AN ALTERNATIVE LUBRICANT: THE POTENTIAL OF DOUBLE FRACTIONATED PALM OLEIN AS A LUBRICANT FOR ENHANCED TRIBOLOGICAL BEHAVIOUR USING A PIN-ON-DISK TRIBO-TESTER

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ABSTRACT

The tribological behaviour of aluminium was evaluated through the processes of rubbing an SKD 11 counter under lubricated conditions using material alloy A5083 and a pin-on-disk tribotester. The wear rates and coefficient of friction of A5083 were found to increase with an applied load. When the wear rates and coefficient of friction of the sliding surface are at different sliding speeds, the wear rates and coefficient of friction will increase. Based on the results, double fractionated palm olein (DFPO) has a lower coefficient of friction compared to hydraulic oil and engine oil-SAE 40. However, DFPO showed a small wear scar diameter compared to the mineral-based oil. These differences in tribological behaviour seem to be affected by the material properties, which are responsible for the differences in tensile strength or hardness and load. The results of this study are deemed useful for material selection, besides providing insights into the understanding of the relationship among friction, wear and lubrication. The results presented herein may facilitate improvements in the future.

Keywords: double fractionated palm olein (DFPO), pin-on-disk, coefficient of friction, wear rate, load.

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INTRODUCTION

In recent years, aluminum has been widely used as one of the tribological components for various machines. There are many type of aluminum which are used for practical purposes. Although the wear resistance of metals is generally higher in proportion to hardness, there is some doubt on whether the wear resistance of aluminum alloys with different chemical composition and processing methods can be estimated only by their hardness. Generally, fatigue fracture of surface asperities occur from the wear and coefficient of friction in well lubricated conditions. Fatigue crack growth and wear for aluminum alloys are closely related to one another. Therefore, the wear behaviour of aluminum alloys may be affected by material characteristics similar to their fatigue test results. Generally, contact pressure and friction coefficient depends on amount of lubricant and a constant forming load during steady-state condition. This means that the forming load is increased as the sliding distance decrease.

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Lubrication is very important for industrial application in view of its popular usage in transportation, and machinery. Lubricant is used to reduce the friction between two moving surfaces or metal-to-metal contact. It can also improve the efficiency of machine or engine as it protects them against wear and corrosion, hence maximising their lifespan (Duzcukoglu and Sahin, 2010; Imran *et al.,* 2013; Quinchia *et al.,* 2014). When lubricants are applied between the contacts interfaces between two surfaces, material loss due to wear and energy consumption due to friction are reduced by several orders of magnitude. According to Michael *et al.* (2006), developing lubricants that could be used in engineering system without replenishment is very important as a way to increase functional lifetime of mechanical component. The conventional lubricant, which is known as lubricating oil in industry can cause serious pollution to our environment and intensify the greenhouse effect. When two metal surfaces are in contact, the amount of the asperities and interaction within the contact area will be increased thereby causing frictions which incur motion wear of the metal parts and generate excessive heat. Surfaces in contact with relative motion will produce friction, which produces unwanted heat and leads to material wear. It is laborious to prevent damage of this kind; there are many ways to minimise this undesirable wear and one amongst them is by exploitation of lubrication (Syahrullail *et al.,* 2005; 2011; Golshokouh *et al.,* 2013). Wear and friction are dependent on the amount of load, speed (Chowdhury *et al*., 2011), temperature (Al-Araji and Sarhan, 2011), surface roughness (Terumasa Hisakado *et al.,* 2000; Sedlacek *et al.,* 2009) and type of material or mating component (Bressan *et al*., 2008).

Joseph *et al.* (2005) highlighted that there is a need for novice researchers to have the knowledge on reaction between material and fluid which present between two moving surfaces. The lubricant is expected to have lower shear strength than that of the materials of the contact surfaces. It is also able to resist the loading of the parts in contact. Lubricant film under boundary lubrication condition plays the main role in construction of film layer and controlling of wear behaviour. Perez *et al.* (2005) discovered that sliding speed and the amount of load applied can affect tribological characteristic. Therefore, a great deal of research has been conducted with the aim to yield significant experimental results using better lubricant with suitable parameters.

