ELSEVIER
Wear 206 (1997) 179–186
WEAR

Investigation of the anti-wear characteristics of palm oil methyl ester using a four-ball tribometer test

H.H. Masjuki, M.A. Maleque *
Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Received 27 June 1996; accepted 16 September 1996

Abstract

The aim of this study was to assess the anti-wear characteristics of palm oil methyl ester (POME) in elastohydrodynamic lubrication of EN31 steel ball bearings. A conventional four-ball wear testing machine with different loads was used at 1500 rev min^{-1} and a test duration of 1 min at ambient room temperature (approximately 28 °C). Optical microscopy of wear worn surfaces revealed the wear mode of mating surfaces. The results provide an understanding of the wear characteristics of ball bearings under POME contaminated lubricants. It was found that POME worked as an additive and improved the anti-wear characteristics. The flash temperature parameter (FTP) of the lubricant after each test was also measured. © 1997 Elsevier Science S.A.

Keywords: Four-ball machine; Palm oil methyl ester; Wear; Flash temperature parameter

1. Introduction:

In 1983, the Palm Oil Research Institute of Malaysia (PORIM) successfully converted crude palm oil (CPO) to palm oil methyl ester (POME) through trans-esterification. The trans-esterification shortens the molecular chain from about 57 to about 20, thus reducing the viscosity and improving the thermal stability. The sulphur content in POME is very low (0.002 wt.%), making it less pollutant and more environmentally friendly. However, the cetane number of this POME is relatively low (50–52) compared with ordinary diesel (53) [1].

Additives such as benzotriozole [2], and benzotriozole acyl derivatives [3] have been identified as useful lubricant additives. They posses anti-wear properties as well as anti-corrosion and anti-rust properties, but their solubilities in mineral oil are extremely limited. *N*-nonyloxy-methyl-benzotriozole is also found to be an anti-wear agent in synthetic lubricants [4]. Sulphurized olefin (SO) and tricresyl phosphate (TCP) are two typical and widely used extreme pressure and anti-wear additives [5,6]. Information about open-chain sulphur compounds as anti-wear and extreme pressure (EP) lubricant additives is available in the literature [7–10]. Bhattacharya et al. [11] reported the preparation and evaluation of the EP activity of certain substituted 2-amino-benzothiazolylbenzoylthiocarbamides (2-amino-BTBTCs) as additives in paraffin oil. Another investigator [12] considered the change in surface properties of bearing material, which improved the anti-wear characteristics.

Many studies using different base oil lubricants [13], paraffin oils [14] and additives [11,15] have been done and published recently. However, none of them have used POME as base lubricant or additive. The present authors' first investigation of the sliding wear of different cast irons under different percentages of palm oil diesel, also known as palm oil methyl ester (POME), contaminated lubricants [16] showed that generally POME acts as an additive and improves the anti-wear characteristics.

This paper presents and discusses results of current studies on the effects of different percentages of POME blended lubricants on the wear characteristics of ball bearings made of EN31 steel using a four-ball machine with varying loads.

2. Apparatus, materials and procedure

2.1. Apparatus

The four-ball wear machine (Fig. 1) was used as required by standard IP-239 in this investigation [17]. This is a simple test rig for testing the anti-wear properties of lubricating oils. It consists of a device by means of which a ball bearing may

* Corresponding author.

PII S0043-1648(96)07351-6

Table 1
Chemical composition (wt.%) and hardness of EN31 steel ball material

Material	C	Si	Mn	S	P	Cr	Fe	VHN
EN 31	1.0	0.35	0.5	0.05	0.05	1.3	Balance	805

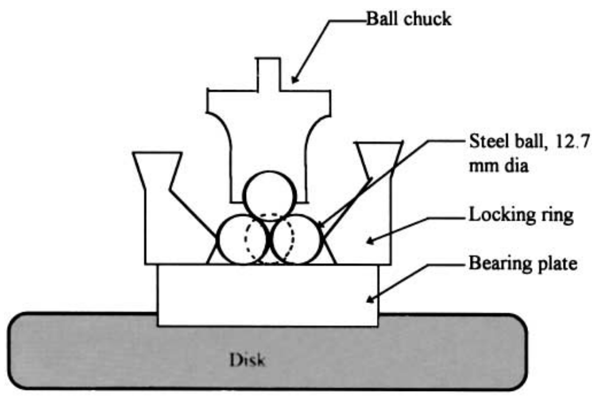

Fig. 1. Schematic diagram of the four-ball wear machine.

be rotated in contact with three fixed ball bearings which are immersed in the sample. Different loads are applied to the balls by weights on a load lever. The upper rotating ball is held in a special chuck at the lower end of the vertical spindle of a constant speed electric motor. The lower fixed balls are held in position against each other in a steel cup by a clamping ring and locking nut. The frictional torque exerted on the three lower balls can be measured by a calibrated arm, which is connected to the spring of a friction recording device. The extension of the spring in resisting the frictional torque is transmitted through a link mechanism, to a pen which records its travel on a drum at 1 revolution in 60–75 s.

