its effect on the lubricant properties.

2. Methodology

Severe lubrication condition in a mechanical system occurs during heavy loading condition at low sliding speed. In this condition, the interaction between contact interfaces mainly occur among the contacting asperities in which viscosity of lubricant has less important role. Therefore, in order to simulate the severe contact condition between the contact interface, a ball on disk tribometer was used in this investigation. A ball on disk contact interaction provides a high pressure contact in a concentrated location and enables the evaluation of the material wear characteristic in a severe contact condition.

![Figure 1 Ball on disk tribometer](image)

The schematic diagram of the ball-on-disk tribometer is given in Figure 1. The tribometer consists of a ball and disk holder, a DC motor, gravitational normal loading cantilever beam, and the motor control system. The ball specimen has a diameter of 8 mm and the thickness of 4 mm. A load cell is installed to record the friction force as the friction took place, which is connected to a strain amplifier and a personal computer installed with a data acquisition software. The lubricant chamber was installed to soak the contact between the disk and the ball. A heater system was installed in the
lubricant chamber to control the temperature of the lubricant. The heater system is controlled independently.

The operating parameter of the friction tests conducted in this investigation is given in Table 1. The friction tests were conducted with the spindle revolution of 100 rpm. During the friction tests, the sliding track has a diameter of 21 mm, resulting in the sliding velocity of 0.0628 m/s. The friction tests were conducted for a sliding distance of 700 m. The friction tests were conducted in ambient room temperature of 27°C. Dead weight of 15 N were given during the test, which resulted in a 15 N normal load.

The friction tests were conducted in three lubricant conditions, as given in Table 2. A commercial lubricant, which has a specification of SAE40, was mixed with various concentration of palm methyl ester, i.e. 0%, 0.5%, and 1%. The mixture were prepared by hand shaking using a bottle container. The prepared lubricants are assigned as PME0, PME5, and PME10 for respective concentration of 0%, 0.5%, and 1% palm methyl ester. The material of the ball and disk specimens are stainless steel SUS304. The properties of SUS304 is given in Table 3. To obtain a relatively similar initial contact roughness at friction test, the contact surface of all specimens were hand rubbed using sandpaper grid #1000.

### Table 1. Operating conditions

| Parameter, unit | Value |
|-----------------|-------|
| Spindle rev, rpm | 200   |
| Sliding distance, m | 1700  |
| Normal load, N | 15    |
| Temperature, °C | Ambient, 27 |

### Table 2. Test conditions

| Ball | Disk | Lubricant + %PME |
|------|------|------------------|
| SUS304 | SUS304 | PME0 - SAE40 + 0% |
| SUS304 | SUS304 | PME5 - SAE40 + 0.5% |
| SUS304 | SUS304 | PME10 - SAE40 + 1% |

### Table 3. Properties of SUS304

| Parameter | Value |
|-----------|-------|
| Young’s Modulus, MPa | 200 GPa |
| Hardness, Vickers | 200 |
| Chemical composition, % | <0.08% C, 17.5-20% Cr, 8-11% Ni, <2% Mn, <1% Si, <0.045% P, 0.03% S |

The properties of the palm methyl ester is given in Figure 2. Palm methyl ester has a viscosity of 4.415 mm²/s at 40 °C which is much lower than that of the commercial lubricant used. Since the volume fraction of the methyl ester added is very small, it is expected to have a negligible effect to the viscosity of the base lubricant. Thus, the properties modification of the mixed lubricant is expected to be caused by the incorporation of elements and component of the methyl ester, given in Figure 2, i.e. methyl palmitate, oleic acid, and methyl stearate. Palm methyl ester also contain oxygen and glycerol as side product.
3. Results and Discussion

3.1. Effect of palm methyl ester addition in lubricant on the coefficient of friction (CoF)

Figure 3 shows the coefficient of friction for various test conditions with different concentration of palm methyl ester in the lubricant. As it is mentioned previously, the contact condition is severe indicated by high contact pressure on the contact interface. In this tests, the diameter of the ball of 8 mm and the normal load of 15 N have resulted in initial contact pressure of 1.2 GPa (Hertzian).