With the rapid growth of modern technologies, attributing to the technology development in automotive industry and manufacturing several issues, with respect to the use of mineral oil resources have been raised. Even though mineral oil possesses the best oil characteristics especially for engineering application, as non-biodegradable substance, it will be a threat to the environment (Bartz, 1998). Mineral oil also contains a very high level of toxicity and it is absolutely impossible to dispose of it (Sevim *et al.,* 2006). The remaining base stock mineral oil remains a problem as a very long period is needed for the drawback of the resources restoration. So far, however, there has been little discussion about palm oil as lubricating oil in mechanical applications. The advantages of choosing vegetable oil rather than lubricants from other sources are the fact that they are biodegradable and are less toxic when compared to petroleum-based oil (Chiong Ing *et al.,* 2012). They are easy to produce from a renewable source. In addition, when Kalin and Vizintin (2006) investigated the tribological behaviour of the two moving metals using biodegradable oil compared to mineral oil, they showed that the vegetable oils possess even a better lubricating ability than the current mineral or synthetic oils because they contain a large amount of unsaturated and polar ester groups components that favourably affected the conditions during reciprocating sliding (Kalin and Vizintin, 2006). Furthermore, the long-chain fatty acids present in vegetable oil have better intrinsic boundary lubricant properties. Vegetable oils show good lubricating abilities because they give rise to the low coefficients of friction. However, many researchers report that even when the coefficient of friction is low with vegetable oil as the boundary lubricant, the wear rate is high.

Thus, the fundamental aim of this article is to evaluate the wear rate and friction coefficient of aluminum alloy under the variables of different sliding speed and lubricants using a pin-on-disk tribo-tester under the condition of different load. The results demonstrated that double fractionated palm olein (DFPO) has lower coefficient of friction compared to mineral-based with various load applied. The findings of this study will help future researchers to gain more insights into the topic discussed, hence inspiring more research related to tribological behaviour of vegetable oil to be conducted in the future.

METHODOLOGY

Before conducting the pin-on-disk experiment, the viscosity experiment was carried out first. The purpose of viscosity experiment is to measure the viscosity of the lubricant used in this experiment. As viscosity of lubricant also has an effect on the wear propagation of the pin, the viscosity of the fluid was used to measure the resistance of the fluid which will be deformed by either shear stress or tensile stress. Generally, in this experiment, viscometer was used as the apparatus to measure the viscosity of lubricant. Theoretically, a pin clamped firmly was attached to hardened jaws specimen holder parallel to the plain disc to ensure that the pin and disc were attached to the maximum contact surface. Then, parameters such as speed (rpm) and time were set up.

Pin-on-disk tribo-tester was conducted through continuous lubrication flow during test in accordance with ASTM G99 standard testing which describes Standard Test Method for Wear Testing. Based on the Standard, pin and disk were cleaned with acetone before the test to remove foreign objects on the surface that will scratch the surface and ultimately affect the results. The tribological system was tested on spherical pin via pin-on-disk machine with a diameter of 6 mm and a height of 30 mm as well as a disk with a diameter of 165 mm and a height of 10 mm. Material for both samples used in the contact pair was made of aluminum alloy (A5083) while the disk is made of SKD 11. The test was run at a room temperature of 27± 2°C. In the tests, the disc was rotated according to sliding speed and the test was carried out for 1 hr (3600 s) with the normal load based on ASTM G 99-95a for each test. The friction coefficient was recorded via a PLC (Programmable Logic Controller) with data. The values of friction coefficient were determined by the ratio between friction load and applied normal load.

After the experiment, the surface roughness was measured to analyse the effect of the lubricant. After the experiment, the picture of the pin surface which has made a direct contact with the disk was captured with a high and low resolution of microscope for observation. After each test was carried out, plain disk was polished using abrasive paper, 1000 μ to grind the surface because each test must be repeated for three times to get an accurate result. To measure the surface roughness of the pin and disk, the surface roughness profile was used to determine the pattern for both specimen surfaces which consist of a stylus protector.

Lubricants

The lubricants used in this experiment were hydraulic oil and engine oil SAE 40. DFPO, or super olein is a softer type of olein obtained through fractionation of the standard olein, in order to achieve the maximum fluidity. The main characteristics of DFPO are slip melting point 13ºC-17ºC, iodine value 60-68 and solid fat content 0%-26% at 10ºC. Its major fatty acids are palmitic acid (35%), oleic acid (45%) and linoleic acid (13%). Different manufacturers set their own limits within the above ranges. DFPO is used for bottling, as it remains fully liquid in both tropical and temperate if it is blended with sufficient seed oil. Its great advantage compared to vast majority of seed oils is its much greater resistance to oxidation.

