

Wear Behavior of Titanium Alloy Lubricated with Palm Olein as Bio-Lubricant Using Pin-On-Disk Tester

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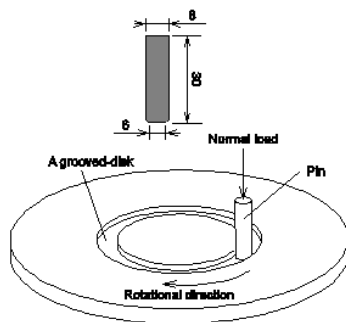
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Graphical abstract



Abstract

The wear mechanism of titanium alloy lubricated with fixed amount of palm olein was investigated using modified pin-on-disk tester. Titanium alloy has high strength-to-weight ratio and excellent mechanical properties such as superb corrosion resistance. This make titanium alloy was chosen for the critical or high temperature/pressure application such as turbine engine parts. Palm oil was chosen for the development of bio-lubricant to replace or minimize the usage mineral oil base lubricant. Palm oil is a vegetable oil which is non-toxic to human and has high decomposition rate. These factors give advantages to palm oil to be produce as an industrial lubricant. The experimental works were performed using a pin-on-disk tribotester, using titanium as the material for both flat ended pin and grooved disk. The test were implemented by dripping 5ml of RBD palm olein as a lubricating oil on the sliding surface at constant speed, which was 0.5m/s using different loads, which were 5N, 20N, 40N and 80N. In this study, the wear rate of the pin and friction coefficient were investigated. The weight loss and surface roughness before and after experiment were analyzed. All the results obtained were compared to commercial hydraulic oil and additive-free paraffinic mineral oil. From the analysis, the friction coefficient acquired with lubrication of RBD palm olein was the lowest compared to commercial hydraulic oil and additive-free paraffinic mineral oil at all loads applied. It could be concluded that RBD palm olein has good lubricity performance and has the capability to be developed as a lubricant.

Keywords: Pin-on-disk; palm oil; palm olein; wear; friction coefficient

Abstrak

Mekanisme haus aloi titanium yang dilincirkan dengan minyak sawit olein dikaji dengan menggunakan mesin tribo pin-atas-cakera yang telah diubah suai. Aloi Titanium mempunyai nisbah kekuatan kepada berat yang tinggi dan sifat-sifat mekanikal yang sangat baik seperti ketahanan kakisan yang luar biasa. Perkara ini menyebabkan aloi titanium dipilih untuk digunakan dalam aplikasi kritikal atau bersuhu/bertekanan tinggi seperti bahagian dalam enjin turbin. Minyak sawit dibangunkan sebagai minyak pelincir mesra alam untuk menggantikan atau mengurangkan penggunaan minyak pelincir berasaskan sumber mineral. Minyak sawit adalah minyak tumbuhan yang tidak bertoksik kepada manusia dan mempunyai kadar penguraian yang tinggi. Faktor-faktor ini memberikan kelebihan kepada minyak sawit untuk dihasilkan sebagai bahan pelincir industri. Ujikaji telah dilakukan dengan menggunakan mesin tribo pin-atas-cakera dengan menggunakan aloi titanium sebagai bahan bagi pin dan cakera beralur. Ujian telah dilakukan oleh menitisikan 5 ml minyak sawit olein di permukaan gelang sar cakera dengan kelajuan tetap 0.5 m/s dengan menggunakan beban yang berbeza iaitu 5 N, 20 N, 40 N dan 80 N. Dalam kajian ini, kadar haus pin dan pekali geseran yang telah dikira. Kehilangan berat pin dan kekasaran permukaan pin sebelum dan selepas ujikaji telah dianalisis. Semua keputusan yang diperolehi dibandingkan dengan minyak hidraulik komersial dan minyak mineral parafin tanpa bahan tambahan. Daripada analisis didapati bahawa pekali geseran pin yang dilincirkan dengan minyak sawit olein adalah yang paling rendah berbanding dengan minyak hidraulik komersial dan minyak mineral parafin untuk semua nilai beban yang dikenakan. Kesimpulannya, minyak sawit olein mempunyai prestasi pelinciran yang baik dan mempunyai keupayaan untuk dibangunkan sebagai pelincir.

Kata kunci: Pin-atas-cakera; minyak sawit olein; haus; pemalar geseran

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1.0 INTRODUCTION

Tribology is a very important mechanical field in industries. There is a need to achieve a better understanding of tribology mechanism of mating components; however, only a limited number of wear and friction revisions about palm oil and other vegetable oils have been stated in the literature. Different investigations had been done in the past for the prediction of wear and friction characteristic. It is generally acknowledged that wear and friction primarily changes with load, speed (Chowdhury *et al.*, 2011), temperature (Nofal *et al.*, 2011), surface roughness (Terumasa *et al.*, 2000; Sedlacek *et al.*, 2009), type of material or mating component (Syahrullail *et al.*, 2011) and environmental.

Wear characteristic complications of operating machines and engines are the main problems faced by industry and it is essential to overcome these problems by searching more alternative ways of designing product prolonging wear. The reduction of high level of wear, friction and surface texture of two contacted surfaces is largely a function of lubrication (Fervel *et al.*, 2003). In the presence of adequate and high quality lubricant, the sliding between two mating components in extended durations in machines and engines will result in low level of wear and friction.

