Jurnal
Teknologi

Full Paper

TRIBOLOGICAL EFFECT OF PALM STERIN AND ENGINE OIL (CMEO) ON PURE ALUMINIUM PIN STEEL DISC WITH VARIES SPEED AND CONSTANT LOAD

Aiman, Y.*, Syahrullail, S., S. M. Azhar, Ummikalsom, A., Mohd Kameil, A. H.

School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
16 April 2019
Received in revised form
4 August 2019
Accepted
7 August 2019
Published online
24 October 2019

*Corresponding author
wmaiman2@graduate.utm.my

Graphical abstract

Abstract

Palm stearin has high biodegradability and produces low pollution to the environment. This oil can be improved based on its natural behaviour and can be used as an alternative to replace widely used commercial mineral oils. Thus, the negative impact towards the environment can be reduced. The purpose of this research is to study the performance of two type of lubricants which are vegetable oil (Palm Stearin) and commercial mineral engine oil (CMEO). The sample will be tested using pin on disc tribotester machine that follows ASTM G99 standard. The materials used for this experiment are pure aluminium pin (A110) with spherical head and stainless steel disc (SKD11) with four grooves. The experiment will take approximately one hour to complete one test. The conditions that were considered before the beginning of the experiment are constant loads of 1 kg, varying sliding speeds of 1.5 m/s to 3.5 m/s with incremental 1 m/s and 2.5 ml volume of oil. The wear rate and coefficient of friction can be determined in this experiment. From the result obtained, the coefficient of friction (COF) of palm stearin is 45% higher than CMEO and also the trend for both oils are inversely proportional with sliding speed. Besides that, the wear rate of palm stearin is also higher than CMEO, which shows that CMEO has better lubrication performance when compared to palm stearin. The additives are needed for palm stearin so that the lubrication performance can compete with the CMEO. Furthermore, the results also reveal that vegetable oil shows a potential to be a commercial lubricant when the deficiencies can be overcome.

Keywords: Pin-on disc tribotester machine, coefficient of friction, wear, tribology, palm oil

Abstrak

Sterin sawit mempunyai kadar biodegrdasi yang tinggi dan secara tidak langsung ia boleh mengurangkan kadar pencemaran kepada alam sekitar. Minyak ini dapat ditingkatkan prestasi berdasarkan sifat semulajadinya dan boleh menjadi bahan alternatif untuk menggantikan minyak mineral komersil yang banyak digunakan. Oleh itu, kesan negatif terhadap alam sekitar juga dapat dikurangkan. Kajian ini adalah untuk mengkaji prestasi dua jenis pelincir iaitu minyak sayuran (Palm Stearin) dan minyak enjin mineral komersil (CMEO). Sampel ujikaji tersebut akan diuji menggunakan pin pada mesin cakera tribotester yang mengikuti standard ASTM G99. Bahan yang digunakan untuk percubaan ini adalah pin aluminium tulen (A110) dengan kepala sfera dan cakera keluli tahan karat (SKD11) dengan empat alur. Eksperimen akan mengambil masa satu jam untuk menyelesaikan satu ujian. Keadaan ujikaji sebelum memulakan eksperimen ialah dengan memastikan beban berterusan sebanyak 1 kg, kelajuan gelongsor 1.5 m/s hingga 3.5 m/s dengan kenaikan 1 m/s dan 2.5 ml minyak. Kadar haus dan pekali geseran boleh ditentukan dalam eksperimen ini. Daripada keputusan eksperimen, pekali geseran (COF) stearin sawit adalah 45% lebih tinggi berbanding CMEO dan juga trend untuk kedua-dua minyak berkadar songsang dengan kelajuan gelongsor. Selain itu, kadar haus stearin sawit juga lebih besar daripada CMEO, ini menunjukkan bahawa CMEO mempunyai prestasi pelinciran yang lebih baik berbanding dengan stearin sawit. Bendasing diperlukan untuk stearin sawit supaya prestasi pelincirannya dapat bersaing dengan CMEO. Dari hasilnya juga, minyak sayuran menunjukkan potensi menjadi pelincir komersil j kelemehannya dapat diatasi.

Kata kunci: Mesin penguji *pin-on-disc*, pekali geseran, mekanisme haus, tribologi, kelapa sawit

1.0 INTRODUCTION

Generally speaking, friction is happening every day and Generally speaking, friction is happening every day and everywhere in our lives. Friction helps to make our lives easier and when friction becomes a cycle in our life, wear will form over time. Examples of such scenarios are found in an internal combustion engine of vehicles; grinding operation, strip movement in metal rolling, control of chatter in a machine tool slide way, etc. [1]. The smoothness of movement is improved by reducing friction which is done by using lubricants. However this is not always the case and there may be instances in which it is more important to maintain steady friction than to obtain the lowest possible friction. Lubricant also acts to reduce wear, to prevent overheating and corrosion, and forms a film thickness that covers the parts of the object that are under friction [2, 3].