Friction and Wear Evaluation

The friction coefficient was recorded using a PLC throughout the experimental process. The experiment was conducted several times to ensure the results were stable and acceptable. The coefficient of friction was calculated using Equation (1), where μ represents a coefficient of friction, F is a frictional force and N is a normal force.

$$\mu = \frac{F}{N} \tag{1}$$

The wear rate in this experiment was calculated using Equation (2). The volume loss of the pin was measured with a digital balance before and after conducting the experiment. At the same time, the volume loss of the pin was calculated to verify the measurement data.

$$\text{Wear rate} = \frac{\text{Volume loss}}{\text{Load x sliding distance}} (\text{nm}^3/\text{N.nm}) \tag{2}$$

After the experiment, the wear scar which had developed on the pin was inspected using a high resolution microscope. First, the diameter of the wear scar was measured. Then, the surface roughness of the wear scar was measured using the surface profiler in order to predict the condition of the lubrication.

RESULTS AND DISCUSSION

As shown in *Table 1*, the viscosity of both lubricants decreases as the temperature of the lubricants increases. *Table 2* illustrates the experimental condition during testing.

Effect of load on Friction Coefficient

Figure 1 shows the graph of the coefficient of friction (COF) with respect to the sliding speeds of three different lubricants. During the experiment, three different load amounts, *i.e.* 10 N, 50 N and 100 N, were used. From *Figure 1*, it is obvious that the trend line for each graph of a different load has shown an increase in COF values at the initial stage with the increasing sliding speed. These results strongly suggested that the COF value is inversely proportional to the sliding speed.

For a load of 10 N, the highest COF value for a pin lubricated with hydraulic oil (HO) was recorded as 0.08286 at a sliding speed of 5 ms^{-1} (1060 rpm). In contrast, the lowest COF value was 0.0254 for a pin lubricated with DFPO at the same sliding speed. Meanwhile, for a load of 50 N, the highest COF value for a pin lubricated with engine oil-SAE 40 was recorded as 0.06016 at a higher sliding speed

TABLE 1. VISCOSITY FOR BOTH TYPES OF LUBRICANT TESTED AT DIFFERENT TEMPERATURE

Lubricant	Double fraction palm oil	Hydraulic oil	Engine oil
Iodine value	66.4	-	-
Melting point (°C)	12	-	-
Cloud point (°C)	2.2	-	-
Flash point (°C)	232	179	265
Pour point (°C)	+9.0	-30	-6
Specific density, 25°C (kg m^{-3})	872.5	872	860
Dynamic viscosity (40°C)	37.9	58.4	110
Dynamic viscosity (100°C)	16.4	10.2	17.8
Viscosity index (VI)	443	164	96

TABLE 2. EXPERIMENTAL CONDITIONS

Load	10 N, 50 N and 100 N
Rotational speed	300, 600, 800, 900, 1000 rpm
Sliding speed	1,2,3,4,5 ms^{-1}
Lubricant	Double fractionated palm olein, hydraulic oil, and engine oil-SAE 40
Oil flow	60 min
Temperature	27°C
Material of pin and disk	Aluminum alloy (A5083) and SKD 11

and the lowest COF value for HO was 0.02076. The result was affected by the different load amounts that were applied during this experiment. Then, for a load of 100 N, the trend line suggests that the highest COF value was achieved by DFPO at 0.04104 and at a sliding speed of 5 ms^{-1} (1060 rpm), while the lowest value of 0.008538 was recorded by a pin lubricated with HO.

Different types of lubricants, namely HO, DFPO and engine oil-SAE 40, have their own lubricant performances. For a load of 10 N, the COF value displayed by DFPO was relatively lower in comparison with other types of lubricants, while for a load of 50 N, the upward slope was found somewhere in between the trend lines of the other two lubricants, suggesting the values are in the middle range. The increase in load has caused a rise in friction due to the contact between the pin and disk. Furthermore, when the pin and disk are attached to each other, heat will be generated and the effects on the surface are thus obvious. However, with a lubricant, the friction and heat can be avoided. As the DFPO lubricant is a pure palm oil, there are no additives to provide anti-friction and anti-wear properties compared to HO and engine oil-SAE 40. For lubricants, such as HO and engine oil-SAE 40, sparks might be produced if only a small amount of lubricant is applied and thus, the heat will lead to an increase in the temperature. The results showed that the frictional force was negatively correlated with the sliding speed for a load of 10 N. The gradual increase might be due to the reason that a layer of the lubricant still remained within the two contact parts. In fact, palm olein has a balanced composition of saturated and unsaturated fatty acids (which are mainly composed of unsaturated fatty acid, triglyceride and non-glyceride); it will stick very well on a metal surface and create a lubricant layer accordingly. The composition of palm olein will also help to reduce metal-to-metal contact between a pin and a disk and thus reduce the COF value accordingly. Furthermore, *Figures 2* and *3* have demonstrated a low COF with an increasing load and sliding speed due to changes in the shear rate. These findings are in parallel with the findings of Chowdhury *et al.* (2011) for aluminium, in general, for surface-comprising moisture, the oxidation of metals and so on.

