Chin. J. Mech. Eng. (2017) 30:644–651
DOI 10.1007/s10033-017-0126-0

ORIGINAL ARTICLE

Tribological Testing of Hemispherical Titanium Pin Lubricated by Novel Palm Oil: Evaluating Anti-Wear and Anti-Friction Properties

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Received: 16 August 2015 / Revised: 23 March 2017 / Accepted: 30 March 2017 / Published online: 18 April 2017

Abstract In this study, the properties of hip implant material and lubricants were examined using a pin on disc apparatus, to compare the effect of metal-on-metal (MoM) contact with a bio-lubricant derived from palm oil. The behaviour of the lubricants was observed during the experiments, in which a hemispherical pin was loaded against a rotating disc with a groove. A titanium alloy was used to modify the hemispherical pin and disc. Before and after the experiments, the weight and surface roughness were analysed, to detect any degradation. The results were compared according to the different kinematic viscosities. The wear rates and level of friction with each lubricant were also examined. The lubricant with the highest viscosity had the lowest frictional value. Therefore, developing suitable lubricants has the potential to prolong the lifespan of prostheses or implants used in biomedical applications. The experiments collectively show that lubricants derived from palm oil could be used as efficient bio-lubricants in the future.

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Keywords Anti-wear · Anti-friction · Bio-lubricant · Palm oil · Titanium pin

1 Introduction

The oil palm (*Elaeis guineensis*) is one of two species of the Areacaceae or palm family, and was first documented in 1434 by a Gil Eannes, a Portuguese sailor [1, 2]. The oil palm tree is easily cultivated in Malaysia, can grow to a height of 20 m at favoured temperatures between 24 °C and 27 °C, and develops pinnate leaves that are 3-5 m long. The oil palm thrives in humid climates, cultivated palms bear fruit from the fourth year onward, and can be harvested for 40 to 50 years [1]. Palm oil is extracted from the fleshy part or mesocarp of the fruit of *Elaeis guineensis*. However, the *Tenera* palm, which is a hybrid of the *Dura* and *Psifera* species, is now a widely cultivated crop in Malaysia, due to greater commercial and processing viability, as the oil yield is higher, harvesting is easier as the trees shorter, and they produce larger bunches of mesocarps with thinner shells [3].

Palm oil has a wide range of applications, and about 80% of the harvest is used for food applications, such as cooking oil, margarine, and shortening. Some of the yield is used as feedstock for a number of non-food applications, such as in soap, detergent, and cosmetics [4]. Palm oil and its products have good resistance to oxidation and can produce heat at prolonged elevated temperatures [5]. Malaysian palm oil is also used in the manufacture of many other downstream oleo-chemical products, including palm fatty acids, and palm methyl esters [2].

Currently, palm oil is one of the main bio-lubricant contenders in medicinal and health-based applications. It is also the Malaysia vision to develop the industry, and it is already one of the largest palm oil producers in the world

[6, 7]. There is still some room for improvement in cultivation and research in the palm oil industry, as production is only the second largest worldwide production, behind soya bean vegetable oil [8]. Palm oil is predominantly composed of unsaturated fatty acid, triglycerides, and non-glycerides. The high level of unsaturated fatty acids creates a high-strength lubricant film, and acts as a boundary lubricant that will interact directly with contacting surfaces. The presence of this boundary also has the ability to reduce friction and wear [9–12].

Hip implant failures are frequently caused by severe friction and wear between MoM articulating surfaces, thus reducing the lifespan of a hip implant or a total hip replacement. In this study, the main focus is to investigate ways to reduce the wear and friction on the biomaterial used in human implants, by conducting experiments with a conventional pin on disc apparatus. The main material used is titanium for both the disc and the hemispherical or radius-ended pin. Many researchers have studied the use of titanium as an implant material in orthopaedics, because of its excellent mechanical properties, corrosion resistance and biocompatibility [13–16]. Mechanical attributes of titanium, such as the ductile and yield strength of titanium alloys, tolerate conditions when used as implants.