The conventional lubricant, which is petroleum based lubricant, is widely used as lubricating oil. The earth is now threatened by the greenhouse effect and climate change, causing more difficulty in industries to use non-biodegradable oil as lubricants in industry. Conventional oil presents a more or less noticeable risk for the environment or for safety due to some degree of toxicity and the generally high flammability. From the studies, nearly 2.5 billion gallons of conventional lubricants were sold in North America. Only 40 percent were used for mechanism purpose; the remaining lubricants would then be released into the air and passed into rivers, seas and lakes, thus adversely affecting the environment. This caused an increase in awareness among the forestry and agriculture industries in particular along with public citizen and government. The presence of vegetable oil as lubricant is attributed to the decrease of mineral oil application in industries due to its biodegradability (Tiong *et al.*, 2012).

On the positive side, vegetable oils can have excellent lubricity, far superior to that of mineral oil. Vegetable oil is labeled as a renewable fuel as it does not release any extra carbon dioxide and carbon monoxide gas to the atmosphere. Vegetable oils and animal fats have been used as lubricants for a long time 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 (Kraipat and Isarawat, 2006). Vegetable oils, known as environmentally friendly lubricants, were selected due to several advantages: high biodegradability, excellent oxidative stability, good low temperature properties and low cost (Syahrullail *et al.*, 2005; Maleque *et al.*, 2000; Syahrullail *et al.*, 2012).

One of the remarkable vegetable oils observed by the industries and currently has become the main candidate preferred to act as lubricant specifically in engines and machines, is palm oil. Palm oil has the lowest per-unit production costs of all vegetable oils and the extraction process is quite simple compared to other vegetable oils. In the current production of palm oil in the world, Malaysia is one of the countries recognized as one of the largest producers in the world (Masjuki and Maleque, 1996). Malaysian Palm Oil Board (MPOB, previously known as Palm Oil Research Institute of Malaysia (PORIM)) has productively produced palm oil methyl ester from crude palm oil by using trans-esterification method.

A lot of industrial companies nowadays have already eyed this alternative solution to apply in fuels for diesel engine, hydraulic fluid and lubricants in engines and machines.

Several studies had been conducted to study the lubricity and the advantages of vegetable oils. In this study, RBD palm olein was used as a test lubricant using a pin-on-disk tribotester. RBD is an abbreviation of refined, bleached and deodorized. There are very limited researches that had been done using RBD palm olein. The objective of this study is to evaluate the friction and wear characteristic using three different lubricants, which are RBD palm olein, additive-free paraffinic mineral oil and commercial hydraulic oil. To study the wear of the materials, the researcher simulated the process of wear in a controlled manner and studied the effect on different samples with the same test conditions by performing pin-on-disk tests. The wear test configuration is applying a flat-end pin against flat rotating disk. A flat ended has some natural advantages, such as it is easier to machine and easier to coat if the wear testing of coatings is required (Garcia-Prieto *et al.*, 2004). At the same time, the surface contact point was simulated that could help the researcher to understand wear mechanism better. Normally, a hemispherical shape of pin is used which will create a point contact. As a result, RBD palm olein showed the lowest friction coefficient compared to additive-free paraffinic mineral oil and commercial hydraulic oil. This result concluded that palm oil has the possibility to be developed as bio-lubricant.

2.0 EXPERIMENTAL

2.1 Apparatus

In the present investigation, the pin-on-disk had been used to study both wear and coefficient of friction. The pin-on-disk test is commonly used as a comparative test in which controlled wear is performed on the samples to study. The volume lost allows the calculation of the wear rate of the material. A pin will be clamped firmly against a rotating disk linked to a certain dead weight with a beam and two pulleys. Next, lubricating oil will be placed on the surface of grooved disk.

In this experiment, a modified disk was used. The lubricant was not pumped and was let to flow through the disk as usual. Only 5 ml of the lubricant was dropped on the disk and to make sure the lubricant do not flow out while the disk rotated; the disk was designed to have a groove with 10 mm width and 5 mm depth.

A linear voltage differential transformer (LVDT) sensor played an important role to read wear rate. The grooved disk needed to be cleaned before the experiment by using acetone. The surface roughness was recorded according to the parameter set up by the researcher. Figure 1 shows the cut-out shape of the disk and pin.