In this experiment, HO was used as a reference, as the purpose of this study is to compare the wear and friction characteristics between palm oil and mineral oil. According to Madakson (1982), the effect of surface oxidation and a lubricant is more significant with a lighter load, in which more lubricant will be forced into the sliding interface, which will then result in a lifting of the slider to give rise to the reduction in metallic contact as the sliding speed increases. This statement is further confirmed by the finding of Chowdhury *et al.* (2011). As is known, an increase in the load applied will

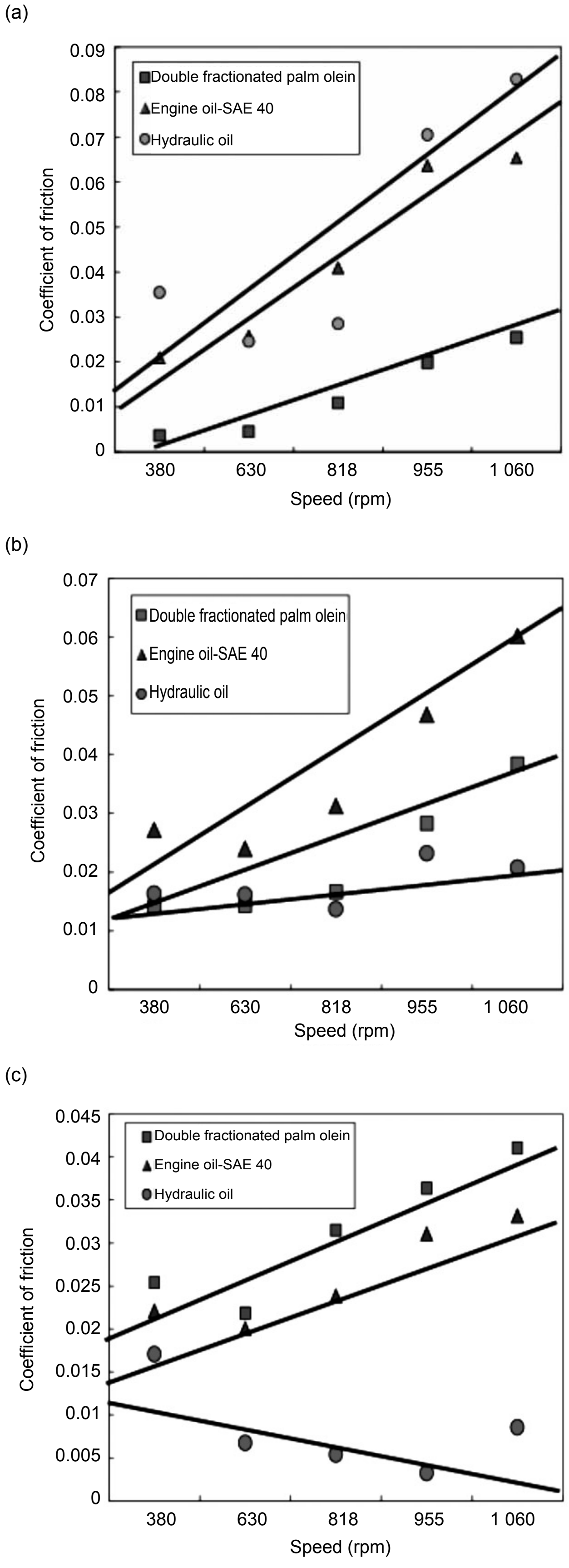

Figure 1. Variation coefficient of friction with different loads: (a) 10 N, (b) 50 N and (c) 100.