The biocompatibility of titanium with human tissues has made it a preferred choice as an implant material [17, 18]. It has a high fatigue strength at 10^7 cycles compared to other metals suitable as biomedical material [19]. The latest generation of orthopaedic-grade titanium has further increased biocompatibility and lower modulus has also been achieved. Tissue engineering in regenerative medicine is another area in which titanium is used, and as a component in artificial heart valves, dental implants, artificial joints, orthopaedic screws, pacemaker cases, and vascular stents [20–23].

The protein-based prosthetic lubricant has been widely appraised in recent studies on MoM devices. The concentrated fluid is used in implants, and reduces prosthetic appliance wear. However, various types of lubricants have undergone *in-vitro* testing [24]. In our novel study, we explore and experiment with the use of a bio-based or artificial lubricant, derived from palm oil, that has biocompatible viscosity properties and are therefore potential future bio-lubricants for use in the human joints. Therefore, the aim of this study is to compare the wear rate and friction coefficient for MoM applications, and investigate how, using palm oil as an innovative bio-lubricant, that can prolong the lifespan of an implant or prosthesis, and also lead to better health and improved quality of life.

2 Experimental

2.1 Materials

A Ducom TR-20LE pin on disc tribometer for screening MOM friction and wear was used. The materials selected for this experiment were made of titanium with density of 4.54 g/cm^3. The pin was 8 mm in diameter and was 30 mm long. Abrasive sandpaper, with a grain size of 1000 µm, was used to scrub the disc after the completion of each experiment, to ensure no particles or debris was trapped between the disc and the pin. The surface textures of the pin and the disc were measured by examining the surface profile. A new pin was used for each experiment, and it was cleaned with acetone.

2.2 Friction and Wear Evaluation

A modified disc with a groove was used, in order to understand the progression of wear and friction during the specified period, and the same amount of lubricant was applied in each experiment. The lubricant was manually dripped onto the modified disc, which had a 10 mm-wide groove with a depth of 5 mm, to prevent the lubricant from escaping as the disc rotated at high speed. As shown in Fig. 1, the wear track was adjusted by loosening and re-fixing the sliding plate at 70 mm, while conducting experiments.

2.3 Surface Profile

The surfaces of the pin and disc were measured before and after the experiment, by examining roughness profiles with a stylus, to evaluate the surface patterning. The surfaces of the disc were ground unidirectionally using abrasive sandpaper to a surface finish with an approximate arithmetic R_a value of 0.4±0.1 µm before the start of the experiment.

2.4 Lubricants

The lubricities of Refined, Bleached and Deodorised (RBD) Palm Olein (PO), was compared to additive-free paraffinic mineral oil (P2) and hydraulic oil (HYDO). The amount of lubricant used for each experiment was approximately 5 mL. The density and viscosity of the oils were measured at several temperatures between 40 °C and 100 °C using a viscometer and the results are shown in Table 1.

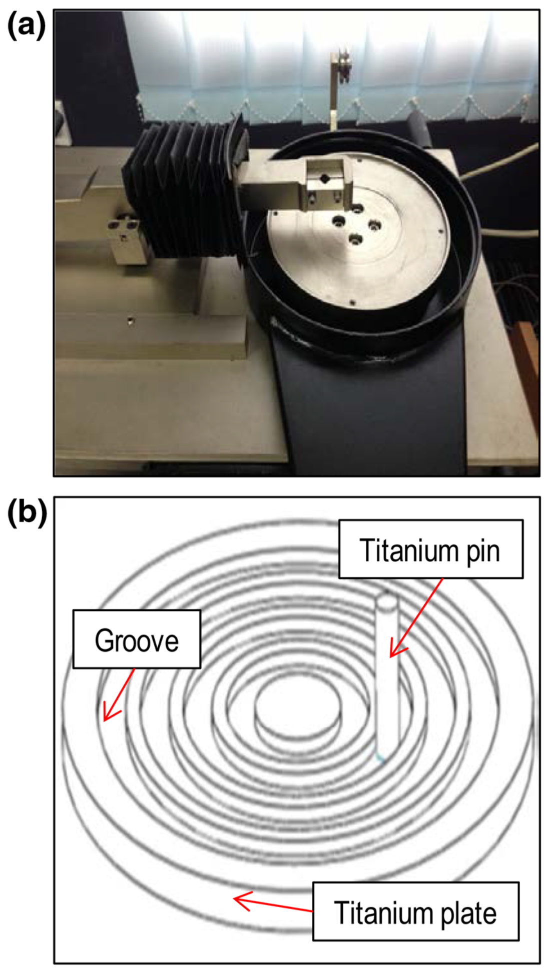

Fig. 1 Tribometer system (a) pin on disk (b) arrangement pin and disk (MoM)