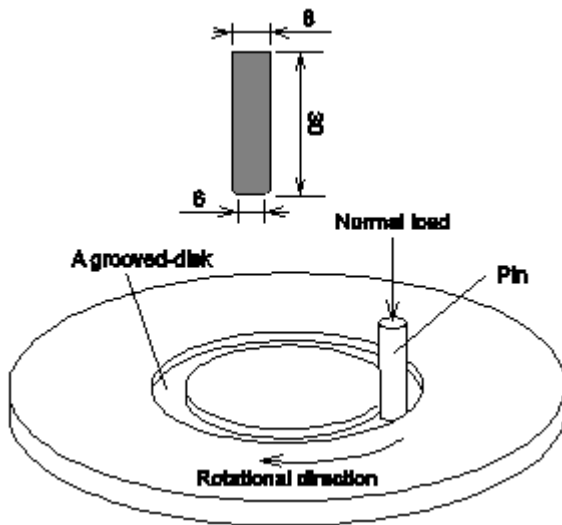


Figure 1 Pin on disk experimental arrangement

2.2 Materials and Lubricants

The studies of wear and friction coefficient behavior were performed with a flat ended pin, made from titanium, chosen for the experiment. Pin samples were prepared as 8mm in diameter and 30 mm in length. The density of titanium is 4.54 g/cm³. A titanium grooved disk had been selected as shown in Figure 1. Upon completion of each test, sandpaper with the grain size of the abrasive material of 1000 μm was used to grind the surface so that the surface finished was between specifications. The surface roughness of the disk was measured using surface roughness profiler, which consisted of a stylus detector to determine the pattern of disk and pin surface before and after the experimental works. RBD palm olein (Palm oil), commercial hydraulic oil and additive-free paraffinic mineral oil were used as the lubricants with the same amount of oil which was 5ml. Before that, the density and kinematic viscosity of three types of lubricants was measured using viscometer at different levels of temperature from 40°C to 100°C.

2.3 Experimental Method

Lubricated friction and sliding wear testing were carried out using a conventional pin on a disk machine. A flat-on-flat surface as test arrangement was used for the present set of experiments. Both the surface of the pins and disk were arranged in parallel to ensure their maximum contact. The principle of sliding consisted of a cantilever loaded pin against a horizontal rotating grooved disk in a lubricant oil bath. All the tests were carried out at room temperature, 24± 2°C. In this experiment, various load and sliding speeds, predicted to affect the friction and wear characteristics, were evaluated. The pin samples were recorded for weight losses, before and after each test. During the wear and friction coefficient test, various loads were applied which were 5 N, 20 N, 40 N and 80 N, respectively using three different types of lubricant. The surface finished of wear sample and grooved disk was measured before and after experiment. Five tests were carried out for each parameter and condition.

2.4 Wear and Friction Evaluation

The frictional force between the pin and rotating disk during test was measured by using a load cell attached to the side of the pin-holding lever arm and the values were shown promptly in the digital display. The coefficient of friction was calculated simply by dividing the frictional force value with the corresponding axial load on the based on the formula below (Wirdata et al., 2011):

$$\mu = \frac{F_p d_p}{F_N d_N} \quad (1)$$

where, μ is coefficient of friction, F_p is rate of angular friction force, F_N is applied normal load, d_p is the distance between center to the pin and d_N is between center to normal force. Coefficient of friction would show a major role in the determination of transmission efficiency through moving mating components.

An LVDT sensor, which was directly connected to a display monitor, detected the wear rate of the pin. Less resistant contributes to higher efficiency. Therefore, in terms of lubricant, less friction and wear is desirable.

2.5 Weight loss evaluation

The wear rate and specific wear rate were calculated based on the pin volume loss obtained during the experiment according to Equation (2) and (3) respectively. The wear rate and specific wear rate were related to cumulative loss volume per unit sliding (Bressan et al., 2008).

$$Q (\text{mm}^3 / \text{m}) = \frac{\Delta V}{s} \quad (2)$$

$$Q' (\text{mm}^3 / \text{Nm}) = \frac{\Delta V}{Ws} \quad (3)$$

where Q is wear rate, V is volume loss, s is sliding distance and W is applied load to the pin. The pins were firstly weighed using an electronic balance with an accuracy of 0.1 mg. Each pin was weighed three times to obtain an average value and reduce the impact of possible measurement errors in the calculation. The weights of the pin were recorded before and after experiment.

2.6 Surface Finished Measurement

Before the beginning of individual test, the disk and pin surfaces were cleaned with acetone to confirm there were no additional particles on the surfaces. The surfaces of the pin and disk were uni-directionally ground using abrasive paper to a surface finish of a roughness value, Ra, of about 0.4±0.1 μm and 0.38±0.02 μm respectively using surface roughness profiler which consisted of a stylus detector to determine the pattern of disk and pin surface. The surface finish after the experiment once again was measured to analyze the influence of lubrication used during the experiment.

3.0 RESULT

3.1 Kinematic Viscosity

Before the experiment was conducted, the density and kinematic viscosity of three lubricants, which were palm oil, hydraulic oil and paraffinic mineral oil, had been measured in order to analyze the effect of temperature on the kinematic viscosity of the lubricating oil. Density of lubricant is defined as its mass per unit volume. The kinematic viscosity is defined as the fluid resistance to shear or flow and is an amount of frictional fluid property. The fluidity of viscosity changes at different level of temperature. So, ISO 8217 was selected as a reference for the experiment and the reference temperature for residual fluid was

100°C, while for distillate fluid the reference temperature was 40°C. A laboratory experiment was carried out by following the standard procedure to measure the density of lubricant, while a viscometer was used to measure kinematic viscosity of the lubricants. A rotor was submerged into lubricants and was left to rotate for 99 seconds and the reading was recorded. From the result, it showed that the fluidity of the three types of lubricant decreased as the temperature increased. The fluidity of lubricants decreased as a result of the decreased intermolecular force within the lubricants. The additional vibrations between atoms breaking down created inter molecular forces and adhesion between molecules. The density and kinematic viscosity of palm oil, paraffinic mineral oil and hydraulic oil are shown in Table 1:

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

Lubricating oil	RBD palm olein	Hydraulic oil	Paraffinic mineral oil	Test method
Density at 25°C kg/m ³	0.873	0.872	0.860	ASTM D1298-85(90)
Kinematic viscosity, ν at 40°C, mPa.s	38.9	37.2	37.8	ASTM D445-94
Kinematic viscosity, ν at 100°C, mPa.s	5.3	7.1	7.4	ASTM D445-94

