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Tribological investigation of RBD palm olein in different sliding speeds using pin-on-disk tribotester

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Abstract. A tribological investigation, in terms of the coefficient of friction and wear resistance of refined, bleached and deodorized palm olein, was conducted using a pin-on-disk tribotester. Palm oil was selected as a candidate due to its superior tribological properties and its large production, which can lead to the mass production of bio-lubricant. The material of the pin and the disk is Titanium (Ti6Al4V). The experiments were conducted following the ASTM G99. The normal load was 9.8 N and the observation time was 1 hour. The sliding speeds were 0.25 m/s and 1 m/s. In this research, only 5 ml of the test lubricant was applied at the beginning of the experiment to investigate the capability of the lubricant to maintain its function. To make sure the lubricant does not subside due to the centrifugal force from the rotating disk; a groove was crafted on the disk. In this research, the coefficient of friction and wear rate were calculated. From the analyses, the coefficient of friction calculated for palm olein was the lowest for both sliding speed conditions, while the wear rate obtained showed that it was efficient lubricating oil at low speed, with a high wear rate at high speed.

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1. Introduction

Nowadays, tribological analysis is one of the most important mechanical fields in the industry. The tribological properties of two contact surfaces of engines and machines generally depend on factors such as load, speed, temperature, sliding time, lubricant and additive formulation [1]. In addition to these, the reactions and the fluid present between the two moving surfaces also need to be understood by the researcher in order to understand the effects on friction and wear. As the engines and machines continuously run and the operating condition becomes more severe, more problems are faced by the mating components, especially due to the damage caused by wear and frictional force. In order to overcome this kind of problem, lubricant was selected as an alternative candidate to reduce wear and the frictional force of two contact surfaces, so that the system can operate for an extended time period. Industrial production faces different types of severe wear and friction, mostly by operating machines and engines, and by the presence of improved lubrication attributing to the reduction of wear and friction problems [2].

With the advancement of technology, industries nowadays are constantly searching for more efficient ways of designing products that help reduce wear. Due to the condition of the planet, now affected by the greenhouse effect and climate changes, there is more pressure for industries to use non-biodegradable oil as lubricants in machines and engines. Due to the increase in environmental and health issues, industries

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are making moves to eliminate or reduce the consumption of non-biodegradable lubricants. There is a growing awareness of the use of vegetable oil as an alternative lubricant for machines due to its technical, environmental and strategic advantages. Vegetable oils do not pollute the environment, unlike fossil fuels that emit carbon monoxide, carbon dioxide, SO_x, NO_x and particulate when combusted [3]. Vegetable oils and animal fats have been used as lubricants since 1650 B.C. Animal tallow was used in Egypt as a lubricant for chariot wheels and is one of the earliest vegetables oil/animal fats recorded [4]. Due to growing environmental concerns, vegetable oils are potential lubricants for industrial and transportation applications. Vegetable oils, also known as environmentally friendly lubricants, were selected due to several advantages: high biodegradability, excellent oxidative stability, good low temperature properties and low cost [5].

Recently, palm oil has been widely used in industrial applications for engines and machines. Palm oil is an extremely multipurpose product which has traditionally been used in foodstuffs and non-food items. At the turn of the century, it was chosen as a new renewable energy source, due to the rise of mineral oil prices and the challenges of climate change and the greenhouse effect. Malaysia is one of the world's largest producers of palm oil, and with the global request for palm oil expected to grow in the future, it offers the most hopeful economic scenario for the country [6]. In 2004-2006, palm oil was selected as the most popular product in world production, due its cheap cost and environmentally friendly characteristics. Also, the yields of selected vegetable oils and palm oil produce almost 4.2 tons per hectare per year [7].