Table 1 The properties of different type of lubricating oil

Properties	Type of lubricating oil		Test method
	RBD palm olein	Paraffinic mineral oil	
Density at 25°C (kg/ m^3)	873	848	ASTM D1298-85 (90)
Kinematic viscosity at 40°C (mPa·s)	38.9	96.5	ASTM D445-94
Kinematic viscosity at 100°C (mPa·s)	5.3	14.1	ASTM D445-94

3 Results and Discussion

3.1 Friction Coefficient

To obtain viscosity measurements, the wear tests were carried out under different loads, described in Fig. 2(a).

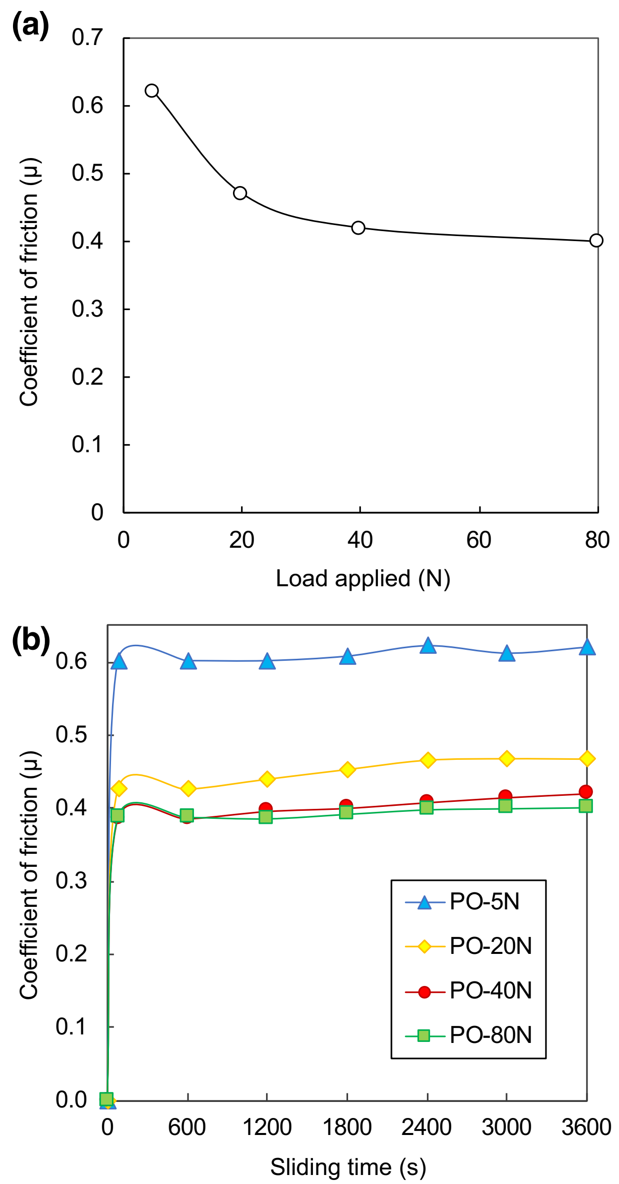

Fig. 2 Graph of (a) coefficient of friction versus load applied and (b) coefficient of friction versus sliding time

The load was exerted onto the pin at a constant speed for 3600 s. A higher coefficient of friction (COF) value was recorded when the load applied was lower. At a load of 5 N, the COF was 0.62, and the COF decreased to 0.47 at 20 N and gradually reduced further to 0.42 beyond loads of 40 N. At the completion of the experiment, a COF of 0.40 was recorded at an 80 N load. The stability of the palm olein COF, demonstrated that the lubricant can reduce friction by forming a film which can easily be sheared. The curves of friction coefficient versus time also recorded and shown in Fig. 2(b).