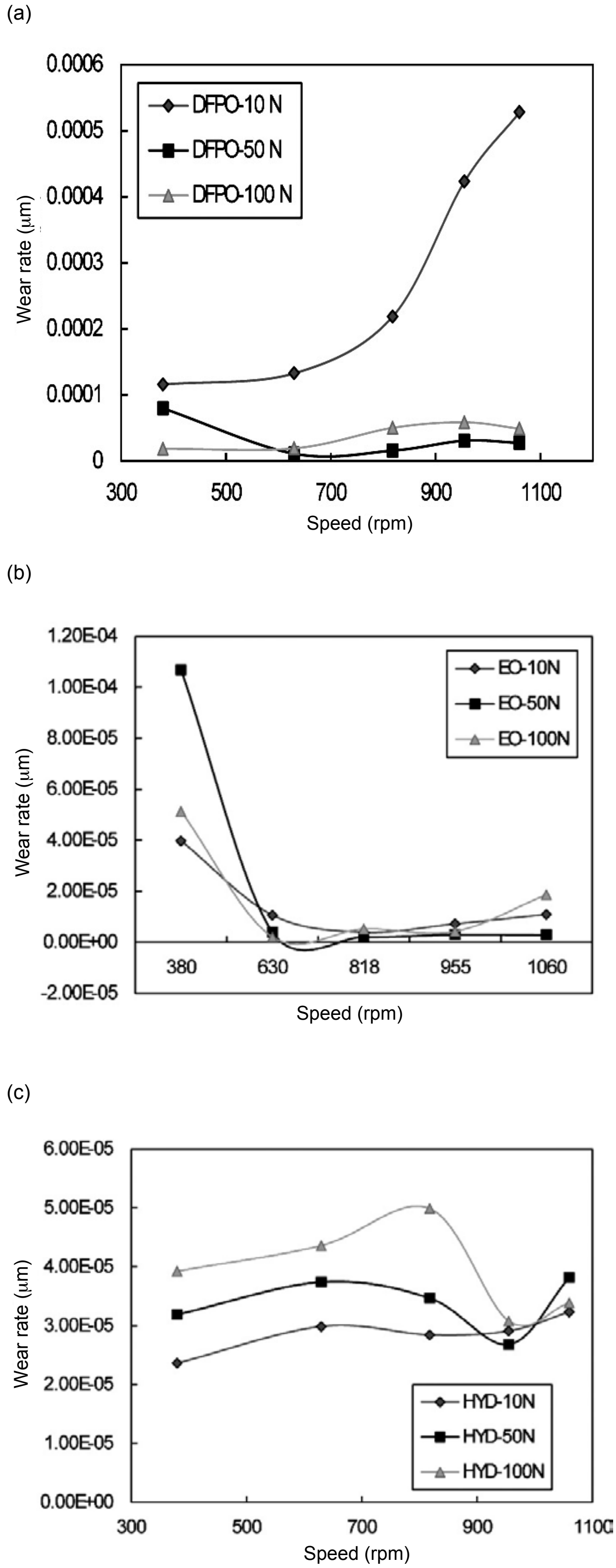

Figure 2. Correlation of volume rate of different tested lubricants and loads.

generate frictional heat between contact surfaces, hence reducing the strength of the material. In this experiment, when velocity was increased, the momentum transferred in the normal direction was increased as well. Therefore, an upward force was produced on the upper surface, which then resulted in an increased separation between the two surfaces. Real areas of contact between the pin and disk will decrease as the separation between the two surfaces has increased. The low COF obtained was mainly influenced by lubricating oil, which was protecting the surface of mating components. The stability of the COF of palm oil when tested proved that palm oil has a stabilising ability and it can reduce the COF by forming a lubricating film that can be easily sheared. The excellent lubricating characteristic of the COF for a hemispherical pin condition is at a high load, specifically for palm oil.

Effect of Load on Volume Rate

A volume rate analysis (wear rate) was used to analyse the wear progression of the pin. In this study, the volume rate of an aluminium alloy pin (A5083) lubricant with different types of lubricants and loads was analysed. The volume rate for each lubricant, with respect to different sliding speeds and loads, was determined in 1 hr in accordance with the ASTM G99 (American Society for Testing and Materials) experiment standard. For each type of lubricant, the experiment was repeated three times to justify and determine the repeatability of the data produced by the pin-on-disk machine. The volume loss of the pin was directly proportional to the wear scar diameter (WSD) of the pin and it was computed with the following formula obtained from the ASTM G99 standard test procedures.

$$\text{Volume loss} = \frac{\pi\,(\text{wear scar diameter, mm})^4}{64\,(\text{sphere radius, mm})} \qquad (3)$$

For a pin lubricated with engine oil-SAE 40, the highest volume rate value was 0.0001068 at a sliding speed of 1 ms^{-1} (381 rpm) and with a load of 50 N. Meanwhile, the lowest volume rate value was 0.000003922 at a sliding speed of 3 ms^{-1} (818 rpm) and with a load of 10 N. For a pin lubricated with HO, the trend line indicates a slight increase in the volume rate values as the sliding speed increases. The highest volume rate value was 0.0000499 at a sliding speed of 3 ms^{-1} (818 rpm) and with a load of 100 N. Meanwhile, the lowest volume rate value was 0.0000268 at a sliding speed of 4 ms^{-1} (955 rpm) and with a load of 50 N. There is a slight decrease in the wear rate for the three different load amounts at a sliding speed of 4 ms^{-1} (955 rpm). For all the lubricants, the volume rate will decrease if the duration of rubbing is long and if the COF reduces. In other words, a ploughing effect and the inclusion