The main material used for this experiment is titanium alloy for both the disk and pin. Titanium alloy is widely used in several industrial applications such as in aircraft engines, the petroleum industry and for biomedical parts. In biomedical parts, titanium alloy was used as the material for implants due to its high strength to weight ratio at elevated temperatures. Besides this criterion, corrosion resistance is an extremely vital factor in titanium selection as this condition is influenced by temperature and humidity in experiments. In this paper, palm olein is developed to be used as a bio-lubricant in human bone-joint implants. To simulate the real implant, a pin and disk made by titanium alloy were used and the sliding simulation was conducted using a pin-on-disk tribotester.

To study the wear of the materials, researchers simulate the process of wear in a controlled manner and study the effects on different samples under the same test conditions by performing a pin on disk test. The wear test configuration used a flat-end pin against a flat rotating disk. A flat end has some natural advantages: it is easier to machine and easier to coat if the wear testing of coatings is required [8]. For this reason, flat-end pins were used in perhaps the majority of pin on disk tests. The volume was considered to calculate the wear rate of the material.

2. Experimental method

2.1. Apparatus

In the present investigation, a pin-on-disk tribotester was used to study both wear and the coefficient of friction. The pin-on-disk test is commonly used in comparative tests, in which controlled wear is performed on the samples to be studied. The volume loss allows calculation of the wear rate of the material. A pin was clamped firmly against a rotating disk linked to a certain dead weight with a beam and two pulleys. The lubricating oil was placed on the surface of the grooved disk. A Linear Voltage Differential transformer (LVDT) sensor plays an important role in reading wear rate. The grooved disk needs to be cleaned with acetone before the experiment. Surface roughness was recorded according to the parameter set up by the researcher. Figure 1 shows a schematic sketch of the grooved-disk and the dimensions of the pin used in the experiment.

3. Materials and lubricants

The study of wear and friction behavior was performed using a flat-ended pin made from titanium (Ti6Al4V). Pin samples were prepared as 8 mm in diameter and 30 mm in length. The density of titanium is 4.54

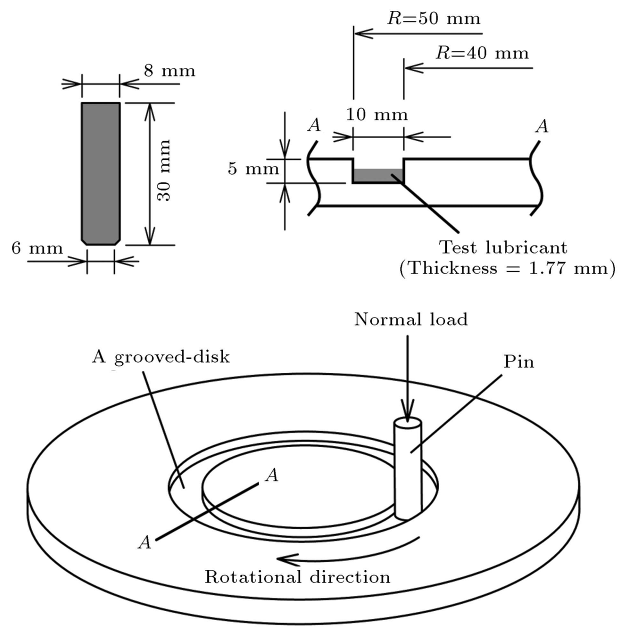

Figure 1. Schematic sketch of the grooved-disk and pin.

Table 1. Viscosity of RBD palm olein, hydraulic oil and paraffinic mineral oil.

Lubricant	PO	HO	PMO	Test method
Specific density at 25°C	0.873	0.872	0.860	ASTM D1298-85 (90)
Melting point (°C)	20	-50	-12	Manufacturer data sheet
Dynamic viscosity at 40°C (mPa s)	38.9	57.1	37.2	ASTM D445-94
Dynamic viscosity at 100°C (mPa s)	5.3	10.5	7.1	ASTM D445-94

PO: RBD palm olein; HO: Hydraulic oil; PMO: Paraffinic mineral oil.