It is shown in Figure 3, high contact pressure has resulted in a relatively high coefficient of friction for all lubrication conditions. The average CoF for the three contact conditions are 0.7, 0.65, and 0.55 for PME0, PME5, and PME10, respectively. This CoF value were achieve for a sliding distance of 600 m. This relatively high value of coefficient of friction indicated that the friction condition was in boundary regime for all test condition. In boundary regime, the contact is dominated by solid friction in which contact interaction occurs among the contact asperities and the viscosity of the lubricant is less important. However, the main role of the lubricant in this boundary regime condition is to form a protective layer (tribofilm) that protects the material from severe wear.

Figure 3. Infrared spectrogram of the palm methyl ester

Figure 3 also indicated that the addition of palm methyl ester in the lubricant has reduced the value of CoF although not significantly. The coefficient of friction reduced from 0.7 to 0.55 with addition of 1% palm methyl ester in the base lubricant, i.e about 10% reduction. This indicates the positive impact of the palm methyl ester on the contact interface, i.e. the palm methyl ester had form some protective layer that reduces the friction. Theoretically, this could occur due to increased lubricity as a result of protective layer formation [13, 14]. Palm methyl ester has an ability to form such a protective layer particularly on stainless steel material SUS304 [12].

This finding is also comparable to that reported by [11] in which the CoF reduced from 0.13 to 0.115 with the addition of 1% palm methyl ester to base oil in the case of using four ball tribometer test and cast iron as the friction material. In that case, the lubricant used has a viscosity of 101.86 cSt, which was relatively similar to the viscosity of the lubricant used in current investigation. The difference of the friction coefficients achieved here compared to those in ref. [11] could be attributed to the difference in the material and contact pressure used.
3.2. Effect of palm methyl addition in base lubricant on material wear

Figure 4 shows the wear of the ball and the corresponding disk for the case of PME0 condition. Figure 4(a) is the 3D micrograph the word track on the disk shown in Figure 4(b) while Figure 4(c) is the 3D micrograph the word track on the ball shown in Figure 4(d). The diameter of worn cross section width of the ball is about 890 µm, which is well correspond to that on the disk side. As it is shown in the figure, severe wear of the material occurred both on the disk (Fig. 4(a) and (b)) and the ball (Fig. 4(c) and (d)). Surface morphology of the disk (Fig 4(a)) indicated plastic deformation on the disk side and transferred material on the ball side (Fig. 4(c)). Plastic deformation and transferred material occurred presumably due to relatively soft material of SUS304.

The contact interface of the disk is quite clear although some small noticeable black spot area existed. Commonly, blackish area on the contact interface occurs due to formation of graphite layer consist of carbon or due to oxidation. In the case of SUS304 material, a relatively small amount of carbon in the material makes it not preferable for graphite formation. Thus, the formation of graphite is not likely in this case. On the other hand, oxidation is also not likely occurring in this case due to the absence of oxygen. Therefore, a relatively clear contact interface in this case could be resulted by the contact condition with small amount of carbon and the absence of oxygen. High contact pressure applied to the contact asperities caused deformation and adherence to each other. Continues sliding of the ball on the disk caused some material of the disk adhered to the ball. Extreme pressure continuously occurring on the ball could also cause high temperature and plastic deformation on the ball contact interface.

The worn morphology of the material for the case of PME5 is shown in Figure 5. With the addition of 0.5% of PME in the base lubricant, the worn cross section area of the ball is about 850 µm, which is also well corresponded to the width of the worn track on the disk. Severe wear condition was also observed at this condition but with less transferred material on the ball contact interface. Ploughing and material removal seemed occurring on both the ball and disc contact interface. Only small effect of 0.5% palm methyl ester addition on the worn area on the ball and the disc compared to the case without palm methyl ester addition. The worn cross section width of the ball decreased from 880 µm to 850 µm. As it is shown for the coefficient of friction, the decrease was also not quite significant, which is from 0.7 to 0.65 in the average.
Figure 4. Contact interfaces of the disk; (a) and (b), and the ball; (c) and (d) for PME0 condition