3.2 Effect of Applied Load on Coefficient of Friction

To study the anti-friction performance of palm olein, hydraulic oil and paraffinic mineral oil under different loads, various experiments had been conducted by varying the applied loads in the range of 5 N, 20 N, 40 N and 80 N, with the sliding velocity of 0.5 m/s at room temperature of 24±2°C. The duration for the experiment was 60 minutes. The results are illustrated in Figure 2 and Figure 3 which show the effect of different applied loads on the anti-friction performance for palm olein, hydraulic oil and paraffinic mineral oil respectively. The antifriction results of all lubricating oils used were compared mutually. The frictional force acquired directly from experiment by LVDT sensor was converted into friction coefficient value according to Equation (1). Figure 2 shows the illustrated curves and all conditions exhibited for all conditions. All results are presented graphically, where on the x-axis, it is marked with applied load and the y-axis which consists of coefficient of friction.

The result in Figure 2 shows the effect of different applied loads on the friction coefficient obtained with lubrication of palm olein, hydraulic oil and paraffinic mineral oil respectively. From Figure 2, it can be seen that friction coefficient obtained from lubrication with palm oil gave the lowest value. Palm oil showed a better characteristic of lubricating oil due to significant difference between the friction coefficients acquired from the lubrication of paraffinic mineral oil and hydraulic oil. The coefficient friction obtained lubricated with palm oil gave the lowest value at low load applied, 5 N which was 0.05 after the experiment. The coefficient increased to 0.44 at 20 N load applied, then decreased to 0.4 after the completion of experiment using 80 N load. The antifriction result of lubricants showed a similar trend for hydraulic oil and paraffinic mineral oil at all applied loads conditions. The friction coefficient obtained using paraffinic mineral oil was slightly lower than hydraulic oil. The presence of lubricating oil at the interface

decreased the coefficient of friction, especially the palm olein. The stability of the coefficient of friction of palm olein proved that palm olein has the ability to stabilize and lessen the coefficient of friction by forming a lubricating film which can be easily sheared. The lowest value coefficient of friction was obtained at low load and high load applied. The preeminent lubricant characteristic condition, specifically for palm olein, was at the low load.

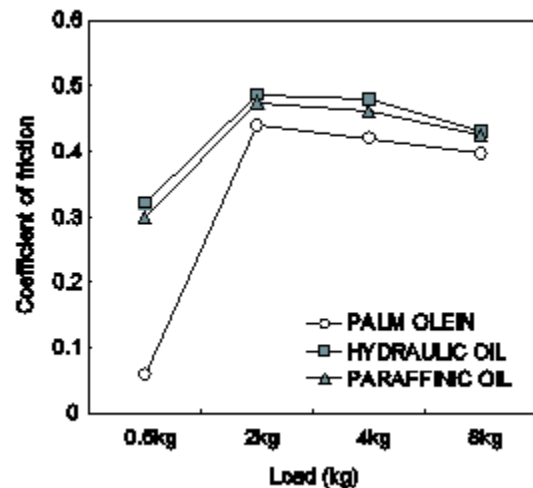


Figure 2 Coefficient of friction versus various load applied

3.3 Effect of Applied Load on Wear

The author also studied the antifriction study in term of wear for the lubricant tested. The results are illustrated in Figure 3, which shows the effect of different loads applied on the wear value for

palm olein, hydraulic oil and paraffinic mineral oil respectively. It was found that the wear obtained with lubrication of palm oil increased up to 90 μm at 40 N applied load, then decreased to 77 μm when a 80N load was exerted. The findings showed that the curves indicated that the wear values obtained with lubrication of palm olein at the start and end of the test were significantly lower. The antifriction result of wear with lubrication of hydraulic oil and paraffinic mineral oil showed a similar trend from the normal load of 5 N to 40 N. Both lubricants showed the lowest wear produced by the pin, at 20 N load applied.

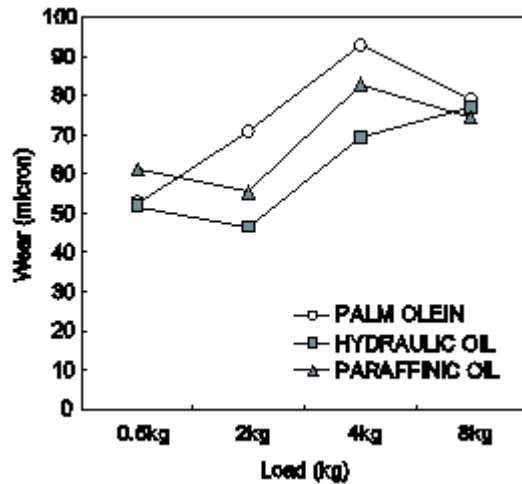


Figure 3 Wear resistance versus various load applied

3.4 Effect Load Applied on Weight Loss of the Pin

From the previous experiment by other researchers, one could say that wear is a very complex system. Wear prediction, even though flawed, there is number of ways to estimate the wear rate and one of them is through the analysis of weight loss of the pin. The wear rate of the pin and weight loss recorded before and after the experiment are much related to each other. Wear comparison, either obtained directly from the analysis using LVDT sensor or by manual calculation using weight loss, is very crucial in validating the approximate value of the wear. Weight loss of the pin is illustrated in Figure 3.