g/cm^3. The average Vickers hardness value for a pin was 200 Hv. A grooved disk of titanium was fabricated, as shown in Figure 1. The width of the groove was 10 mm and the depth was 5 mm. The groove design would prevent the test lubricant from centrifuging away while rotating. The average Vickers hardness value for the disk was 335 Hv. Upon the completion of each test, sandpaper, with a grain size of an abrasive material of 1000 μm, was used to grind the grooved bottom surface until it met the specification (0.4 $\pm$ 0.1 μm). The surface roughness of the disk was measured using a surface profiler, which consisted of a stylus detector to determine the pattern of the disk and the pin surface. RBD palm olein, hydraulic oil and additive-free paraffinic mineral oil were used as lubricants with the same amount of oil, which was 5 ml. The amount of test lubricant was limited to 5 ml to give close simulation of the lubrication conditions inside a human implant. The density and kinematic viscosity of three types of lubricant were measured using a viscometer, at 40°C and 100°C, as shown in Table 1.

4. Experimental methodology

Lubricated friction and sliding wear testing were carried out on a conventional pin-on-disk tribotester. A flat-on-flat test arrangement was used in the present set of experiments. Both the surface of the pins and disk were made parallel to ensure their maximum contact. The principle of sliding was of a cantilever loaded pin against a horizontal rotating grooved disk lubricated with the test lubricant. All the tests were carried out at room temperature, which is around 32°C. The melting point for RBD palm olein is around 20°C. In this experiment, the normal load applied was set at 9.8 N, and the sliding speeds were set at 0.25 m/s and 1 m/s. The mass of the pin was weighed before and after each test and the weight losses were recorded. At the same time, the surface roughness, Ra, of the grooved disk and pin were also measured before and after the experiment.

5. Wear and friction evaluation

The frictional force between the pin and rotating disk during the test was measured using a load cell attached to the side of the pin-holding lever arm, and the values were shown promptly in a digital display. The coefficient of friction was calculated simply by dividing the frictional force value with corresponding axial load (normal load), as shown in Eq. (1):

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

where, μ is coefficient of friction, F is friction force and N is normal load.

The coefficient of friction would become the best dimensionless parameter to show the capability of a lubricant in reducing friction. An LVDT sensor directly connected to a display monitor detected the wear rate of the pin in unit micrometers per second. The greater the value, the more material of the pin would have been scribed away by the rotating disk.

6. Weight loss evaluation

Wear rate was calculated based on the pin volume loss obtained during the experiment, according to Eq. (2), relative to cumulative loss volume per unit sliding [9]:

$$Q = \frac{\Delta V}{s}, \tag{2}$$

where Q is wear rate in mm^3/m, ΔV is volume loss and s is sliding distance. The pins were firstly weighed using an electronic balance with an accuracy of 0.1 mg. Each pin was measured three times to obtain an average value and to reduce the impact of possible measurement error in the calculation. The weights of the pin were recorded before and after the experiment.

7. Surface finished measurement

Before the beginning of individual tests, the disk and pin surfaces were cleaned with acetone to confirm that there were no additional particles on the surfaces. The surfaces of the pin and disk were unidirectionally ground using abrasive paper to a surface finish of a roughness value, Ra, of about 0.4 $\pm$ 0.1 μm, using a surface profiler, which consisted of a stylus detector to determine the pattern of the disk and pin surface. The surface finish after the experiment was once again measured to analyze the influence of the lubricant used during the experiment.

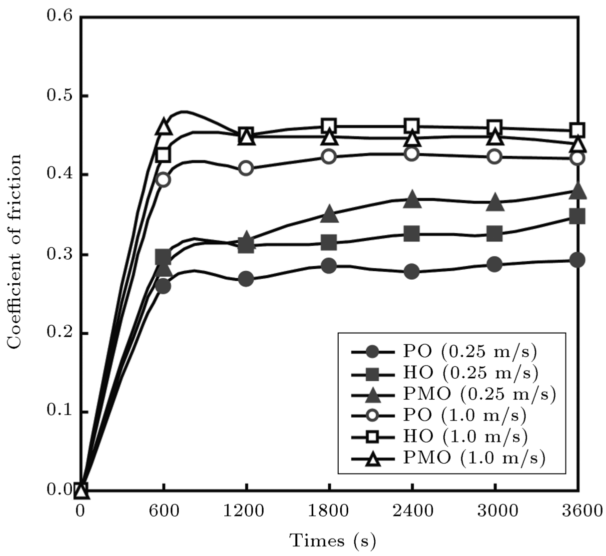

Figure 2. Distribution of coefficient of friction.