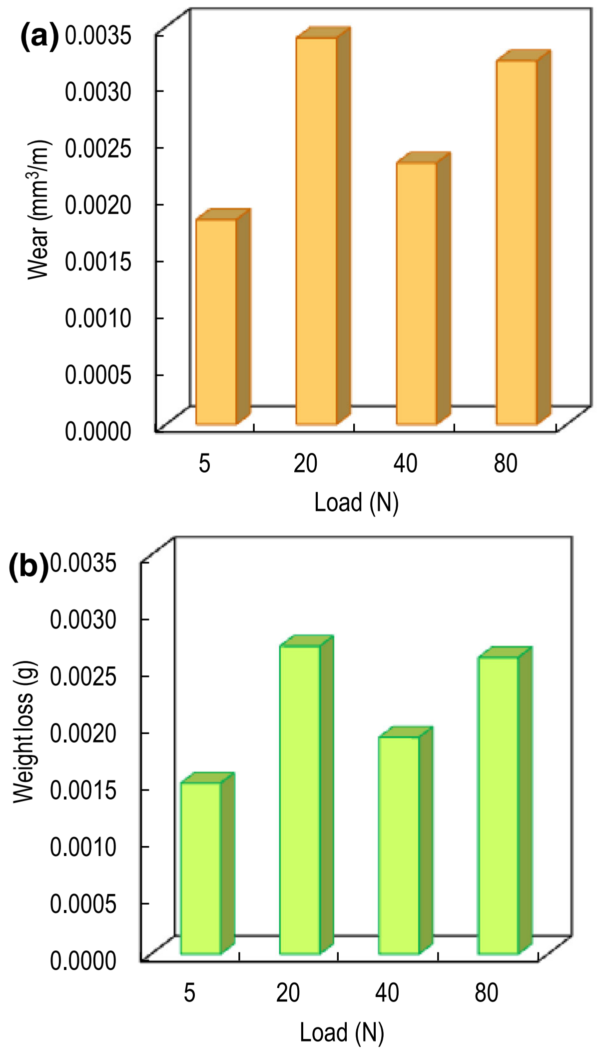

Fig. 3 Graph of (a) wear (b) weight loss of the pin metal versus various load (after experiment)

3.2 Wear Testing and Evaluation

Wear was studied using a Linear Variable Differential Transformer (LVDT). The wear rate and specific wear rate were calculated from the loss in weight detected after the experiment, illustrated in Fig. 3(a). It was observed that for each of the three lubricants applied at the interface, there is a similar curve pattern for all load conditions. The wear caused by the pin increased when 5–20 N loads were applied, then decreased after a 40 N load was exerted, and ultimately wear increased again evenly, as the load approached 80 N. The highest level of wear recorded was approximately 240 μm, after 20 N and when 80 N loads were applied. In Table 2, the minimum values of film thickness (h) are quantified. The minimum film thickness (h_{min}) is calculated using the Hamrock and Dowson equation [25].

Table 2 Experimental data of screening wear MoM by different load

Load (N)	COF	Wear resistance (mm^3/m)	Weight loss of metal (g)	Minimum film thickness	Sommerfeld value
5	0.631	0.0018	0.0015	<3	1.56×10^{-5}
20	0.484	0.0034	0.0027	>3	3.89×10^{-6}
40	0.428	0.0023	0.0019	<3	1.95×10^{-6}
80	0.402	0.0032	0.0026	>3	9.73×10^{-7}

The incremental wear of the titanium pin at different loads, caused by sliding against the titanium disc, is shown in Fig. 3(b), and was confirmed by the loss in weight. Loads of 5–20 N were tested. There was an inconsistent reduction in weight, and a spontaneous rise to 0.0027 g. The loss in weight then decreased to 0.0019 at loads greater than 40 N, before further hikes to 0.0024 and 0.0026 for P2 and PO respectively at loads beyond 80 N. The similarity of graphs plotted from the results of the LVDT sensor show a correlation, between weight loss and the wear rate. However, the pin lubricated with HYDO had a much greater reduction in weight compared to the other oils, although the trends were similar.