From Figure 3, the weight loss of the pin lubricated with palm olein increased as the increment of the load exerted up to 40 N. When 80 N load was applied, the weight loss decreased to 0.001 g. The curve of weight loss with lubrication of hydraulic oil showed a similar trend with palm olein but the weight loss dominated by the pin lubricated with hydraulic was only slightly lower than palm olein. For paraffinic mineral oil, weight loss decreased up to 20 N load applied and then increased as the load applied increased. Wear rate and specific wear rate were manually calculated according to Equation (2) and Equation (3) and are presented in Table 2.

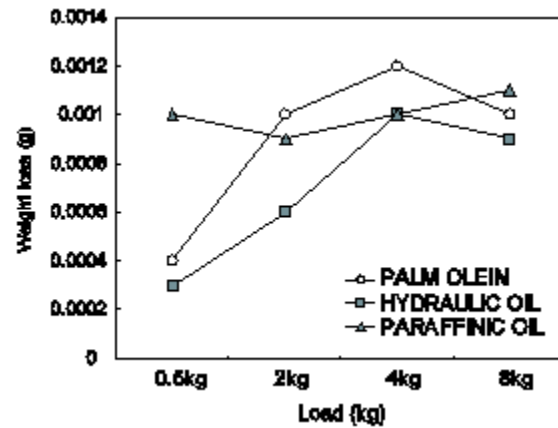


Figure 4 Weight loss of the pin after experimental works

Table 2 Weight loss, wear rate and specific wear rate

(a) Applied load 5 N

Type of lubricating oil	Weight loss, Δm , (g)	Wear rate, Q (mm^3/m), $\times 10^{-5}$	Specific wear rate, Q' ($\text{mm}^3/\text{N.m}$), $\times 10^{-6}$
Palm oil	0.0004	4.8948	9.86847
hydraulic oil	0.0003	3.6711	7.40135
Paraffinic mineral oil	0.001	12.237	24.6712

(b) Applied load 20 N

Type of lubricating oil	Weight loss, Δm , (g)	Wear rate, Q (mm^3/m), $\times 10^{-5}$	Specific wear rate, Q' ($\text{mm}^3/\text{N.m}$), $\times 10^{-6}$
Palm oil	0.001	12.237	24.6712
hydraulic oil	0.0006	7.3421	14.8027
Paraffinic mineral oil	0.0009	11.013	22.2041

(c) Applied load 40 N

Type of lubricating oil	Weight loss, Δm , (g)	Wear rate, Q (mm^3/m), $\times 10^{-5}$	Specific wear rate, Q' ($\text{mm}^3/\text{N.m}$), $\times 10^{-6}$
Palm oil	0.0012	14.684	29.6054
hydraulic oil	0.001	012.237	24.6712
Paraffinic mineral oil	0.001	12.237	24.6712

(d) Applied load 80 N

Type of lubricating oil	Weight loss, Δm , (g)	Wear rate, Q (mm^3/m), $\times 10^{-5}$	Specific wear rate, Q' ($\text{mm}^3/\text{N.m}$), $\times 10^{-6}$
Palm oil	0.001	12.237	24.6712
hydraulic oil	0.0009	11.013	22.2041
Paraffinic mineral oil	0.0011	13.461	27.1383

3.5 Effect Load Applied on Surface Roughness of the Disk and Pin

Improved tribological performance can be obtained by analyzing the microstructural parameter such as surface roughness. Surface roughness is one of the most essential parameters in determining the wear rate and friction coefficient, and to also summarize the behavior of lubrication effect during the sliding time of mating components. The experimental surfaces were prepared by sand paper polishing as discussed earlier in the research methodology and had been measured by using stylus surface roughness profiler. The average values of

the arithmetic surface roughness R_a of the experimental surface of the pin and disk were measured after each individual test; and all were recorded and plotted as shown in Figure 5, Figure 6, Figure 7 and Figure 8. From the figures, one could say that palm olein and hydraulic oil gave the lowest value of R_a for all applied loads, which the average of R_a was around 1 at 5 N load and the average was around 4 at 80 N for both pin and disk. The value of R_a also increased as the increment of load exerted. The graph also shows a similar trend for paraffinic mineral oil except when 40 N load was applied, where the R_a value reached up to 10 micron for the disk.