Figure 5. Contact interfaces of the ball; (a) and (b), and the disk; (c) and (d) for PME5 condition

However, the wear scar of the disk appears darker with the presence of 0.5% palm methyl ester on the base lubricant. This could be caused by the oxidation assisted by the oxygen content in the palm methyl ester, which has a chemical formulae of R3-COOCH3. The oxidation process could also be promoted by local high temperature at contact asperity during the friction due to high contact pressure. Darker contact interface could also indicate the formation of tribofilm on the contact interface due to a tribo-chemical reaction. However, this has not been clarified yet and further analysis using surface characterization equipment is necessary to investigate the tribofilm formation.

Figure 6 shows the topography of contact interface of friction condition of PME10, i.e. 1% palm methyl ester mixed in base lubricant. In this case, the worn cross sectional width of the ball is about
800 µm, which is well correspond to the width of the worn track on the disk. The wear condition on the ball in this case is quite similar to that of PME0. Material removal on the ball occurred as well as plastic deformation on the disk side and the wear properties still indicate severe wear of the material. However, the width of the worn cross section of the ball is 10% smaller than that in the case of PME0. This also well correspond to 10% reduction of the CoF in the case of PME0 compared to PME10, which is 0.7 compared to 0.55. This, somewhat, shows the positive effect of palm methyl addition to the base lubricant on the wear of stainless steel material, particularly SUS304.

The contact interface of the disk indicates darker area across the worn track. Similar to the case of PME5, this indicates the presence of oxidative layer on the contact interface promoted by the palm methyl ester. It has been reported in ref [11] that palm methyl ester added lubricant produced a black-coloured contact interface, especially at high temperature. This is due to oxidation of the lubricant at higher temperature, producing corrosive acids, thus promoting corrosive wear [15].

The formation of this blackish layer has some positive effects on the tribological performance of the contact pair because the layer can act as a sacrificial layer which is removed at friction continues [16]. The formation of lubricating film on the contact interface can also be accelerated with the presence of inorganic acid such as Fe3O4 and Fe3O4 form due to oxygen existence [17].

Therefore, the reduction of CoF and the improvement of wear on the material in this investigation could be related to the formation of some oxidative layer, indicated by the presence of dark layer on the contact interface. In this case, the source of oxygen is the palm methyl ester. Thus, a hypothesis that can be proposed is that the addition of small amount of palm methyl ester to the base lubricant could accelerate the formation of oxidative layer acting as a lubrication film on the contact interface. Therefore, the properties of base lubricant could be enhanced by adding a small amount of palm methyl ester, in this case 1%. Nevertheless, the existence of such oxidative layer must be clarified further using surface characterization method.

![Figure 6. Contact interfaces of the ball; (a) and (b), and the disk; (c) and (d) for PME10 condition](image)

In this investigation, the maximum addition of palm methyl ester used is 1%. Further addition of palm methyl ester on the base lubricant could either give better or worse effect on the lubricity at the contact interface. As reported in [11], an optimum number of palm methyl ester is 3% to 5%. However, at 3% addition, surface delamination of the contact interface occurred.

This investigation has not taken into account the effect of temperature in the friction test. As it has been mentioned before, temperature effect is important because it may affect the oxidation rate at contact interface thus affecting the properties and behaviour of the oxidative layer formation. This effect needs to be clarified in the future.
4. Conclusion
The investigation on the effect palm methyl ester addition on a base lubricant on friction and wear behaviour of stainless steel SUS304 has been conducted. The results shows that palm methyl ester addition to the base lubricant has reduced both the friction and wear scar dimension of the contact material by 10% with 1% concentration of the methyl ester in the base lubricant. Although the real cause of this friction and wear reduction is still not clarified, it is hypothesized that the reduction is attributed to the existence of oxidative layer on the contact interface indicated by darker contact interface in the case of palm methyl added lubricant. While the existence and the properties of this oxidative layer needs to be investigated further, it has been shown that palm methyl ester is potential to be applied as bio-additive to enhance the performance of a mineral based lubricant, thus requires further investigation and analysis.

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