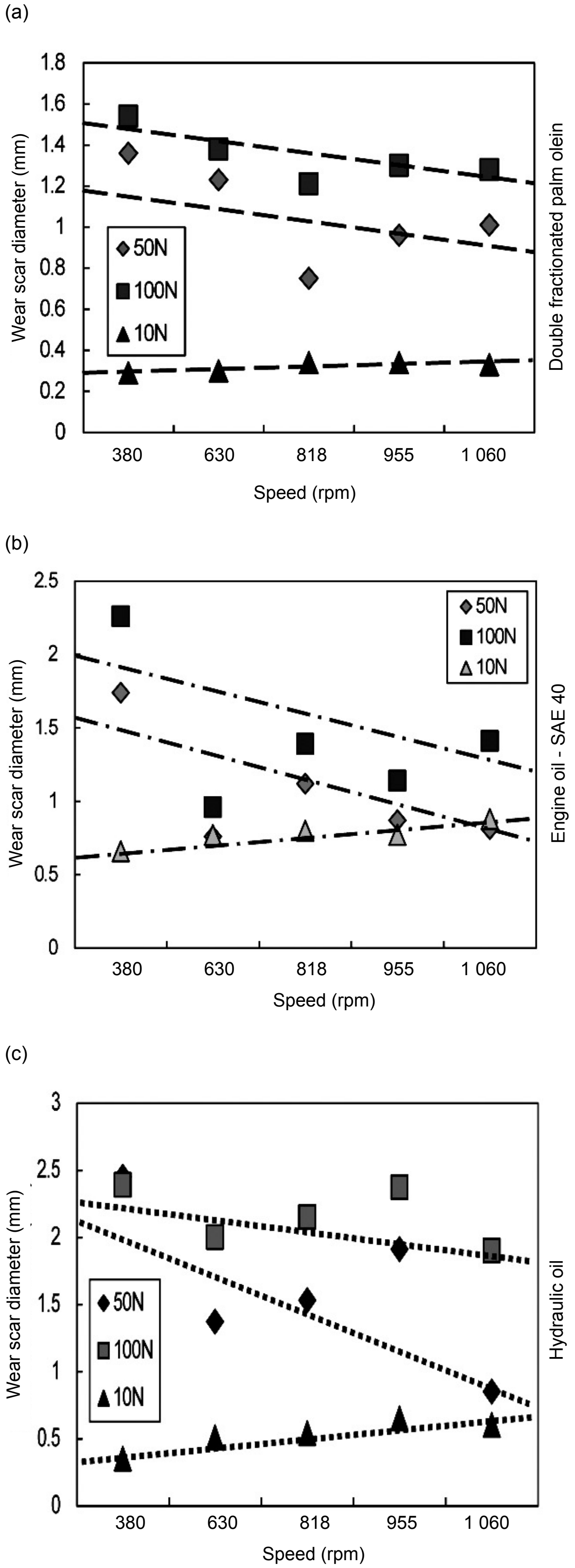

Figure 3. Variation of wear scar diameter of different tested lubricants and loads.

of wear debris will affect the wear rate. There is strong evidence that a decrease in the volume rate is due to a lubricant in the hydrodynamic regions, which separates fluid films when it is rubbed against mechanisms. As can be seen from the graph for DFPO, the wear rate increases as the sliding speed increases. The reason is that the duration of rubbing is the same as the sliding speed and the length of the rubbing process is increased. Meanwhile, for engine oil-SAE and HO, there was a drop in the volume loss, which may be attributed to an increase in the hardness of the material.

The results will complement the WSD results and further explain the relationship between wear and sliding speed. A good lubricant is expected to reduce and minimise the volume loss of a material. Metal is always covered by an oxide film that is very thin and invisible. This film prevents true contact between metals and hinders severe wear. In the experiment, the lowest value of the loss of material volume was recorded for the pin lubricated by DFPO with a load of 50 N, instead of 10 N or 100 N. Initially, when the pin has started rubbing the plain disk, it will ruin the surface layers and create a high effectiveness of the shear strength. Regarding lubricant thickness, DFPO, which is thicker than other lubricants, will increase the shear rates. The volume rate will decrease if the duration of rubbing is long and if the COF also decreases.