In this modern day, a typical and crucial part of engines usually uses commercial mineral engine oil. The performance of this oil is seen through its viscosity, ability to dissolve additives and contaminants, and thermal and oxidative stability. The demand for this type of oil is increasing and becoming more expensive each year. Usually the source of these oils comes from the petroleum base and each year this oil will be depleted and thus become expensive when the supply is low. Therefore, as an initial choice of lubricant, vegetable oils have the potential to reduce the coefficient of friction and also wear. Additionally, vegetable oil is best known for its low pollution of the environment, high biodegradability, compatibility with additives, low production cost, low toxicity and wide production possibilities [4].

One of the famous vegetable oils is palm oil. As Malaysia is the largest palm oil producer, the development of palm oil uses is very important to expand its market other than the food industry. Palm oil has been tested by several researchers for different engineering applications. For example, researchers have investigated the characteristics of palm oil in a metal forming lubricant [5]. Besides that, palm oil was also investigated to be used as diesel engine and hydraulic fluid [6]. There are four major groups of palm oil that have been investigated by researchers around the world; namely using 100% palm oil as a test lubricant [7], palm oil with additives [8] and palm oil with nano particles [9]. All of the research proved and found that palm oil shows satisfactory results and has a bright future to be used widely in engineering applications. There is no argument on the performance of palm oil as a lubricant. It has also been proven that palm oil has good performance in terms of lubrication and has the potential to reduce the dependency on mineral-based oil lubricants.

This paper will discuss the Tribological effect of palm stearin and engine oil (CMEO) on pure aluminium pin steel discs with varying speed and constant load, tested using pin on disc tribotester machine following ASTM G99 standard. The materials used for this experiment are pure aluminium pin (A110) with spherical head and stainless steel disc (SKD11) with four grooves.

2.0 METHODOLOGY

This test is done by using a pin on disc tribotester machine that is connected to a controller and able to display the data on the computer. It follows the standard ASTM G99. There are a few conditions that have been recognized before running the experiment. These are as follows: the speed varies from 1.5 m/s to 3.5 m/s with an increment of 1 m/s. The load is constant at 1 kg. The volume applied on the disc is 2.5 ml. The specimens used are pure aluminium pin (A110) and stainless steel disc (SKD11) as shown in Figure 1.

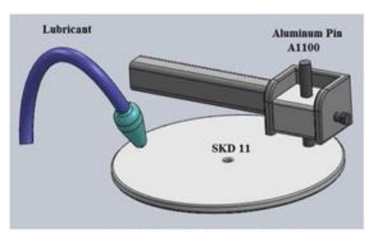


Figure 1 Schematic diagram of pin on disk

Refined, bleached and deodorized (RBD) palm stearin was used in this research that will be compare to commercialize mineral engine oil (CMEO) as shown in Table 1. Lastly the run time is one hour. In this experiment, the data obtained from the controller of pin-on disc machine are wear and frictional force. The pin-on-disc machine is attached with LVDT sensor that able to detect the wear rate of the pin and disc.

Then the coefficient of friction is calculated by using this formula:

$$coefficient\ of\ friction = \frac{frictional\ force}{normal\ load} \quad (1)$$

Table 1 Viscosity of lubricant sample

Temperature (˚C)	Kinematic Viscosity (mm²/s)	
	Palm Stearin	CMEO
40	38.01	128.8
100	8.55	15.2
Viscosity Index	212.56	96

After that, the wear scar diameter (WSD) of the pin can be measured using a charge-coupled device (CCD) microscope. This equipment can be connected to the computer, allowing the image of the wear scar to be stored and measured using i-Solution software. Moreover, the surface roughness of the pin is measured using the surface roughness tester (Mitutoyo SJ210). The wear scar diameter and surface roughness of the pin is reflected by the wear mechanism highlighted in the objective. Table 2 shows the composition of fatty acid in palm stearin.

Table 2 Fatty acid composition in palm stearin

Fatty acid composition	Palm stearin
C12:0	0.1-0.3
C14:0	1.1-1.7
C16:0	49.8-68.1
C18:0	3.9-5.6
C18:1	20.4-34.4
C18:2	5.0-8.9
C18:3	0.1-0.5
C20:0	0.3-0.6

3.0 RESULTS AND DISCUSSION

3.1 Coefficient of Friction (COF)

From Figure 3, the values of the COF of both oils decrease when the sliding speed increases. This is due to wear debris that when produced, will interact with the metal surface and act as a protective layer to overcome high frictional force and metal to metal direct contact [10]. Other than that, the COF of Palm Stearin (PS) is higher than CMEO. This is due to PS having a low resistance to oxidative degradation and poor low temperature properties, whereas CMEO has the existence of the additives [9].