8. Results

8.1. Coefficient of friction

To study the antifriction behavior of RBD palm olein, several experiments were conducted using different velocities: 0.25 m/s and 1.0 m/s, with 9.8 N of normal load. The duration of the experiment was 1 hour (3600 seconds). The antifriction behaviors of RBD palm olein (written as PO) were compared with Hydraulic Oil (HO) and additive-free Paraffinic Mineral Oil (PMO).

Figure 2 shows the distribution of the friction coefficient with sliding time at an applied load of 9.8 N for both sliding speeds of 0.25 m/s and 1.0 m/s for the lubricants of RBD palm olein, hydraulic oil and paraffinic mineral oil. All test lubricants showed an increment of coefficient of friction at the early stage, and reached a steady state approximately after 1000 s. From Figure 2, for sliding speed 0.25 m/s (shown in black mark), RBD palm olein created the lowest coefficient of friction (0.28), followed by hydraulic oil (0.35) and paraffinic mineral oil (0.38).

For sliding speed 1.0 m/s (shown by a white mark), all test lubricants showed an increment of coefficient of friction compared to those obtained with sliding speed 0.25 m/s. RBD palm olein showed the lowest coefficient of friction (0.41). However, the difference in the coefficient of friction obtained by hydraulic oil (0.43) and paraffinic mineral (0.42) was not too much compared with those obtained by RBD palm olein.

9. Wear rate

At the beginning of the experiment, the flat-ended pin was clamped firmly and touched onto the grooved surface, and set as zero micron. As the groove-disk rotated, the contact between the pin surface and the disk created wear and produced wear material. Gradually, the wear value became greater. The greater value of wear means more material of the pin has been galled away. The maximum value of wear at the end of each experiment was recorded and plotted as Figure 3. For all experiment conditions, the wear value increased from the beginning to the end of the experiments.

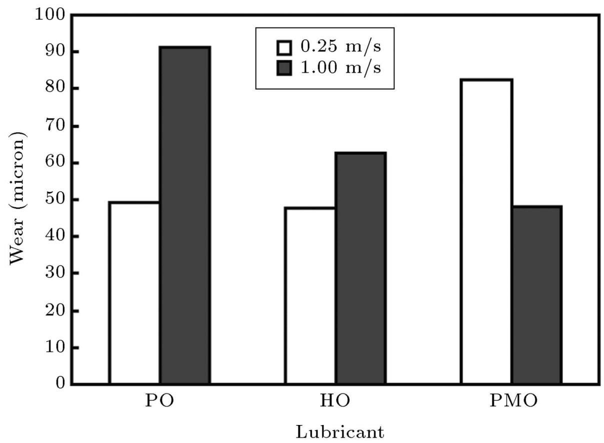

Figure 3. Mutual comparison of the wear at steady state condition ($t = 3600$ s).

For low sliding speed (0.25 m/s) (marked with a white bar) RBD palm olein and hydraulic oil showed a low wear value of about 50 microns. Paraffinic mineral oil showed the highest wear value at around 84 microns. For high sliding speed (1.0 m/s) (marked with a black bar graph) RBD palm olein showed a contrasting result that gave it the highest wear value of around 91 microns, followed by hydraulic oil and paraffinic mineral oil. Comparing the results from low and high sliding speeds, hydraulic oil showed the most stable result, while the wear value showed not much difference.