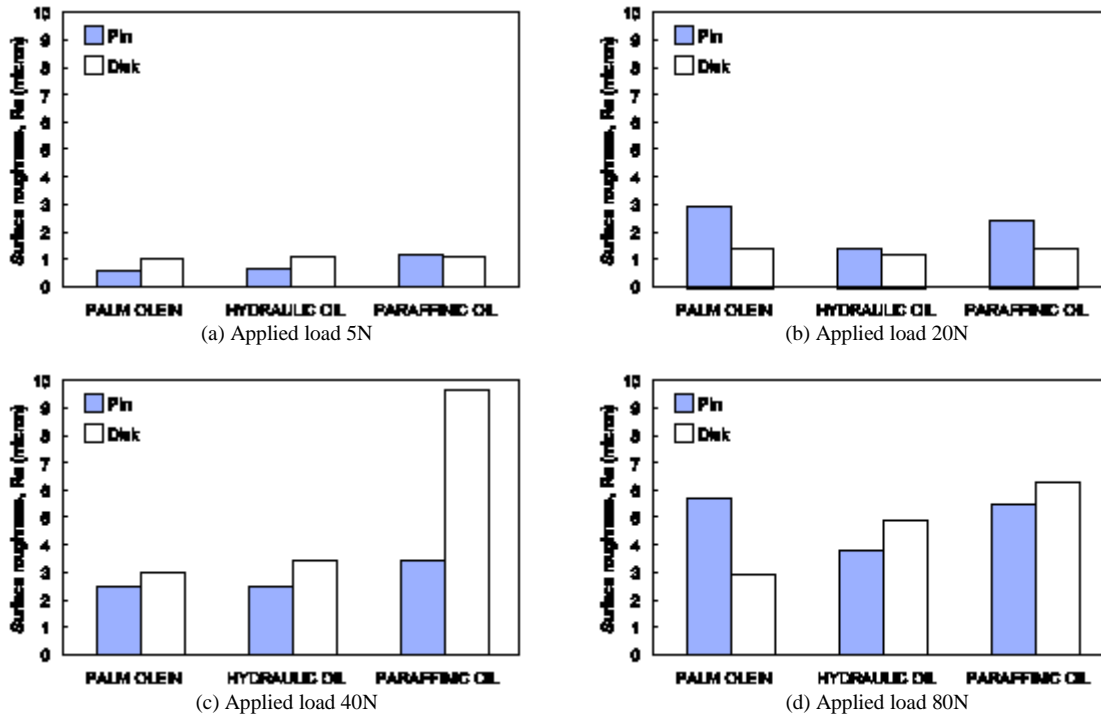


Figure 5 Surface roughness R_a for the pin and disk at load (a) 5N, (b) 20N, (c) 40N and (d) 80N

36 Worn Surface Observations

The micrographs of worn surface were analyzed after 3600 seconds tests with lubrication of palm oil, hydraulic oil and paraffinic mineral oil under various loads applied are shown in Figure 6, Figure 7 and Figure 8. The results were compared mutually. From the figures, the surface became rougher as the

increment of load exerted. At low loads applied, surfaces lubricated with palm oil and hydraulic oil showed smooth surfaces due to the formed thin lubricant layer and was enough to preserve metal to metal contact of rubbing surfaces. As the load applied increased, the layer tended to become thinner and unstable, thus attributing to the increase of surface damage.