The graph for a pin lubricated with DFPO indicates that the composition of the palm oil itself, *i.e.* consisting of palmitic acid, helps to reduce the WSD. Masjuki and Maleque (2000) explained that due to this lack of stability, a molecular layer that is created by the unsaturated fatty acid will develop due to the temperature of the lubricating oil. Oxidation caused by fatty acids in vegetable oil (palmitic) might cause a chemical reaction that could oxide the lubricant oil. This statement was supported by Amurugam and Sriram (2012), who demonstrated that the presence of a long-chain fatty acid produces a hydrocarbon layer that protects the wearing surface.

Perrin and Rainforth (1997) discovered that damage is caused by the wear rate pressure acting in relation to the subsurface depth. The application of a resistant force to the pin as it was touching the disk was one of the factors causing wear. The finding in this experiment also supports the results of this experimental study in which at the highest sliding speed, the wear rate decreased because, as the COF greatly increases, the height of the pin touching the rotating disks will be affected. Another explanation is that the wear rate increased at a high velocity due to the increased temperature of the lubricant, which was caused by the heat that was generated from the rubbing action. The increasing lubricant temperature has an effect on the stability of the thin film layers, as it will make it easy for them to breakdown.

Furthermore, an increase in the volume rate of the pin was due to the heavy load that was applied on it and to an increase in the sliding speed. An increasing load has also led to an increase in wear, which will accordingly increase the volume loss of the metal due to the impact between the pin and disk. The factors of increasing loads, pressures and high temperatures during the sliding process have facilitated the collision of the different variations of hard asperities between the pin and disk. As the load was increased from 10 N to 100 N, the increased pressure produced during sliding accelerated the formation of adhesive wear, as the oxide layer did not fully protect the surfaces, attributing to the shearing of more junctions at the interface. As the adhesion forces during sliding were high, the shear of the asperities took place at the weakest point, resulting in a detachment of the fragments of the pin surfaces and an attachment to the disk surface.

WEAR SCAR DIAMETER

The WSD is the diameter of the rubbed surface that is affected by wear during sliding contact between the aluminium alloy pin and the SKD 11 disk. The study focused on the WSD of the aluminium alloys, as it was used to compute wear volume loss. Generally, there was a proportional relationship between wear volume loss, which is calculated from the WSD, and wear rate. A WSD analysis was carried out using a CCD microscope, after the experiment was conducted for 1 hr in accordance with the ASTM G99 standard. The entire aluminium alloy pin, which was lubricated with three different types of lubricants, was measured using 3X magnification under a CCD microscope.

Figure 4 shows the graph of WSD against sliding speed. For all the experiments, the WSD was found to be directly proportional to the sliding speed. DFPO, with a load of 100 N, has shown the highest WSD value, followed by the loads of 50 N and 10 N. As for engine oil-SAE 40, the highest WSD value was for the pin with an applied load of 100 N, while the lowest value was recorded with a load of 10 N. On the other hand, with a load of 100 N, HO yielded the highest WSD value, while the lowest WSD value was recorded when the applied load was 10 N and 50 N, respectively. The three oils have yielded similar results, as seen in the graph in *Figures 5* and *6*. Through observation, it was found that the use of engine oil-SAE 40 has resulted in lower WSD values on average if all sliding speeds were taken into account.

The trend of the graph reflected the findings gathered from the observation of wear scar micrographs of the pin lubricated with three different types of lubricants at different sliding speeds.

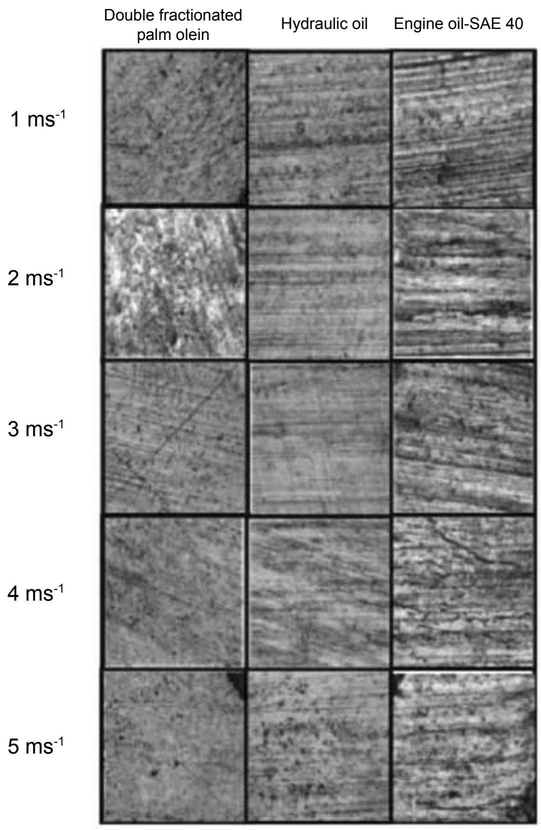

Figure 4. Wear scar surface picture of three different tested lubricants (high resolution) for different speeds: (a) 1 ms^{-1} , (b) 2 ms^{-1}, (c) 3 ms^{-1}, (d) 4 ms^{-1} and (e) 5 ms^{-1} at load 10 N.