A more concrete method to calculate the wear rate is using the ratio of the mass loss of the pin relative to the sliding distance, as introduced by Bressan et al. [9], and as shown in Eq. (2). To achieve this, the mass of the pin before and after the experiment was weighed and recorded, as shown in Table 2. The result showed almost a similar pattern with the wear value, as shown in Figure 3, in which RBD palm olein gave the lowest wear rate at low sliding speed, but the highest wear rate at high sliding speed.

10. Surface roughness and worn surface characteristics

The Vickers hardness for both the pin and disk were measured after the experiments. There was slight increment in the hardness value for the pin (205 Hv) and disk (339 Hv). However, the hardness change was neglected in this analysis.

Before the experiment, the pin and groove-disk

Table 2. Mutual comparison of the weight loss and wear rate.

Lubricant	Sliding speed 0.25 m/s		Sliding speed 1.0 m/s	
	Weight loss ($\times 10^{-4}$ g)	Wear rate, Q ($\times 10^{-6}$ mm^3/m)	Weight loss ($\times 10^{-4}$ g)	Wear rate, Q ($\times 10^{-6}$ mm^3/m)
RBD palm olein	6	14.6	48	29.4
Hydraulic oil	10	24.4	27	15.5
Paraffinic mineral oil	29	71.0	17	10.4

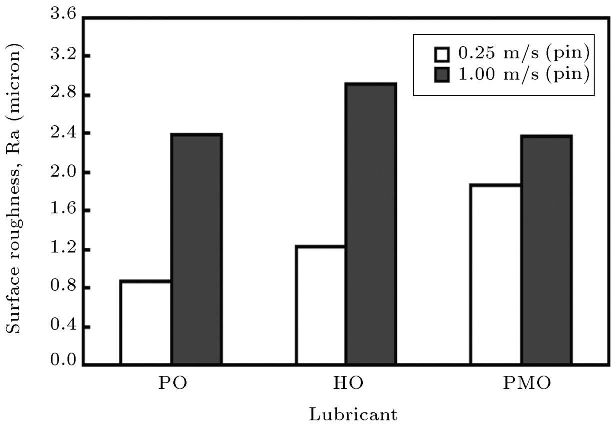

Figure 4. Mutual comparison of the pin surface roughness after the experiment.

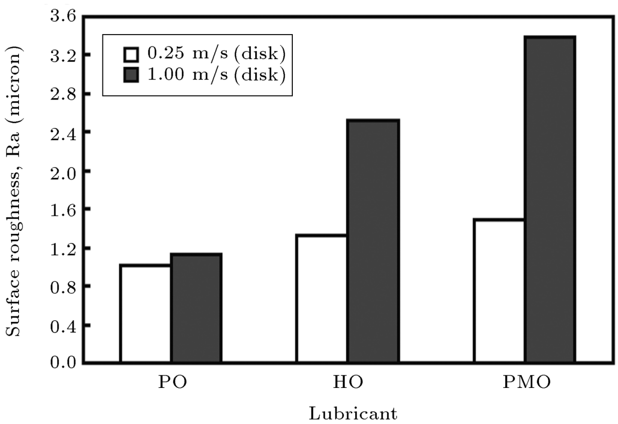

Figure 5. Mutual comparison of the groove surface roughness after the experiment.

surface were polished with an abrasive paper until they had a surface roughness, Ra,, of about 0.4 ± 0.1 μm. After the experiment, the surface roughness, Ra, for both the pin and groove surface, was measured. From the data, surface roughness, Ra, for the pin and groove were compared mutually, as shown in Figures 4 and 5, respectively.

In Figure 4, the pin surface became coarser after the experiment for both low (white bar graph) and high (black bar graph) sliding speeds compared to the surface roughness, Ra, before the experiment (0.4 ± 0.1 μm). At low sliding speed, RBD palm olein showed the finest surface roughness, about 0.866 microns, followed by hydraulic oil and paraffinic mineral oil. However, for high sliding speed, all lubricants produced a coarser pin surface, between 2.4 and 2.9 microns. No significant difference of surface roughness due to the lubricant used could be concluded.