2.2. Materials

The ball test material was EN31 steel, 12.7 mm in diameter, with a surface finish of 0.1 μm CLA. The chemical composition and hardness of this material are listed in Table 1 and its microstructure is shown in Fig. 2. Before starting a series of tests, four new balls for each test run were cleaned using spirit alcohol and dried with dry air.

2.3. Lubricants

The lubricants used for each test were diesel engine oil of SAE 10 (oil A) and SAE 30 (oil B) grades. These oils were then contaminated with 3%, 5%, 7% and 10% by volume of palm oil methyl ester (POME). Details of the properties of POME are given in Table 2 [18].

2.4. Test procedure

At the beginning of the experiment, POME contaminated lubricants are placed on the erected plate, three balls are held in position in the cup with the clamping ring, and the assembly

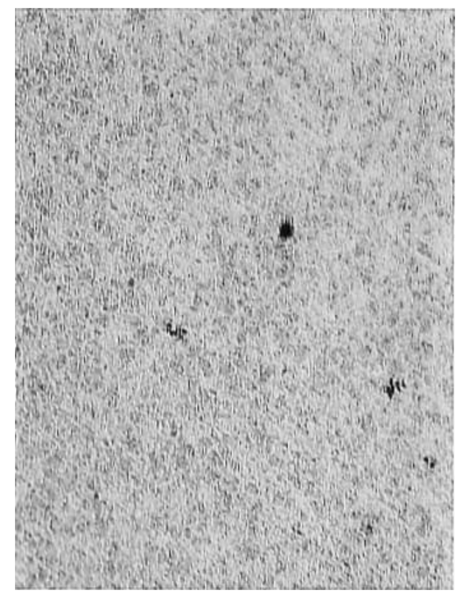
Fig. 2. Microstructure of as-received EN31 ball bearing material (200×).

is secured by tightening the locknut. The fourth ball is fitted into the upper ball chuck and the chuck is fitted into the taper in the end of the motor spindle. Mounting disks are placed between the thrust bearing and the cup and the required loads are then placed on the load lever to give the desired load.

2.5. Friction evaluation

The appropriate spring (extra weak range of loading up to 80 kg) was fitted to the friction recorder. On the friction recorder chart the peak was measured in millimetres to the nearest 0.2 mm. The coefficient of friction was calculated by multiplication of the mean friction trace and spring constant as given in Ref. [17].

2.6. Wear test

The test run was carried out at load range from 51.2 kg to 64 kg and at 1500 rev min^{-1} with a test duration of 1 min. The wear scar diameter (WSD) was measured using a meas-

Table 2
Properties of palm oil methyl ester (POME)

Specific gravity	0.8700 at 28 °C
Colour (visual)	Reddish
Sulphur content (wt.%)	0.002
Kinematic viscosity at 40 °C (cSt)	4.5
Flash point (°C)	174
Cetane number	50–52