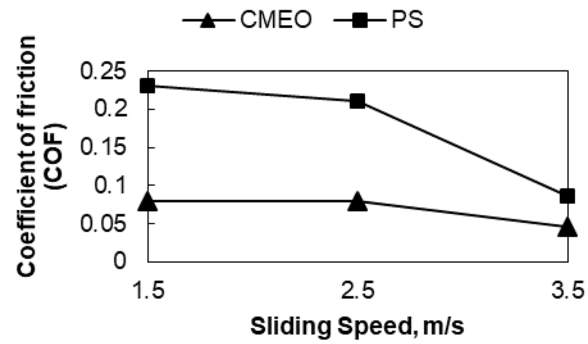


Figure 3 Coefficient of friction versus sliding speed

However, some researchers indicate that petroleum-based mineral oils, those which are still pure and without additives, have lower lubricity and natural viscosity temperature properties compared to vegetable oils such as PS [11]. By comparing the viscosity of both oils, clearly palm stearin has a lower value. This may be due to the fact that the value of the COF is higher when viscosity is low. It can be said that palm stearin already has a low COF due to its ability to form a lubricant film which can prevent direct contact between surfaces. Vegetable oils comprised of triglycerides consist of a glycerol molecule with three different long-chain fatty acids attached with an ester linkage. As the increase in fatty acid content occurs, a decrease in the coefficient of friction is observed [12]. CMEO is already established in the market. It has been made up with many additives to form a better lubricant. However, palm stearin still has a lower COF when compared to pure mineral oils.

3.2 Wear

Figure 4 shows graph of wear against sliding speed for PS and CMEO. In this graph wear of PS is increasing when sliding speed increase and wear of CMEO decreasing when sliding speed increase. For CMEO this is due to at early stage of sliding speed, the static friction is high and when the speed become high its already enter dynamic friction and in stable sliding condition. While for PS wear higher because high temperature produce when the speed is high. Therefore the bulk temperature will decrease the yield strength of the material and lead to changes in the wear mechanism and the real contact configuration [13].

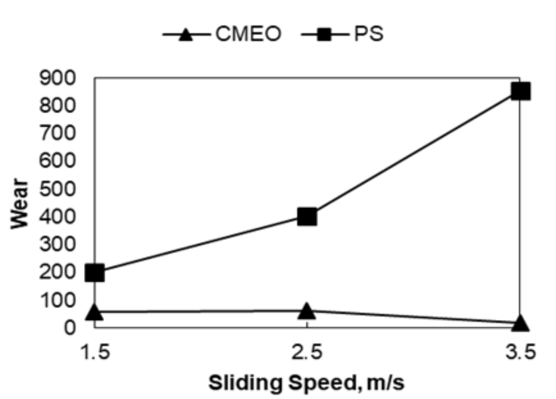


Figure 4 Wear versus sliding speed

Besides, fatty acid additive play an important role in reducing the wear [14]. This statement was supported by Amurugam and Sriram [15] and Adhvaryu *et al*. [16] the presence of long-chain fatty acid produces hydrocarbon layer that protects wearing surface. These researchers also suggested that increasing the level of unsaturation will give a negative influence on the performance of fatty acids as boundary wear reducers [16, 17]. In other word, when the level of unsaturated fatty acids increases, the wear rate will also increase. The wear rate of palm stearin is highest, this is may be due to large number of unsaturated fatty acids. Whereas, CMEO also has fatty acids but only a little amount and the fatty acids is saturated. That is why the wear rate of CMEO is better than palm stearin. Low wear rate of a lubricant will increase the performance of daily application and maintain the life cycle of material.

3.3 Wear Scar Diameter (WSD)

Table 3 and 4 show the wear scar diameter of CMEO and PS oils. The WSD is measured by using same magnification power which is 1.5×10. The enlarge pictures is 15 times of its original size. The value of the WSD then plotted against sliding speed so that the relation between them can be seen.

Table 3 Wear scar diameter of CMEO

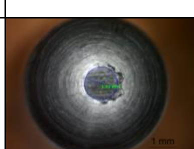
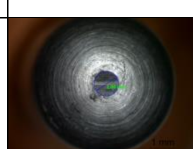
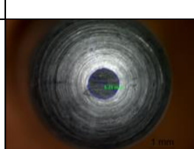
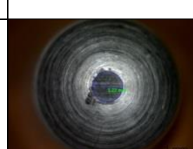
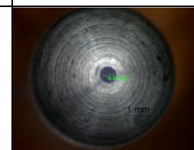
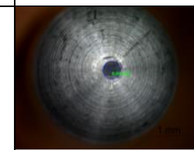
Sliding Speed, m/s	Commercialized Mineral Engine Oil (CMEO)			
	Groove 2 (G2)	WSD, mm	Groove 3 (G3)	WSD, mm
1.5		1.33		1.00
2.5		1.22		1.22
3.5		0.61		0.69

Table 4 Wear scar diameter of PS

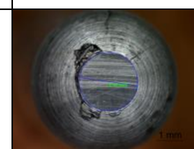
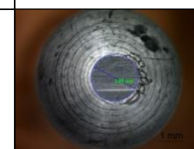
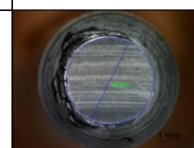
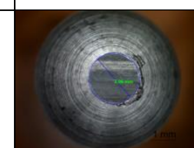
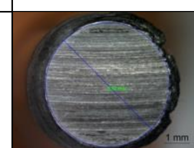
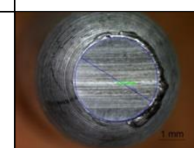
Sliding Speed, m/s	Palm Stearin (PS)			
	Groove 2 (G2)	WSD, mm	Groove 3 (G3)	WSD, mm
1.5		2.37		1.89
2.5		3.53		2.06
3.5		5.02		3.35