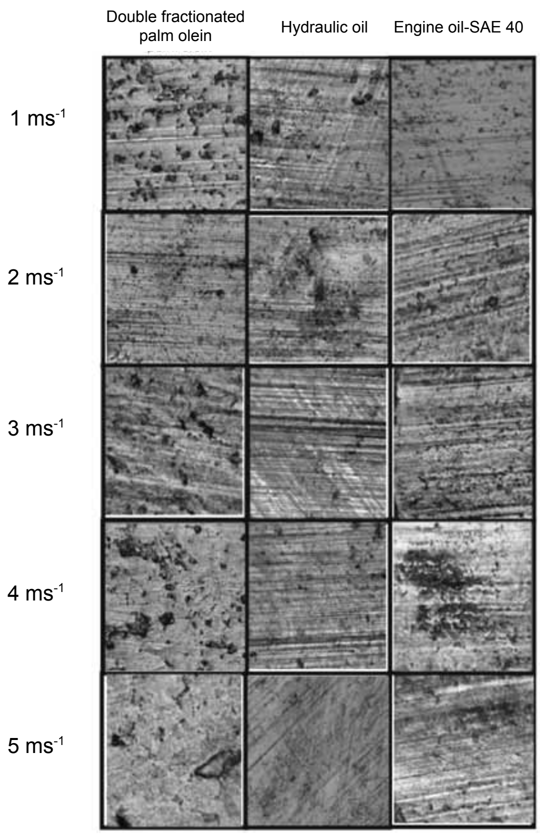

Figure 5. Wear scar surface picture of three different tested lubricants (high resolution) for different speeds: (a) 1 ms^{-1}, (b) 2 ms^{-1}, (c) 3 ms^{-1}, (d) 4 ms^{-1} and (e) 5 ms^{-1} at load 50 N.

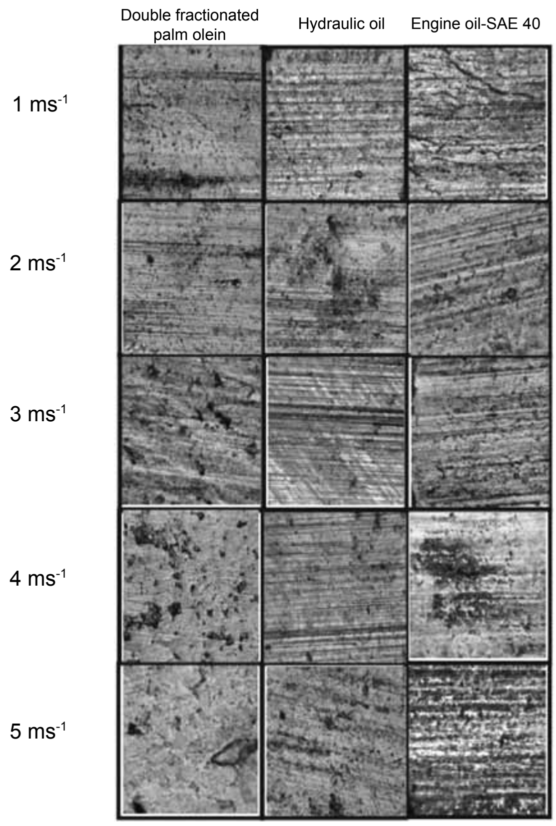

Figure 6. Wear scar surface picture of three different tested lubricants (high resolution) for different speeds: (a) 1 ms^{-1}, (b) 2 ms^{-1}, (c) 3 ms^{-1}, (d) 4 ms^{-1} and (e) 5 ms^{-1} at load 100 N.

CONCLUSION

It can be concluded that the COF value for DFPO is lower compared to that for HO and engine oil-SAE 40 with an increase in sliding speed, depending on the load applied. In addition, from the wear rate values, it was obvious that a positive correlation exists between the load and the pin loss because of the impact of the load applied to the pin when the sliding speed was increased. This study implies that DFPO is the better lubricating oil due to its viscosity compared to HO, as the palm oil helps to reduce the wear rate and friction. The findings have thus provided insights into palm olein commercialisation in the engineering industry.

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