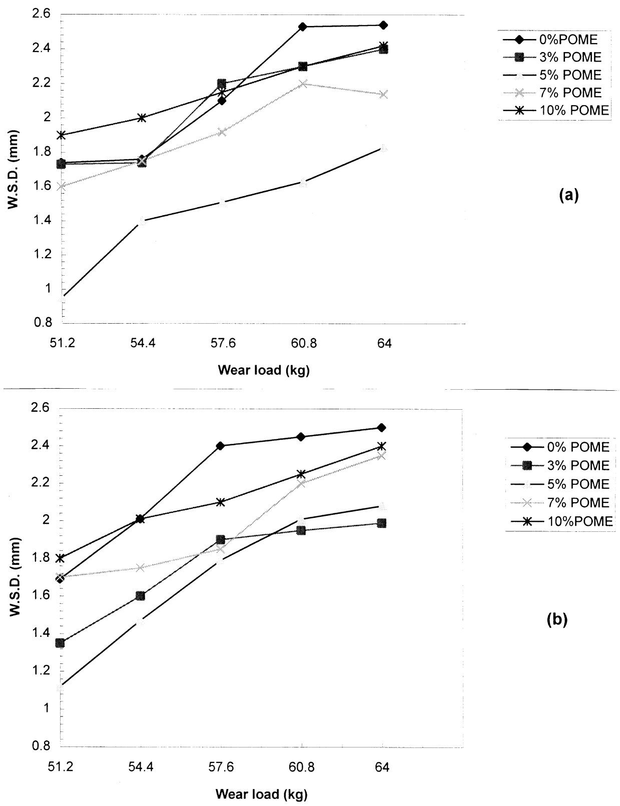

Fig. 3. The effect of different loads on the wear scar diameter for different percentage of POME.

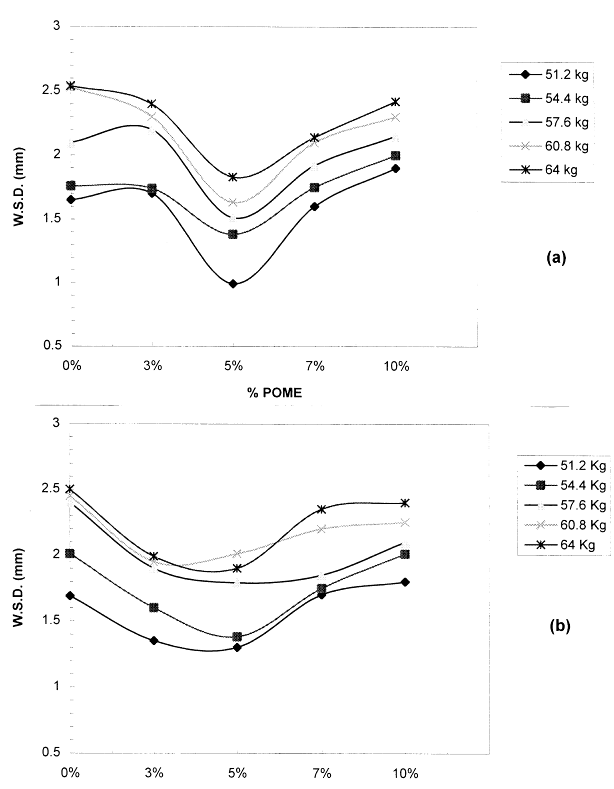

Fig. 4. The effect of different percentages of POME on the wear scar diameter for different loads.

uring microscope according to the procedure of Stanhope-Seta Ltd. which is similar to ASTM D2266.

2.7. *Flash temperature parameter*

A single number is used to express the critical flash temperature above which a given lubricant will fail under given conditions. For conditions existing in the four-ball test, the following formula was used:

$$\mathrm{FTP}=\frac{W}{d^{1.4}}$$

where W is the load in kilograms, and d is the mean wear scar diameter (WSD) in millimetres at this load. Detailed explanation of the FTP can be obtained from Ref. [19].

2.8. *Microstructure*

Before metallurgical study, the ball specimen was polished and etched according to standard procedure and the microstructure was observed under an optical microscope. Finally, after wear testing, the metallurgical interaction of the mating surfaces including the area around the wear scar and worn surfaces was observed by optical microscopy.

3. Results and discussion

The performance of POME as a lubricant additive in tribometer tests was investigated. The results obtained in the