In Figure 5, all test lubricants showed an increment in groove surface roughness compared to the condition before the experiment. The experiment conducted using RBD palm olein produced the lowest surface roughness, Ra, of the groove surface, followed by the hydraulic oil and paraffinic mineral oil. However, only RBD palm olein showed a similar value of surface roughness of the groove surface for both low (white bar graph) and high (black bar graph) sliding speeds.

From this comparison, RBD palm olein is shown to be the best in maintaining the surface finish of the rubbing material. A detailed discussion of the surface finish is described in the discussion section later.

11. Worn scar characteristic

The CCD pictures of the wear worn surface of the pin obtained after one hour tests, lubricated with RBD palm olein, hydraulic oil and paraffinic mineral oil, under test speeds of 0.25 m/s and 1.0 m/s, are exhibited in Figure 6. All lubrication conditions showed the rough surface of the pin, except the pin lubricated with RBD palm olein, which showed a slightly smooth surface when operating at the speed of 0.25 m/s.

12. Discussion

From Figure 2, the coefficient of friction for three types of lubricant: RBD palm olein, hydraulic oil and paraffinic mineral oil, increased as the increment of sliding time increased. The lowest value of friction coefficient was the one lubricated with RBD palm olein. It was predicted from the presence of a long chain of fatty acids in RBD palm olein, such as oleic and palmitic acids. RBD palm olein contains mostly 50-70% palmitic acid, $C_{15}H_{31}COOH$. It means that RBD palm olein contains a long covalently bonded hydrocarbon chain, which plays an important role in reducing the coefficient. The presence of long hydrocarbon in the lubricants used in between mating

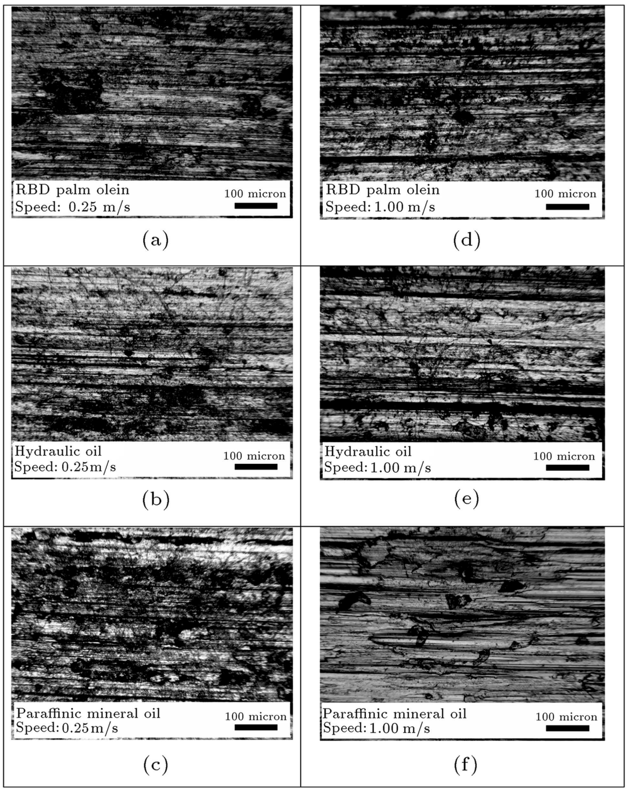

Figure 6. CCD pictures of the worn surface of the pin specimens.

components will produce a layer acting as a barrier between the surfaces directly [1,2]. Hydrocarbon plays an important role in resisting the lubricating oil, thus, preserving the surface of the mating components.