Figure 5 shows that graph of wear scar diameter against sliding speed for lubrication of CMEO and PS. The trend of WSD is same as the wear for both oils. For PS, the WSD is increasing when the sliding speed increase whereas for CMEO, the WSD decreasing when the sliding speed increase. As for PS, high sliding speeds clearly affect the WSD. When the sliding speed is increase, the WSD also increases. At high speed, usually the temperature of the collision material of pin and disc will also increase. This is due to high friction force between them [15, 22]. Ing *et al*. [21] conclude that at higher test temperatures, the palm stearin showed larger WSD. The WSD results of PS of this experiment coincide with the statement. The researchers give a reason of this behaviour happens is due to the fact at high temperature, the lubricant film formed by fatty acids tended to be less stable or was more likely breakdown. As for CMEO, at high speed and thus at high temperatures, the WSD value is decreasing when the speed increase. CMEO already has stable fatty acids additives that help to survive at high temperature and it still not reached it limits in this experiment. Besides, CMEO already reach dynamic friction which means it in steady state of its performance.

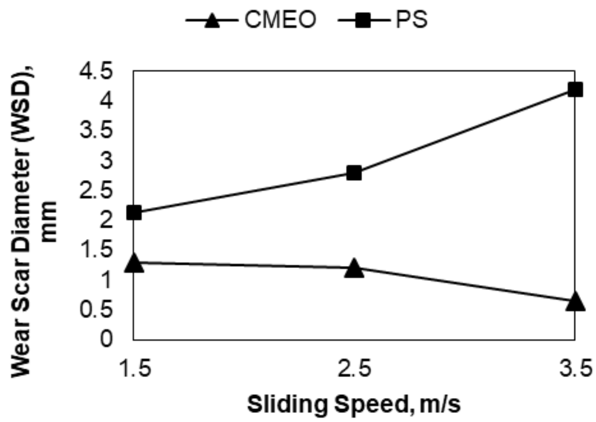


Figure 5 Wear scar diameter versus sliding speed

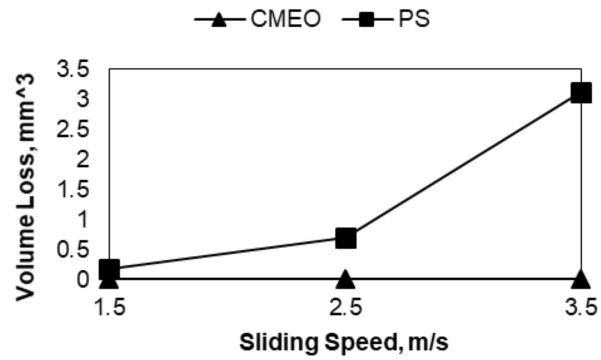


Figure 6 Volume loss versus sliding speed

3.4 Volume Loss

The volume loss from this experiment can be calculated by using equation from standard ASTM G99 of pin on disc [18]:

$$Volume\ loss, mm^3 = \frac{\pi \times (wear\ scar\ diameter, mm)^4}{64 \times (sphere\ radius\ of\ pin, mm)} \quad (2)$$

Table 5 Volume loss value

Sliding Speed (m/s)	Volume Loss (mm³)	
	CMEO	PS
1.5	0.016892	0.181276
2.5	0.018127	0.708923
3.5	0.001494	3.113381

Table 5 shows the value of volume loss for CMEO and PS at different sliding speed. From the table, it is clearly seen that there are big gap between CMEO and PS in the value of volume loss at each sliding speed. The volume loss of CMEO is not exceed more than 0.1 mm^3 for all sliding speed. The highest volume loss for CMEO is 0.016892 mm^3 at sliding speed of 1.5 m/s. While for PS, the highest volume loss 3.113381 mm^3 at sliding speed 3.5 m/s. The results of volume loss for both oils are correlated to wear and WSD of this experiment.

Figure 6 shows the graph from the Table 5. The graph of CMEO cannot be seen clearly because the value is too small and PS has large value. Therefore, it can be concluded that the volume loss of PS certainly higher than CMEO with huge different.

3.5 Wear Worn Surface

In this section, it shows that the graph of surface roughness of pin for both oils and both selected grooves. As it can be seen, the graphs of CMEO become smoother when the sliding speed is increasing. But the graphs of PS become rougher as the sliding speed increase. Therefore, the surface roughness of the pin for both oils has correlation to the wear rate, wear scar diameter and volume loss.