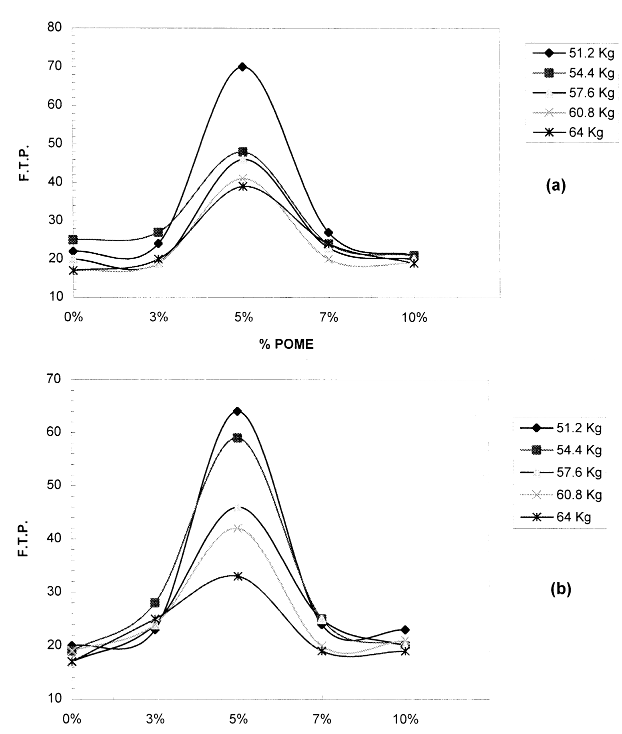

Fig. 5. Plot of POME percentage vs. flash temperature parameter for different wear loads.

tribometer tests present a good opportunity for discussing the significant performance of POME as a lubricant additive which improves the anti-wear characteristics in a four-ball tribometer test.

3.1. Wear behaviour

Figs. 3 and 4 show the effect of different percentages of palm oil methyl ester (POME) on the wear scar diameter (WSD) for different loads when blended with different categories of commercial lube oils. From the figures it is clear that the WSD increases gradually with an increase in wear load [11]. This increase in the value of WSD could be due to either the POME–metal surface interaction or a reduction in pressure or both. The decrease in pressure may be attributed to an increase in the wear scar or contact area, especially when the lube oil was contaminated with higher percentages of POME, i.e. 10% or pure lubricant. However, the rate of increase of WSD can be reduced by adding lower percentages of POME. This is clearly observed in the case when 5% POME was added to the lubricants. The WSD was reduced by about 20% compared with the use of pure lube oil. However, for other percentages of contamination, the WSD was observed to be slightly higher compared with 5% POME contamination (Figs. 3 and 4). With the addition of 10% POME, the WSD increased and was slightly higher than that for 7% POME contaminated lubricant, indicating intermediate behaviour of the wear. The maximum wear occurred when pure lubricant was used, particularly at loads beyond 57.6 kg, indicating lubricant failure at this high load.

3.2. Flash temperature parameter

Fig. 5 is the plot of POME percentage vs. flash temperature parameter (FTP) for different wear loads. From the figure, it can be seen that the maximum and minimum FTP were obtained from 5% contaminated lubricant and pure lubricant respectively. The maximum FTP value means that good lubricating performance occurred, indicating less possibility of lubricant film breakdown. This phenomenon is also observed by other workers [11]. This seems to indicate that POME is a potential anti-wear additive for lubricating oil. The 5% POME in this investigation improved the lubricant performance, based on the higher value of FTP observed compared with pure lubricant. The graphs also show the effect of applying load on the FTP of lubricants. Generally, the lower the load applied the higher the FTP, while the higher the load

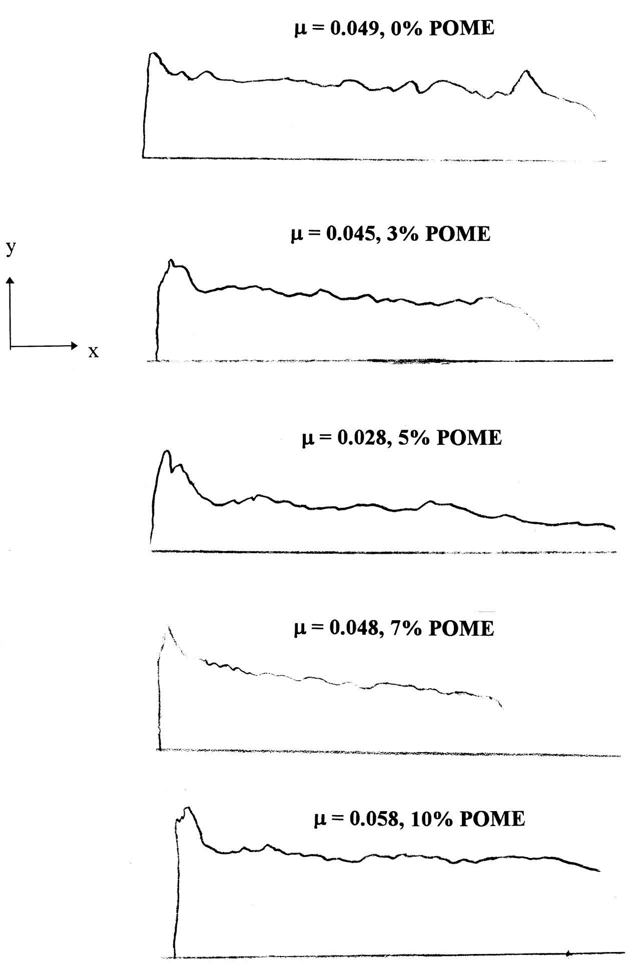

Fig. 6. Friction force plot for the ball specimen under oil A lubricant, recorded for 1 min, at a load of 64 kg. In the figure, the y-axis indicates friction force and the x-axis indicates time. The peak value in friction confirms that this load is the initial load.