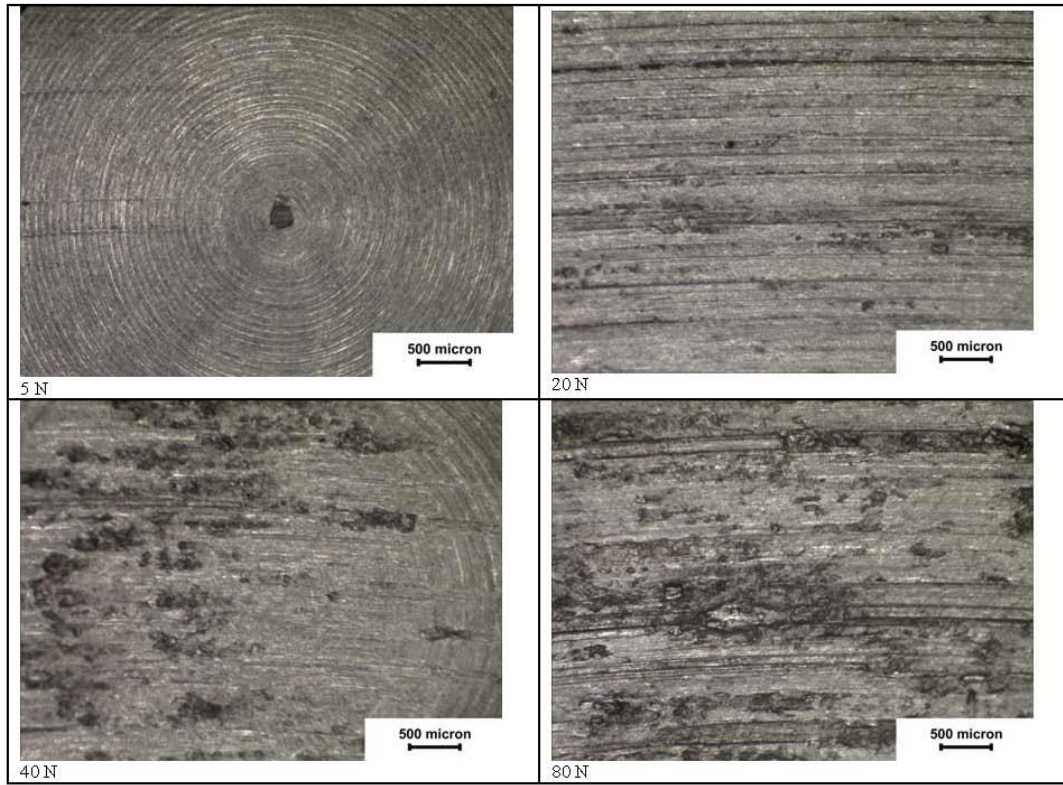


Figure 6 Worn surface of pin surface lubricated with RBD palm olein

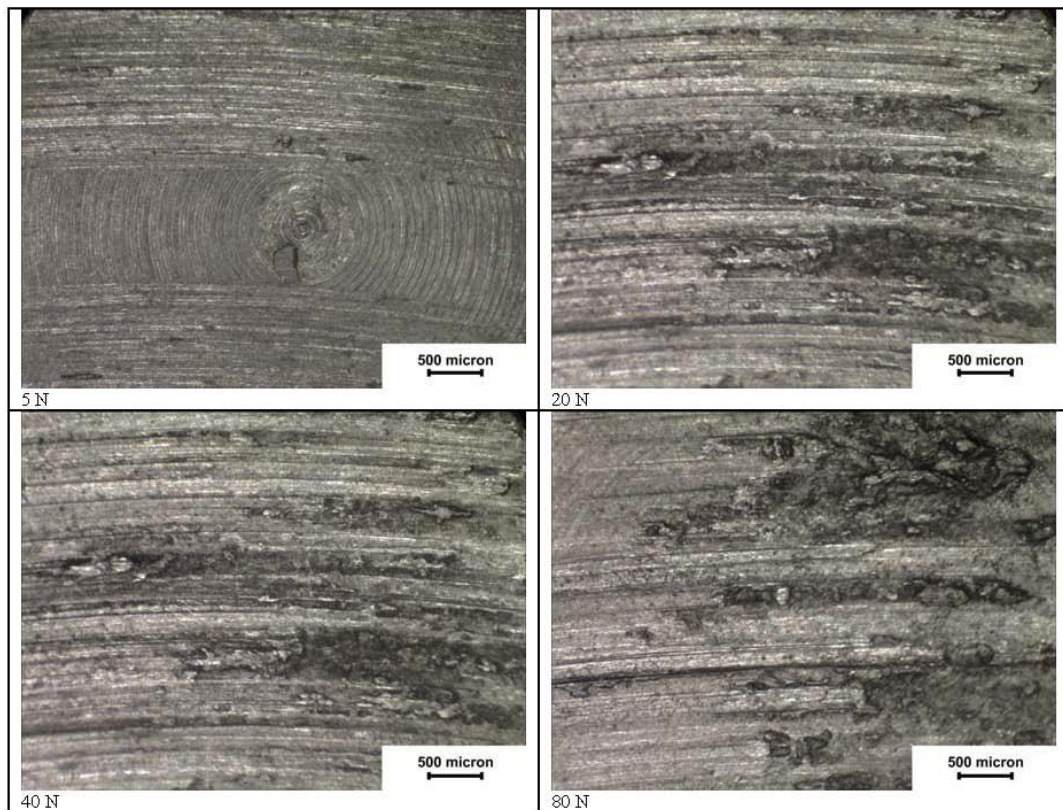


Figure 7 Worn surface of pin surface lubricated with hydraulic oil

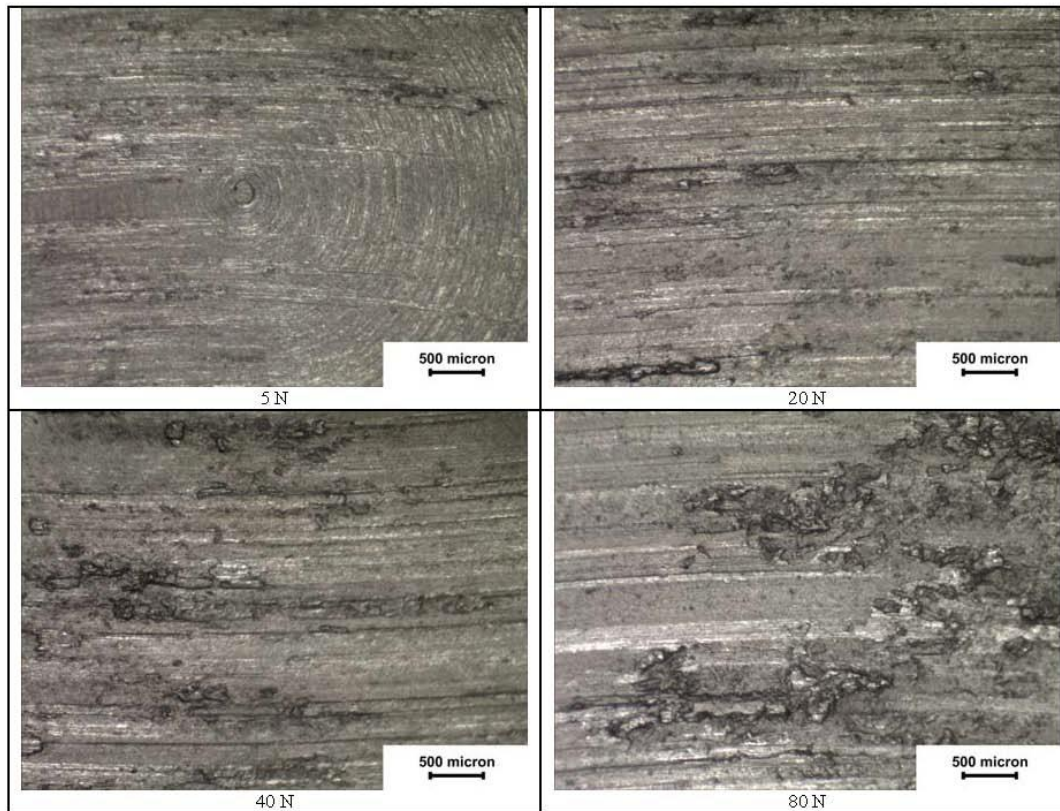


Figure 8 Worn surface of pin surface lubricated with paraffinic mineral oil

4.0 DISCUSSIONS

From the earlier analysis, the author could say that the all parameters obtained with lubrication of palm oil showed better antifriction characteristics compared to hydraulic oil and paraffinic mineral oil. Palm oil produced low coefficient of friction in all conditions after the experiment. Basically, palm olein contains tryglicerides, glyceride, free fatty acid and non-glycerides substance (Maleque *et al.*, 2000; Masjuki *et al.*, 1999). The presence of free fatty acid with general formula of $C_nH_{2n+1}COOH$; in which the molecule consists of a long covalently bonded hydrocarbon chain, had influenced the reduction of friction. The material transfer and adhesion of two surfaces were minimized by the presence molecule layer of lubricant between the surfaces. This was attributed to the fact that the molecular weight of palm oil is more consistent than that of mineral oil. Palm olein is composed mainly of ester, which has high affinity towards metal to metal contact owing to their functional group. This phenomenon produced a thick layer of lubricant between the surfaces of mating component. The asperities on the surface of pin and disk were protected by thicker molecular layers (Syahrullail *et al.*, 2011). As a result, it produced low friction coefficient value. This finding proved that low friction coefficient were obtained due to the long chain of fatty acids present in palm olein, which have the ability to show better lubricating property compared to mineral oil.

The friction coefficient obtained from lubrication with palm olein decreased as the load applied increased. These findings were in agreement with the findings of Chowdry *et al.*, (2011) for friction and wear property of Aluminum. It could reasonably be expected that the lubricant film was sheared caused by the frictional resistance. As the pressure of the surface increased; which means the load applied increased, the

condition could cause higher shear strain and directly increase the strength of material which would result in a lower real area of contact and a lower coefficient of friction (Ching-Fang and Fort, 2004). The reduction of friction coefficient was also expected due to the surface texture of the pin and disk. It was observed that as the applied load was increased, the arithmetic surface texture, R_a also increased. The rougher the surface, the more quantity of wear debris retained on the surface and it is believed to be responsible for the decrease of friction (Pradeep *et al.*, 2008). However, a slight increase in friction were observed when 20N was applied due to the production of more debris, which were not able to compress appropriately between the mating components and led to the process of abrasion and micro-cutting, then leading to higher friction coefficient. However, as the load increases, the friction is decreasing. As explained earlier, the frictional heat increased as the load applied increased. The higher frictional heat helped in better compression and for large coverage of transfer layer, hence reduced the production of debris and resulted in lowering the friction (Ing *et al.*, 2012).