The COF for the palm oil showed better anti-friction characteristics, with low values for all loads exerted on the hemispherical titanium pin. The main factor is the high proportion of Free Fatty Acids (FFA) and the presence of the polar –COOH group in palm olein [26, 27]. The FFA contain long, covalently bonded, hydrocarbon chains [9, 28]. This study suggests that the presence of a monolayer film or the molecule layer formation of FFA in palm olein is most promising. The formation of the film is particularly significant, because it is easily absorbed to the metal surface, and can minimise material transfer and reduce the mating surface [9, 29]. The film allowed the hemispherical pin to slide smoothly against the disc with less resistance. This phenomenon could reduce the amount of energy converted to heat or noise, instead of motion.

Table 2 confirms that the friction coefficients for palm oil steadily decreased with loads from 5 N to 80 N. This can be explained by the shear rate, which is proportional to the hardness and strength of the titanium implant material. As the load increased, so did the shear rate produced during movement. This is because the surface area of the MoM contacting surfaces is smaller, which facilitates the movement of the titanium pin, therefore reducing friction [30]. Unexpected results can be explained by the temperature of the lubricant. The temperature at the interface is proportional to the load [31]. Viscosity of the lubricant is inversely proportional to the temperature [32].

It is believed that the phenomenon occurs only in hydrodynamic lubrication. The coefficient is generally influenced by the sliding speed, load exerted, and viscosity [33]. As the load is increased, the temperature of the

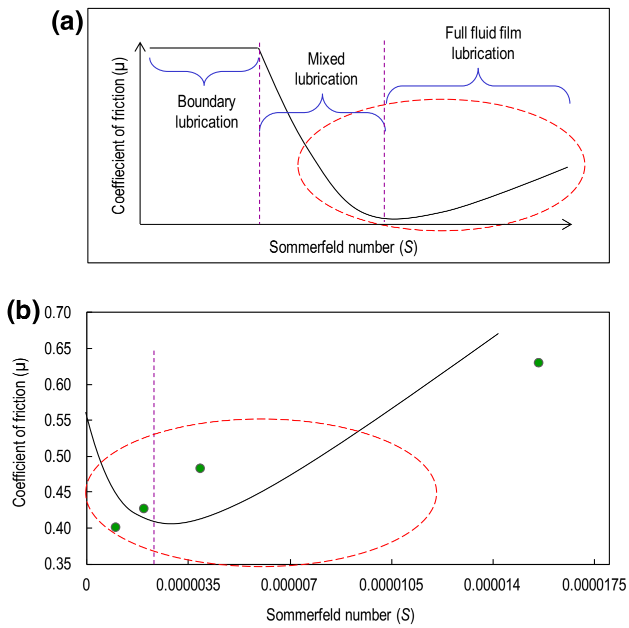

Fig. 4 Stribeck curve (a) theoretical (b) MoM (Ti-Ti) with palm oil lubrication

lubricant increases. The loading is fully carried by the asperities in the contact area, by the combination of decreased viscosity, increased load, and a constant sliding speed, with the surfaces completely separated by a thin oil-film. This is attributed to the reduction in the friction coefficient, which can be demonstrated by the Stribeck curve in Fig. 4. The high wear rate obtained after high load is exerted specifically at 20 N and 40 N. It is believed that wear particles of titanium pin may get locked between sliding surface or transferred and embedded to mate disks subsequently gave many damages to the pin and led to the adhesive action, and promote three bodies which should enhance volume loss in wear [34, 35].

The wear debris from MoM will be trapped at the interface and will act as an extra layer to aid the motion of the pin and disk, thus decreasing the friction coefficient as the load applied is increased. It is also believed that the high temperature generated at the interface influences the wear dominated by the pin. The lower viscosity could attribute to reduction of protective film resulting in breakdown of boundary lubrication [36]. The thin film formed by free fatty acid which acts as a barrier from a direct metal to metal contact become less stable, thinner and insufficient and thereby causes an increment of wear resistance [9, 27].

3.3 Effect of Bio-lubricant Toward Anti-Friction and Anti-Wear

The studies on the effects of lubrication on two surfaces in the hip joint between metal on metal materials were already conducted by several researchers. Most of the study imbued a notion that the condition of mixed lubricant and fluid film can determine the effects of surface friction and wear especially in MoM. The Stribeck curve was shown in Fig. 4 at 5 N loads to 80 N to categorize the friction properties between metal on metal material. The friction regimes for sliding lubricated surfaces may be categorized in three conditions. There is (a) solid/boundary friction; (b) mixed; and (c) fluid friction. In this study, the characteristic of palm oil as lubricant was presented against the analysis of Stribeck curve.