Table 6 Surface roughness profile for CMEO G2

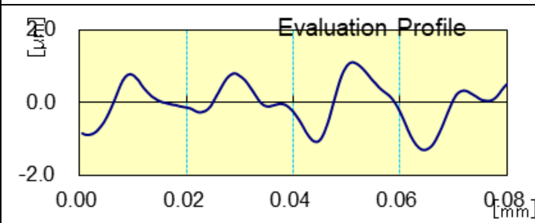
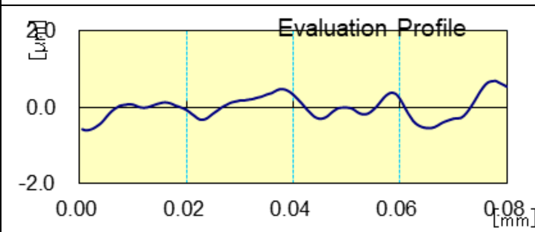
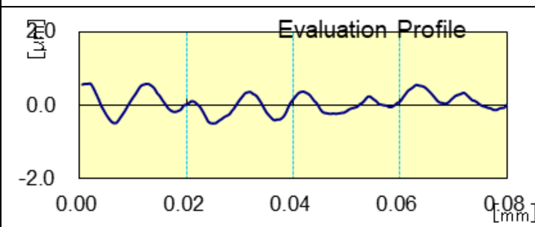
Sliding Speed, m/s	CMEO G2
1.5	
2.5	
3.5	

Table 7 Surface roughness profile of pins for CMEO at G3

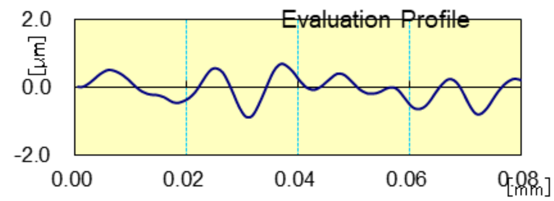
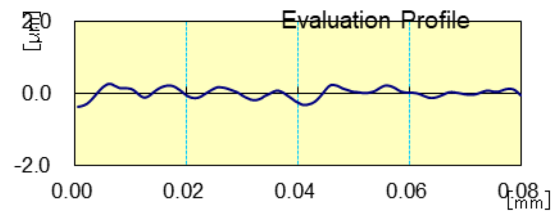
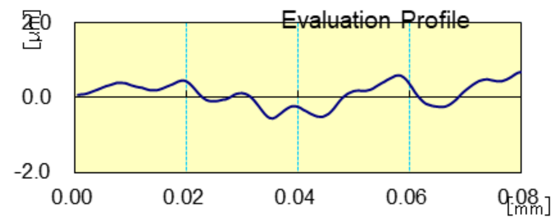
Sliding Speed, m/s	CMEO G3
1.5	
2.5	
3.5	

Table 8 Surface roughness profile of pins for PS at G2

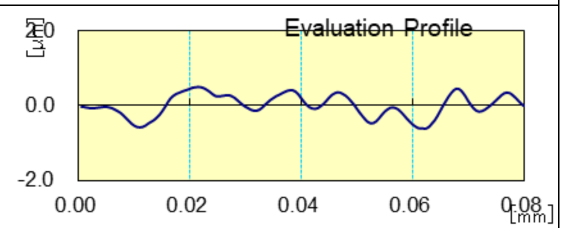
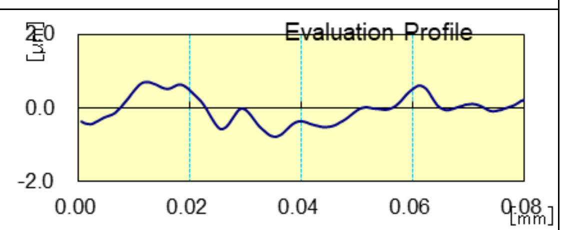
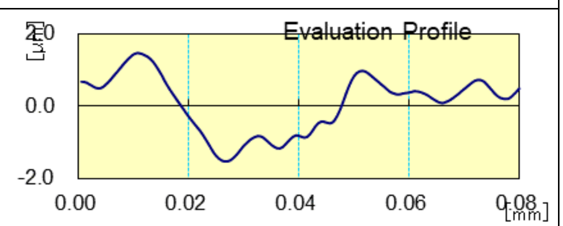
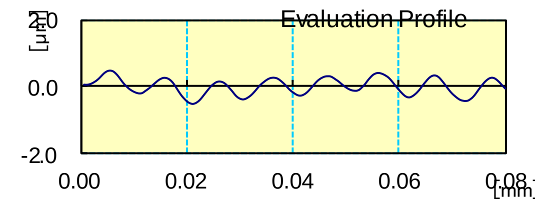
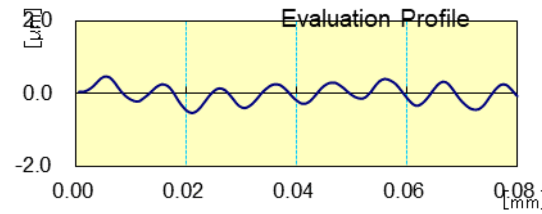
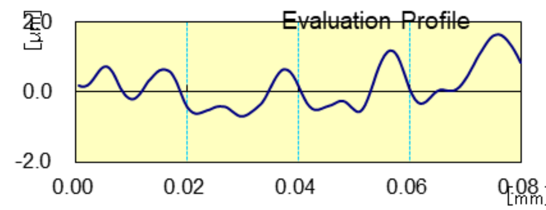
Sliding Speed, m/s	PS G2
1.5	
2.5	
3.5	

Table 9 Surface roughness profile of pins for PS at G3

Sliding Speed, m/s	PS G3
1.5	
2.5	
3.5	

Charge-coupled Device microscope is used in high power or high magnification to see clearly the worn out surface of the pins. The i-Solution software is used to capture the micrographs of the worn surface. The main reason capture the micrographs of the pin surface is because to see the type of wear happen on the surface of the pin and to see the amount of wear with three different sliding speed for both lubricants [23 - 25]. The sliding direction of the CCD micrograph pictures is from left to right of the page.