From Figure 2, it was clearly observed that as the sliding speed increases, the coefficient of friction also increases for all lubricants. This only took place under mixed lubrication conditions. This was due to the fact that the duration of rubbing was the same for all sliding speeds, while the length of rubbing was more in cases of higher speed. Generally, as the sliding speed of the disk increased, the temperature of the lubricating oil also increased and increased the pressure of the lubricating oil [10,11]. Referring to the Stribeck curve [12,13], even the viscosity was inversely proportional to the temperature of the lubricating oil; with an increased sliding speed, the friction coefficient continued to increase, as exhibited in the figure. The Stribeck curve concludes the function of viscosity, speed and load, and this finding proved that the sliding speed at the interface of the lubricating oil has a more powerful effect on the friction coefficient of the mechanism than the viscosity of the lubricating oil. In a mixed lubrication regime, the friction coefficient also increased due to fluid drag, in which the friction resistance was caused by the fluid, by shearing the lubricating oil at the interface as the sliding speed increased, which also increased the pressure of the lubricating oil. This could be due to frictional heating when the pin slid at a high speed on the disk surface [12]. For some reasons, RBD palm olein still maintained its properties, thus, was able to reduce the friction coefficient compared to the hydraulic oil and paraffinic mineral oil, particularly at low sliding speed. This is because, at high sliding speed, although RBD palm olein had the lowest friction coefficient, there was only a slight difference between them.

The wear of the material is very significant, specifically related to the sliding speed of two mating components. From Figure 5, it clearly shows that as the sliding time increased, the wear rate of the pin also increased. At low speed, 0.25 ms (shown as a white bar in Figure 5), the high wear rate was dominated by the pin lubricated with paraffinic mineral oil, while RBD palm olein and hydraulic oil as the lubricating oil, showed a low steady linear wear rate, and had approximately the same curve at the beginning and at the completion of the experiment. The low wear rate was due to the affinity of the fatty acid in RBD palm olein towards the wear resistance of the titanium pin, as discussed before, which has thicker molecular layers [2] compared to paraffinic mineral oil. A mating component, which was separated by molecular layers, was attributed to reducing the wear generated by the pin, and the thicker the molecule, the better it is. The fatty acid within RBD palm olein has the ability to absorb the chemical composition of RBD palm olein and creates a monolayer film formation and fatty acid. A phenomenon, called soap film, formed between the active end of the fatty acid and the two contacted surfaces [14,15]. Thus, the mating component would be separated by the soap film created and would increase the wear resistance of the titanium pin. While the pin lubricated with hydraulic oil showed a wear resistance as good as RBD palm olein, due to the replenished additive formula to improve its wear resistance, the interface between the additive and the titanium surface lessens the wear obtained. In contrast, the wear rate obtained with the lubrication of RBD palm olein at high speed, 1.0 m/s, was the highest, followed by hydraulic oil and paraffinic mineral oil (shown as a black bar in Figure 3). A possible explanation for this situation could be described as being due to free fatty acids, and because more than 50% of palmitic acid contained in RBD palm olein would have caused the corrosion wear, and, thus, caused the corrosion of the mating surface [1,6]. The application of RBD palm olein as lubricant saw that the temperature increased due to high rotation speed. The increment of lubricating oil temperature caused the molecular layer formed by the fatty acids chain to be less stable, thereby, causing a comparatively higher wear [2]. Also, the metal oxide layer or soap film formed by the fatty acid became thinner and insufficient to preserve metal to metal contact, thus, reducing the wear resistance of the wear sample and rotating disk. The wearing process could be more aggravated by the debris generated, as the oxidative wear would be transported onto the interface of the sliding surface of the mating components to produce body wear and heighten the volume loss in the wear sample as the sliding speed was increased [14]. The wear of the pin lubricated with all three types of lubricant was precisely identical with the weight loss or volume loss recorded before and after the experiment, as shown in the figure and as mentioned earlier. Weight loss is another alternative in estimating the wear rate of the sample, by calculating the wear rate, as shown in Table 2.

As exhibited in Figures 4 and 5, the surface roughness of the pin and disk lubricated with RBD palm olein has a low value of Ra, after an individual test along the experiment. Generally, one could say that RBD palm olein is represented as a protective lubricant which creates an oxide layer to prevent the surface finish from wear damage and enhances the reduction of the friction coefficient [16]. The smoother surface of the wear sample caused a reduction in friction coefficient by upholding more lubricating oil in between the interface of the sliding component, had small variations in asperity height, and thus, less metal to metal contact [17].