The data coefficient of friction and Sommerfeld number that used to plot the curve was collected from Table 2. The plotted result was implemented in mixed and fluid film lubrication. Mixed lubricant used for 5 N to 20 N loads consequently stabilizes the MoM. This is a positive condition for MoM shows lower friction. Meanwhile, 20 N frictions were recorded in fluid film condition. The condition may cause the MoM to be dislocated or misplaced. Therefore, in order to maintain the dislocation caused by lubricant, other factors such as the speed and load have to be considered. The future of palm oil as lubricant would work together with protein to enhance the performances which may influence the MoM mechanism. Brockett, et al[37] found that the friction factor increasing significantly with load added in MoM by using 25% bovine serum. Determinations of friction of contact surface of hip implant were also varied with surface, cup and femoral size, load and lubricant [38].

The MoM implants study demonstrated increased both friction, wear and weight loss when the load applied was increased. Similar results for the MoM implants were also achieved, and the trend for increasing friction factor with increasing phase load is existed. From the Stribeck curve plotted (Fig. 4), the condition of the lubricant was expected in the mixed lubrication regime and full fluid film lubrication. At a lower COF (below around 0.4) suggests mixed lubrication, where $h_{min} < 3$. The result shows that MOM materials with palm oil are the preferable condition in order to reduce friction and wear as followed by a red dotted circle.

In the first regime boundary film lubrication, the load between 5 N to 20 N were carried by the surface asperities rather than by the lubricant supplied. At this boundary, the coefficient of friction is the ratio of the effective shear stress and the MoM of the contact materials (Titanium versus Titanium) and is typically in the range of 0.4 and higher. The MoM sliding surfaces with palm oil as lubricant is more significant. Palm oil helps to reduce friction by forming a low-shear strength interface between hard metal contacts. The presence of fatty without protein show the capability of palm oil as bio-lubricant in the future that stand a low shear-strength layer that minimizes friction on the MoM.

The full fluid lubrication regime is similar to hydrodynamic lubrication with the significant difference that the pressure is generated by human hip that maintains a continuous supply of pressurized lubricant. The frictional force is minimal at a very slow sliding speed, making this type of lubrication useful for smooth movement and other joint. One of the disadvantages of hydrostatic lubrication is that the process depends on the reliability of the surface and material used. Overloading and extreme speed may cause wear and dislocation, thus is seen as a risk. The mixed lubrication is placed between hydrodynamic and boundary due to the viscosity of palm oil decreases parallel to the increased speed, and the load affecting the sliding MoM surfaces. The Stribeck curve indications friction as a function of viscosity, speed and load.

3.4 Surface Roughness Analyses

The nature and surface texture of hip implant surface significantly affect the wear and friction coefficient of the mating component (MoM). The main parameter which defines the surface smoothness which can easily be controlled is the surface roughness. The strong influence of surface roughness on wear and friction as well as the improvement can be achieved in this aspect are shown in Fig. 5.

The correlation between surface roughness and wear and friction could be achieved as well. The graphs clearly demonstrate that the wear and friction coefficient depend on surface roughness as well. The low value of R_a lubricated with palm olein is due to the fatty acids of palm oil stuck well on pin and disk surface. This created a thin layer of film and it preserved the surface, resulting in better surface finishing and also lower wears resistance and friction. The surfaces were captured using a microscope with the magnification 200× and the mean wear scar diameter after is 3600 s during testing (Fig. 5). As the load applied is increased, the surfaces of the pin become more severe as shown in Fig. 5. Abrasion and adhesion consistently dominated the wear pin surfaces. The abrasion and adhesion increased considerably as the higher load is exerted to the pin. This condition is indicated by the removal of surface material, thus resulting in creating a groove surface of the pin metal.