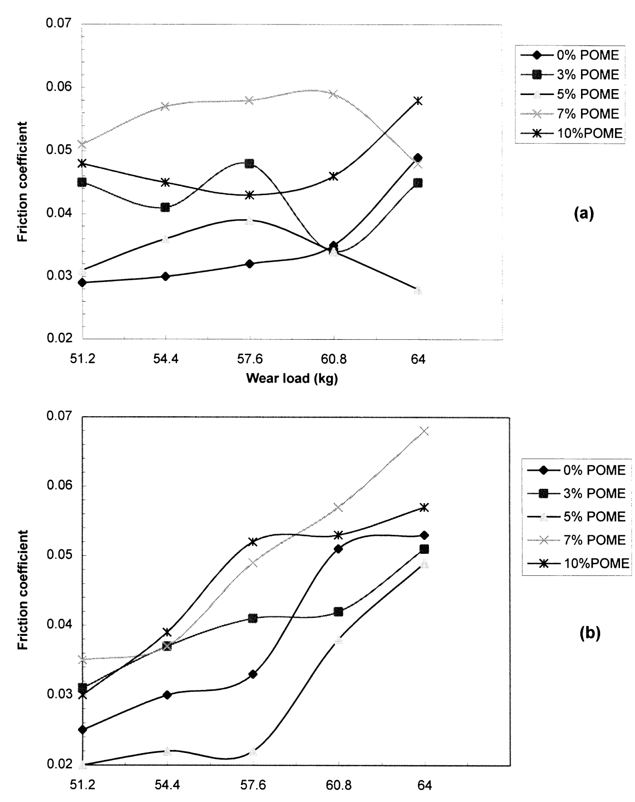

Fig. 7. Variation of friction coefficient vs. load for different percentages of POME contamination.

applied the lower is the FTP. This may be attributed to the WSD of worn specimens, because the WSD increases with increasing load. It can also be seen that pure lube oil A exhibits a higher value of FTP (Fig. 5(a)) compared with oil B (Fig. 5(b)). This means that oil A is a comparatively better lubricant and blending with POME enhances its lubricating performance.

3.3. Friction properties

Fig. 6 shows the friction force of ball-bearings under lube oil A with different percentages of POME contamination. An almost constant and lowest value of friction force was found for 5% addition of POME to lube oil compared with other additions. However, for other combinations of POME with