Abrasive wear is the common wear that can be seen in all surface of the pin for CMEO and PS at both grooves. For CMEO at groove 2, there are few adhesive wear that can be seen at 1.5 m/s. There is also a little adhesive wear at sliding speed of 2.5m/s at groove 2 for CMEO. Other than that for CMEO there are no others that show adhesive wear. Besides, for PS adhesive wear can be seen mostly at sliding speed 3.5 for both grooves. At this rate the PS has lost the ability to protect the surface of the pin that slide on the disc.

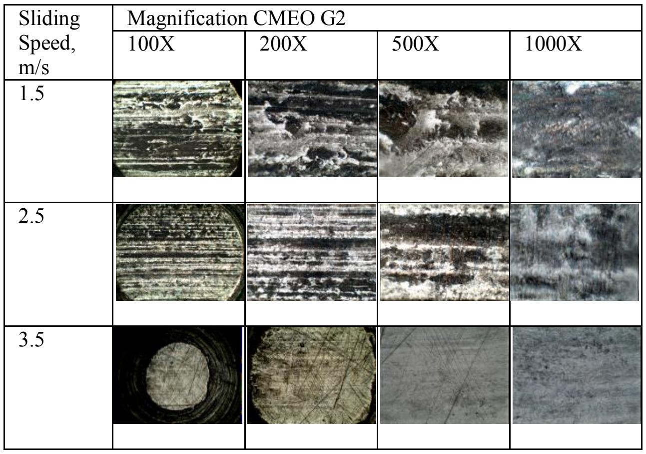


Figure 7 Micrographs of pin worn surface at different magnification levels for CMEO at groove 2

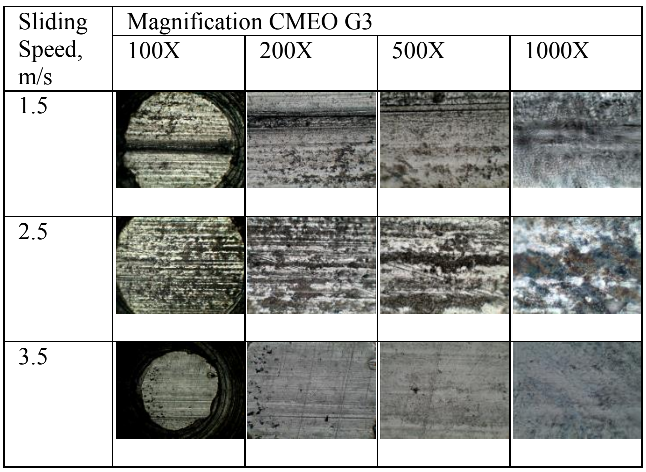


Figure 8 Micrographs of pin worn surface at different magnification levels for CMEO at groove 3

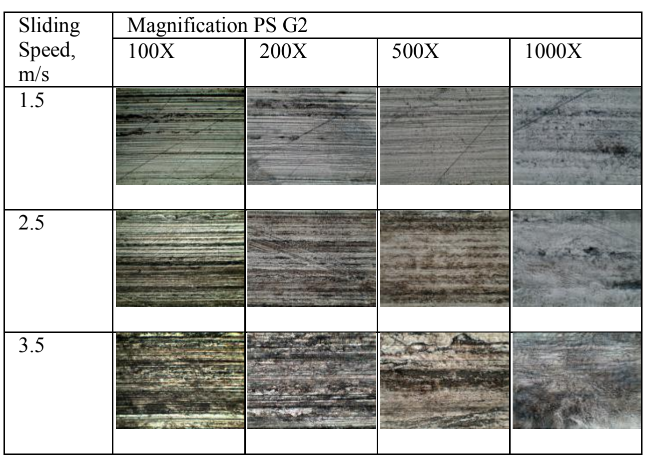


Figure 9 Micrographs of pin worn surface at different magnification levels for PS at groove 2

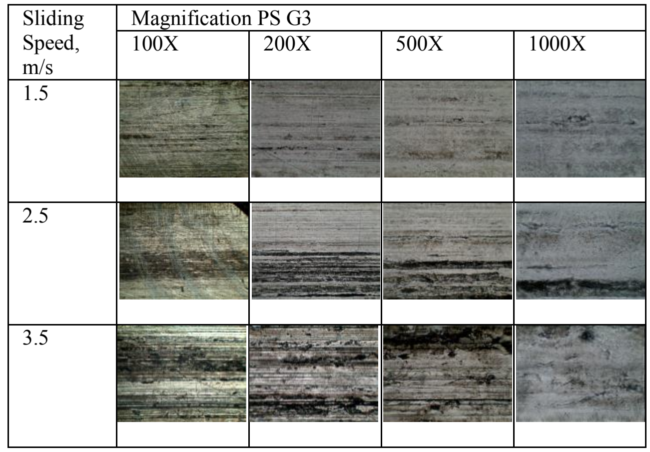


Figure 10 Micrographs of pin worn surface at different magnification levels for PS at groove 3

3.6 Surface Roughness

In this section, surface roughness test was conducted in order to understand the wear scar texture of the pin and its correlation to the coefficient of friction [19, 20].