From the analysis, the author concludes that the surface roughness obtained by lubricating with palm olein is the lowest compared to HO and PMO. The rougher surfaces or random texture will eventually be attributed to massive amounts of lubricating oil preserving the random texture, hence reducing friction. This proves that the wear debris of the titanium pin could get secured between the sliding surfaces or transferred and stuck to the mated disks, consequently affording much damage to the pin and resulting in adhesive action and enhanced three bodies, which should increase the volume loss in wear. At low speed, the fatty acids of palm oil were trapped adequately on the pin and disk surface, and built a thin layer to sustain the surface, thus, leading to a good surface finish and low wear resistance [15].

From observation of the worn surface of the pin specimens, as shown in Figure 6, all pin surfaces showed uniformly parallel groove with different depths. They resulted from the stiff particle of the wear debris and showed that the abrasive wear was dominant under this condition [18]. There was no material transfer found. A black spot on the surface, visibly observed in Figure 6(b), (c), (d) and (e) occurred due to the oxidation of the surface material. When abrasive wear occurred, the asperities of the pin and the disk were in contact with each other and the collision occurred due to the rotation of the disk. The hill of the asperities collapsed or was plucked off, which made a clean surface. This clean surface reacted with oxygen in the air to create an oxide film layer [19].

For RBD palm olein at speed 0.25 m/s, the surface showed a tiny parallel groove. It showed an abrasive wear; however, at the same time, the polishing wear was predicted [20]. The molecules of fatty acids in RBD palm olein were well absorbed on the metal surface and prevented metal-to-metal contact. As a result, the coefficient of friction and the wear value were the lowest compared to those lubricated with hydraulic oil and paraffinic mineral oil (Figure 2). For paraffinic mineral oil at 0.25 m/s, the surface had a lot of black spots and the coefficient of friction and the wear value were the highest. It showed that a breakdown of lubricant film occurred.

For RBD palm olein at speed 1.0 m/s, due to the increment of the speed, the lubricant temperature increased and lessened the viscosity, as the lubricant film tended to become thinner and, thus, attributed to an increment in wear rate. However, the fatty acids of the RBD palm olein were still effective in preventing severe metal-to-metal contact [21]. As a result, the coefficient of friction for RBD palm olein at speed 1.0 m/s was the lowest compared to other lubrication conditions at the same speed. For hydraulic oil and paraffinic mineral oil, abrasive and polishing wear occurred. As a result, the wear value was the lowest, and the coefficient of friction was in close proximity to the condition using RBD palm olein at 1.0 m/s.

For the specimen lubricated with commercial hydraulic oil, the results showed intermediate performances between those lubricated with RBD palm olein and paraffinic mineral oil. The wear values were not so much different at speeds 0.25 m/s and 1.0 m/s. The additional additive helped hydraulic oil to prevent wear at this range of speed.

13. Conclusion

A tribological study of the behaviour of RBD palm olein using a pin-on-disk tribotester was conducted. A set of results from RBD palm olein was compared with the commercial hydraulic and additive-free paraffinic mineral oil. The findings could be concluded as follows:

1. The coefficient of friction for specimens lubricated with RBD palm olein showed the lowest value compared to hydraulic oil and paraffinic mineral oil at both low speed (0.25 m/s) and high speed (1.0 m/s). The friction coefficient for all lubrication conditions increased as the sliding speed of the disk increased.

2. At low speed of 0.25 m/s, RBD palm olein showed the lowest wear value; however, at high speed of 1.0 m/s, the wear rate obtained was the highest compared with those lubricated with hydraulic oil and paraffinic mineral oil.
3. From observation of the pin surface using a CCD camera, the abrasive wear was dominant for all lubrication conditions. No severe adhesive wear and material transfer were found.

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