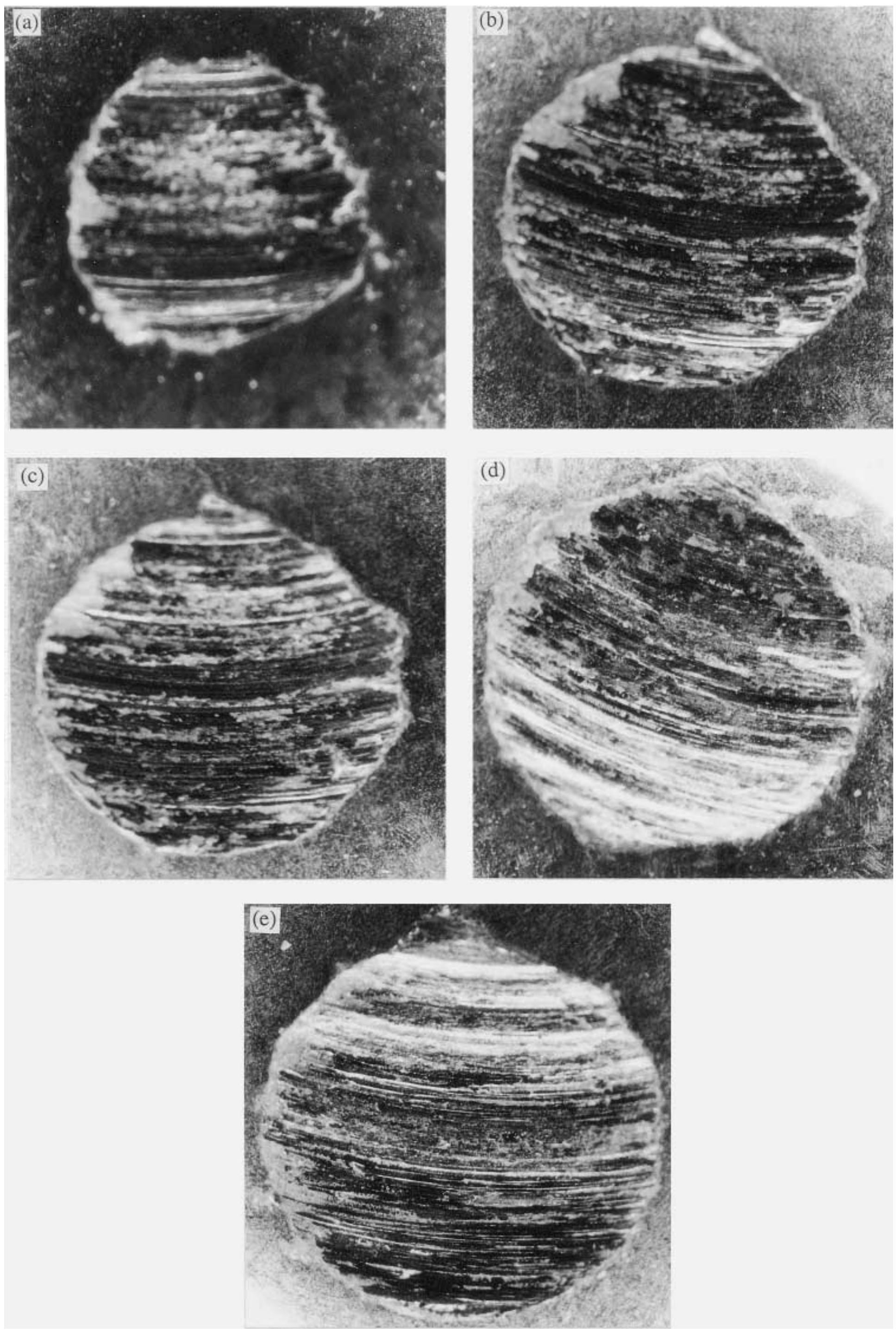

Fig. 8. Optical micrographs of the area around the wear scars of ball specimens at the end of different applied loads after a 1 min run with 5% contaminated lubricant (oil B) at fixed magnification (approximately 30×): (a) 51.2 kg, (b) 54.4 kg, (c) 57.6 kg, (d) 60.8 kg and (e) 64 kg.

lube oil, the trend was similar, with little fluctuation of the peak except for the pure lube oil which showed a sharp fluctuation in the friction force plot. Intermediate behaviour was found when the lube oil was blended with 3% POME, showing less fluctuation of peaks in the friction force.

The average value of coefficient of friction measured from the friction force is also shown in Fig. 6 for different percentages of POME. The friction coefficient increased with the following order of POME contamination: 3%, 7%, 0% and 10% (Fig. 6). The lowest friction coefficient was observed when the lube oil was contaminated with 5% POME. The above result can be attributed to the fact that 5% POME contamination acts as a friction reducing additive for the lube oils. By having a great affinity for metal surfaces, it forms a strong additional monolayer or chemical coating between moving surfaces, thus reducing the wear tendency significantly.

Fig. 7 shows the variation of friction coefficient vs. load with different percentages of POME contamination. From the figure, it can be seen that the friction coefficient of 7% POME contaminated lubricant is much higher than that of pure lube oil. The second highest was found from 10% POME blended lube oil. This means that contamination of higher percentages of POME is not effective in reducing friction. When pure lube oil was contaminated with 5% POME, the friction coefficient decreased even with an increase in load. This result again proves the beneficial effect of POME as a friction reducer.