Figure 11 shows that the graph of surface roughness of pin against the sliding speed for both lubricants palm stearin and CMEO. It was observed that the trend for CMEO is surface roughness of pin is inversely proportional to the sliding speed while palm stearin surface roughness of pin is directly proportional to the sliding speed. The CMEO surface roughness of pin has value 0.3875 micron at speed of 1.5 m/s and decrease to 0.2680 micron at speed 2. 5 m/s and lastly decrease only a little difference to 0.2585 micron at speed 3.5 m/s. For palm stearin surface roughness value of pin has highest value 0.600micron at speed 3.5 m/s. At the starting it has value of 0.2285 micron at speed 1.5 m/s and then increase to 0.3450 micron.

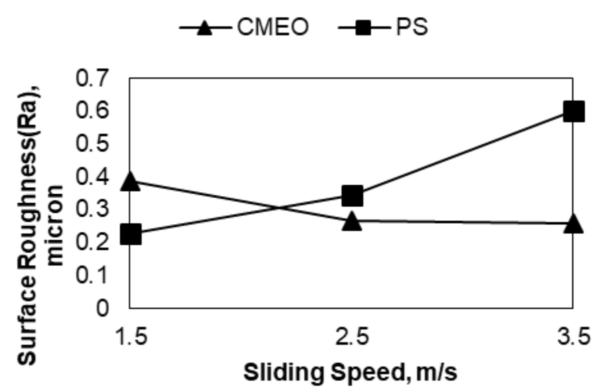


Figure 11 Surface roughness of pin versus sliding speed

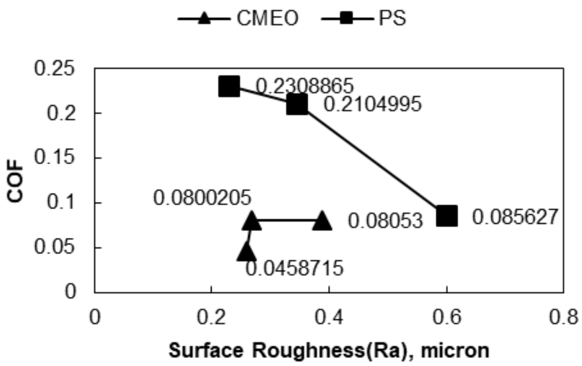


Figure 12 COF against surface roughness

Figure 12 shows the graph of COF versus surface roughness of the pin of both oils. From this graph the trend that can be seen for PS is the COF inversely proportional to the surface roughness of the pin. For the CMEO, the COF value increase drastically from 0.046 to 0.080. Then it remains constant until at the surface roughness of 0.4micron. In other words, the trend for CMEO is COF increase when the surface roughness of the pin increases. But, it only has very little different.

4.0 CONCLUSION

The tribological behaviour of RBD palm stearin and CMEO was evaluated using a pin on disc tribotester machine. The findings show that as sliding speed increases, the coefficient of friction value decreases for both oils. Palm stearin has a 45% higher coefficient of friction when compared to CMEO. The value of wear rates is directly proportional to the sliding speed for palm stearin and has higher wear rates compared to commercial mineral engine oil. Whereas commercial mineral oil has wear rates inversely proportional to the sliding speed. The wear scar diameter and volume loss is increasing as the sliding speed increases from 1.5 m/s to 3.5 m/s.

Acknowledgement

The authors would like to express their thanks to the RMC of UTM for the Research Grant, GUP (17H96,15J28,20H29), TDR Grant (05G23), FRGS Grant (5F074), School of Mechanical Engineering, UTM and Ministry of Higher Education for their support.

References

[1] Zulhanafi, P., & Syahrullail, S. 2019. The Tribological Performances of Super Olein as Fluid Lubricant Using Four-ball Tribotester. *Tribology International*. 130: 85-93.

[2] Noorawzi, N., & Samion, S. 2016. Tribological Effects of Vegetable Oil as Alternative Lubricant: A Pin-On-Disk Tribometer and Wear Study. *Tribology Transactions*. 59(5): 831-837.

[3] Afifah, A. N., Syahrullail, S., & Sidik, N. A. C. 2016. Magnetoviscous Effect and Thermomagnetic Convection of Magnetic Fluid: A Review. *Renewable and Sustainable Energy Reviews.* 55: 1030-1040.

[4] Shashidhara, Y. M. Ã., & Jayaram, S. R. 2010. Tribology International Vegetable Oils as a Potential Cutting Fluid — An Evolution. *Tribiology International*. 43(5-6): 1073-1081. doi:10.1016/j.triboint.2009.12.065.

[5] Razak, D. M., Syahrullail, S., Sapawe, N., Azli, Y., & Nuraliza, N. 2015. A New Approach Using Palm Olein, Palm Kernel Oil, and Palm Fatty Acid Distillate as Alternative Biolubricants: Improving Tribology in Metal-On-Metal Contact. *Tribology Transactions.* 58(3): 511-517.