Wear is a comparatively uniform phenomenon as shown in the figures and tables as mentioned before. There are correlations between the wear obtained directly using LVDT sensor with weight loss recorded, wear rate and specific wear rate calculated. At low load applied, the wear obtained from lubrication with palm oil showed the lowest value. It could be reasonably expected that the palm oil would have the ability to form a thin film by chemical adsorption of fatty acid to the interface. This phenomenon is called soap film, which could reduce direct metal to metal contact and avoid severe wear (Ching-Fang and Fort, 2004; Sharma *et al.*, 2008). As the load applied was increased up to 40 N, the wear also increased. The increase of the pressure caused the film thickness to decrease,

due to more amount of oil was thrown away due to high centrifugal force. Metal to metal contact also decreased, attributed by the metal oxide layer or soap film formed by the fatty acid, which later however, became thinner and insufficient to preserve metal to metal contact, thus leading to the increment of wear resistance (Temel and Zaki, 2008). Wear resistance decreased as higher load was applied. This can be explained in term of wear process. The higher the pressure applied, more debris will be produced during the oxidative wear. These particles will later get compacted on the sliding surface to form a protective transfer layer, resulting in reduced wear.

Surface roughness is another parameter that can influence the wear resistance and friction of the mating components. It was hard to draw direct conclusions between the roughness parameters and tribological behavior, because the roughness of different surfaces was not the same. From Figure 5 to Figure 8, one could say that the arithmetic surface roughness obtained after the experiment for all lubricants increased as the load applied increased. Palm olein showed the lowest value of Ra obtained through the experiment. It means that the interaction of the surface asperity was well protected and the surface finish became a greater influence to reduce wear and friction using palm olein rather than hydraulic oil and paraffinic mineral oil. In addition to this, the increasement of surface roughness value can be attributed by random texture to store more lubricant in between the asperities and can attribute to low friction coefficient.

5.0 CONCLUSION

The investigation on the wear behavior of titanium alloy lubricated with RBD palm olein was obtained using pin-on-disk tester. The result was compared mutually with those lubricated with commercial hydraulic oil and additive-free paraffinic mineral oil as lubricants. From the results, the friction coefficient obtained from the lubrication with palm oil was better than hydraulic oil and paraffinic mineral oil for various loads applied. The friction coefficient for all three lubricating oils increased as the applied load increased. The arithmetic surface roughness Ra of the pin and disk influenced the reduction or increment of the resulting friction coefficient and wear. Rougher surface would produce less friction coefficient. Also, the higher load applied, the higher the increment of arithmetic surface roughness.

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