3.4. Wear worn surface characteristics

Figs. 8 and 9 are optical photomicrographs of the area around the wear scar and worn surfaces of ball specimens respectively for different loads as well as different percentages of POME taken after the 1 min tests. From Fig. 8 it can be seen that the size of scar diameter increases with increase in applied load as shown quantitatively in Fig. 3. At lower load, the wear scar was found to be circular, but at higher load with high percentage of POME or pure lubricant, the edges are frequently ragged and sometimes may be obscured by metal. For applied loads of 57.6 kg and 64 kg, fusion of metal between the mating surfaces was observed, having a pyramidal shape (Fig. 8(c) and (e)), with large amounts of metals fused into each other (known as welding). The same behaviour can be seen from Fig. 9(a) and (b) where it can be clearly seen that welding occurs at 57.6 kg load with 3% POME contamination. Usually this type of welding takes place above the final seizure load, indicating complete breakdown of the lubricant film. At 64 kg load there was increased layer removal and mutual material transfer showing welding

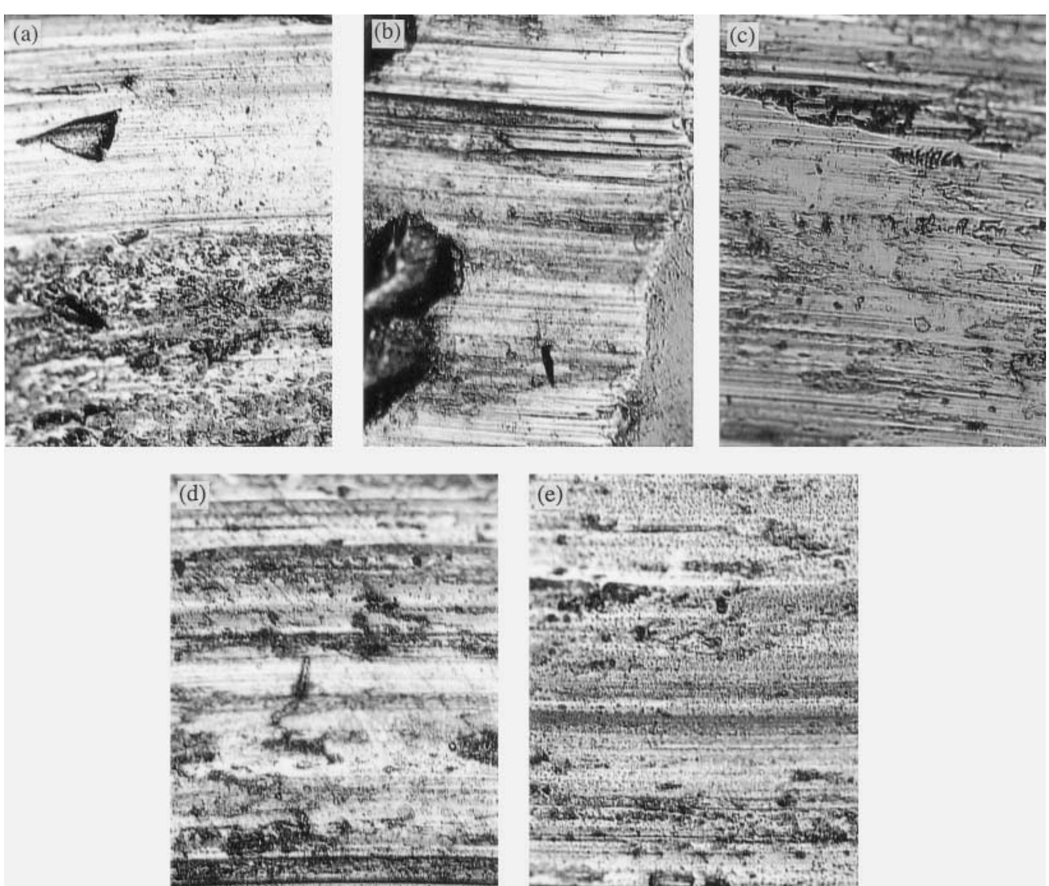

Fig. 9. Optical micrographs of wear worn surfaces of ball specimens with different POME contaminations at 57.6 kg load (magnification 200×): (a) plain lubricant (oil A), (b) 3% POME + oil A, (c) 5% POME + oil A, (d) 7% POME + oil A and (e) 10% POME + oil A.