[6] Golshokouh, I., Syahrullail, S., Ani, F. N., & Masjuki, H. H. 2013. Investigation of Palm Fatty Acid Distillate as an Alternative Lubricant of Petrochemical Based Lubricants, Tested at Various Speeds. *International Review of Mechanical Engineering.* 7(1): 72-80.

[7] Hassan, M., Ani, F. N., & Syahrullail, S. 2016. Tribological Performance of Refined, Bleached and Deodorised Palm Olein Blends Bio-Lubricants. *Journal of Oil Palm Research*. 28(4): 510-519.

[8] Sapawe, N., Samion, S., Zulhanafi, P., Nor Azwadi, C. S., & Hanafi, M. F. (2016). Effect of Addition of Tertiary-Butyl Hydroquinone into Palm Oil to Reduce Wear and Friction Using Four-Ball Tribotester. *Tribology Transactions.* 59(5): 883-888.

[9] Sidik, N. A. C., Khakbaz, M., Jahanshaloo, L., Samion, S., & Darus, A. N. 2013. Simulation of Forced Convection in a Channel with Nanofluid by the Lattice Boltzmann Method. *Nanoscale Research Letters*. 8(1): 178.

[10] Jabal, M. H., Ani, F. N., & Syahrullail, S. 2014. The Tribological Characteristic of the Blends of RBD Palm Olein with Mineral Oil Using Four-Ball Tribotester. *Jurnal Teknologi.* 69(6).

[11] Dolan, G. K., Yakubov, G. E., & Stokes, J. R. 2018. Bio-Tribology and Bio-Lubrication of Plant Cell Walls. *Annual Plant Reviews Online*. 1-42.

[12] Baumgart, P., Canzi, G., Hanashiro, T., Doezema, L. A., & Siniawski, M. T. 2010. Influence of Fatty Acid Additives on the Tribological Performance of Sunfl Ower Oil. August: 393-403. doi:10.1002/ls\.

[14] Saikko, V. 2017. Effect of Contact Area on the Wear of Ultrahigh Molecular Weight Polyethylene in Noncyclic Pin-On-Disk Tests. *Tribology International*. 114: 84-87.

[15] Baskar, S., Sriram, G., & Arumugam, S. 2015. Experimental Analysis on Tribological Behavior of Nano Based Bio-Lubricants using Four Ball Tribometer. *Tribology in Industry*. 37(4).

[16] Rani, S., Joy, M. L., & Nair, K. P. 2015. Evaluation of Physiochemical and Tribological Properties of Rice Bran Oil–Biodegradable and Potential Base Stoke for Industrial Lubricants. *Industrial Crops and Products.* 65: 328-333.

[17] Gusain, R., Dhingra, S., & Khatri, O. P. 2016. Fatty-Acid-Constituted Halogen-Free Ionic Liquids as Renewable, Environmentally Friendly, and High-Performance Lubricant Additives. *Industrial & Engineering Chemistry Research.* 55(4): 856-865.

[18] Ing, T. C., Mohammed Rafiq, a. K., Azli, Y., & Syahrullail, S. 2012. The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin. *Tribology Transactions*. 55(5): 539-548. doi:10.1080/10402004.2012.680176.

[19] States, U. (n.d.). Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. 1: 1-5. doi:10.1520/G0099-05.2.

[20] Zulkifli, N. W. M., Kalam, M. a., Masjuki, H. H., Shahabuddin, M., & Yunus, R. 2013. Wear Prevention Characteristics of a Palm Oil-based TMP (trimethylolpropane) Ester as an Engine Lubricant. *Energy*. 54: 167-173. doi:10.1016/j.energy.2013.01.038.

[21] Syahrullail, S., Nakanishi, K., & Kamitani, S. 2005. Investigation of the Effects of Frictional Constraint with Application of Palm Olein Oil Lubricant and Paraffin Mineral Oil Lubricant on Plastic Deformation by Plane Strain Extrusion. *Japanese Journal of Tribology.* 50(6): 727-738.

[22] Aiman, Y., & Syahrullail, S. 2017. Development of Palm Oil Blended with Semi Synthetic Oil as a Lubricant Using Four-Ball Tribotester. *Jurnal Tribologi*. 13: 1-20.

[23] Suresha, B., Hemanth, G., Rakesh, A., & Adarsh, K. M. 2019. Tribological Behaviour of Pongamia Oil as Lubricant with and Without Halloysite Nanotubes Using Four-Ball Tester. *AIP Conference Proceedings*. AIP Publishing. 2128(1): 030011.

[24] Golshokouh, I., Golshokouh, M., Ani, F. N., Kianpour, E., & Syahrullail, S. 2013. Investigation of Physical Properties for Jatropha Oil in Different Temperature as Lubricant Oil. *Life Science Journal.* 10(8s).

[25] Hafis, S. M., Ridzuan, M. J. M., Farahana, R. N., Ayob, A., & Syahrullail, S. 2013. Paraffinic Mineral Oil Lubrication for Cold Forward Extrusion: Effect of Lubricant Quantity and Friction. *Tribology International.* 60: 111-115.