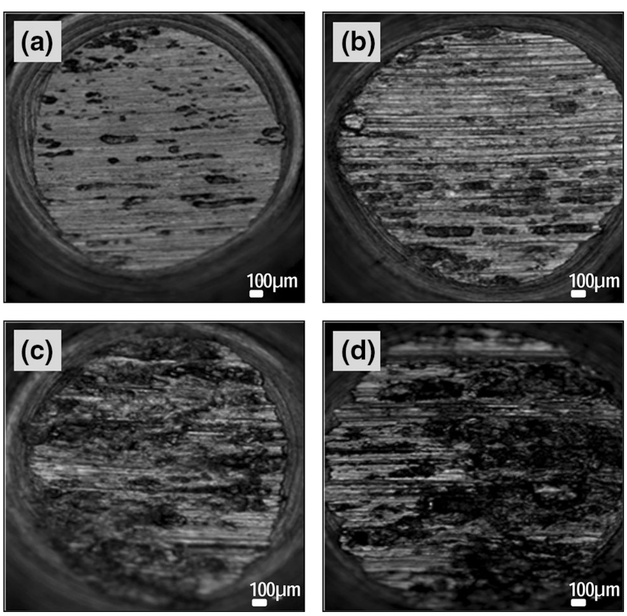

Fig. 5 Micrographs of wear worn surfaces on head/pin with load (a) 5 N (b) 20 N (c) 40 N (d) 80 N in 200× magnification

3.5 Mechanism of Wear Scar

As the load increased from 5 N to 20 N, the abrasion mechanism was noted on the worn surface for all lubricating oils excluding the surface lubricated. The abrasive wear formed on the worn surface possibly ploughed by stiff debris or particles from the environment and was squeezed against the softer mating component. These ploughing mechanisms occurred when the particles or debris was unnoticeably embedded between the surfaces is greater than the oil film thickness [39]. The deep grooves observed indicates that the collision of a slight difference asperities of the contacted surfaces and may become one of the sources of further damage for the contacting surfaces.

The mild erosive wear had also been observed on worn surfaces lubricated with palm oil. These minor losses or removal of material could be reflected as a form of abrasive wear. The surfaces entrapped with internal particles of ploughed material endure constant impact during sliding may be one of the initial causes for abrasive wear. The narrow groove surfaces observed for samples lubricated with palm oil were continuously protected by thin film form or oxide layer attributed to less direct contact of mating components.

As the load increased to 80 N, the findings in Fig. 5 reveal that the worn surfaces are dominated by severe adhesive wear mostly occurred at load 80 N. It is believed to have occurred because of the combination of high loads; pressured and high temperatures influence and facilitate the collision of the different variation of hard asperities of the pin and disk (MoM). During continuous sliding between contacting surfaces, the material will be transferred across the contact [40].

As the load increased from 40 N to 80 N, the increased pressured produced during sliding accelerates the formation of an adhesive wear due to the oxide layer could not fully protect the surfaces attributed to the shearing of more junctions at the interface. As the adhesion forces during sliding are high, the shear of the asperities takes place at the weakest point resulting in detachment of fragments of pin surfaces and attached to the disk surface. The worn surfaces lubricated with palm oil shows a severe adhesion mostly at 80 N. This situation indicates that the breakdown of lubricant and a protective layer will not withstand resulting in the metal on metal direct contact.

4 Conclusions

The investigation of hip feature is represented as MoM wear in the tribological behavior of palm oil was obtained using a pin on disk tester. The viscosity of lubricant is inversely proportional to lubricant applied. The friction coefficient obtained lubricated with palm olein is better. The friction coefficient for MoM by lubricating palm oils decreased as the applied load increased. The factor of unsaturated fatty acids plays an important role in reducing the friction coefficient and wear. Finally, a great bio-lubricating oil-based palm oil was generated due to no additive formulation and reducing friction coefficient at various applied loads.

Acknowledgements The authors are grateful for the financial support by the Research University Grant (RUG) from Universiti Teknologi Malaysia (Grant No. 03H58), Fundamental Research Grant Scheme (FRGS) from Ministry of Higher Education (MOHE) Malaysia, E-ScienceFund Grant and Exploratory Research Grant Scheme (ERGS) from Ministry of Science, Technology and Innovation (MOSTI) Malaysia, the awards of the UTM-RMC Postdoctoral Fellowship (Norzahir Sapawe), and also the Faculty of Mechanical Engineering Universiti Teknologi Malaysia for their support.

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