and adhesion. Occasional layer removal and mutual material transfer was also observed for 3% POME blended lubricant at 57.6 kg load (Fig. 9(b)). In Fig. 9(d) it is seen that there is microcutting with abrasive wear resulting from the penetration of hard particles into the brittle solid surface. In the case of 10% contamination, some oxidation and corrosive wear were found on the wear worn surface. The general reduction of wear for the 5% POME contaminated lubricant was found in this investigation. The wear scar surfaces in the 5% POME blended tests (Fig. 8(c) and Fig. 9(c)) appear to be much smoother, and less material transfer occurred from one ball to another than was found for the wear scars in the pure lubricated tests (Fig. 9(a)). This is because of the non-breakdown of the lubricant film, thus preventing metal to metal contact [13]. The results indicate again the excellent anti-wear properties of POME when blended with pure lube oil, even at higher loads, when the POME contamination was 5%. However, when the POME concentrations were above 5% (weight per cent) the WSD increased and large amounts of metal merged into each other. This may be attributed to the occurrence of oxidation or chemical corrosive wear during the wear process [20].

4. Conclusions

For the tests performed on a four-ball wear machine with different percentages of POME contaminated lubricant, the conclusions drawn are as follows.

1. The wear of the ball specimens increases with the increase in normal applied load but this increase could be reduced with the addition of POME.
2. The 5% POME improves the lubricant performance based on the higher value of flash temperature parameter (FTP) observed as compared with pure lubricant.
3. The addition of 5% POME to the lubricant functions as an additive which decreases the coefficient of friction even at higher load.
4. From physical observations on worn surfaces of specimens it can be suggested that POME (5 wt.%) acts as an anti-wear lubricant additive.
5. Study of micrographs showed that wear scar surfaces in the 5% POME contaminated lubricant tests appear to be much smoother, thus having less material transfer. When the POME concentration was above 5%, some oxidation or chemical corrosion occurred.

Acknowledgements

The authors are grateful to the University of Malaya, Department of Mechanical Engineering, University College of Wales, Swansea, and PORIM for support, making this study possible.

References

[1] O.M.I. Nwafor and G. Rice, The use of neat rapeseed oil in diesel engine, presented at the *Fifth Int. Conf. on Small Engines, their Fuels and the Environment, The University of Reading, 5–7 April 1995*, pp. 26–30.
[2] A.B. Cardis, Benzotriazole derivatives and organic compositions containing them, *US US4, 626, 368*, 1986. Quoted from J. of Wear 173 (1994) pp. 167–170.
[3] Zahang Jinhe, *Modern Lubricants and Fuel Additives*, Chinese Petrochemistry Press, Beijing, 1991, p. 138.
[4] G.A. Zeinalova, A.A. Gadirov and A.K. Kyazimzade, N-nonyl-oxymethyl benzotriazole as antioxidant and anti-wear additive for synthetic lubricants, *USSR SU1, 456, 422*, 1989. Quoted from J. of Wear 173 (1994) pp. 167–170.
[5] C.V. Agarwal, V.K. Verma, R.S. Singh and A. Mammen, *Indian J. Technol., 19* (1981) 507.
[6] T. Sakurai, *Petroleum Products Additives*, Petroleum Industry Publisher, Beijing, 1982 (in Chinese).
[7] X. Hua and W. Rulin, XPS study of the frictional behaviour of sulfur–phosphorus–nitrogen type additives in gear oils, *Proc. JSLE Int. Tribology Conf. 1985, Tokyo, 8–10 July 1985*, pp. 667–672.
[8] F.P. Bowdem and D. Tabor, *The Friction and Lubrication of Solids*, Clarendon Press, Oxford, 1954.
[9] A. Mammen, C.V. Agarwal and V.K. Verma, *Wear, 71* (1981) 355.
[10] K.G. Allum and E.S. Forbes, *ASLE Trans., 11* (1968) 162.
[11] A. Bhattacharya, T. Singh and V.K. Verma, The role of certain substituted 2-amino-BTBTCs as additives in extreme pressure lubrication of steel bearing balls, *Wear, 136* (1990) 345–357.
[12] F.A. Davis and T.S. Eyre, Wear of plain bearing materials with particular reference to role of soft phases, *Mater. Sci. Technol., 7* (1991) 746.
[13] J.J. Liu, Y. Chen and Y.Q. Cheng, The generation of wear debris of different morphology in the running-in process of iron and steels, *Wear, 154* (1992) 259–267.
[14] S.C. Kang and K.C. Ludema, The breaking-in of lubricated surface, *Proc. 5th Int. Conf. on Wear of Materials, Vancouver, 1985*, ASME, New York, 1985, pp. 280–286.
[15] P. Studt, Boundary lubrication: adsorption of oil additives on steel and ceramic surfaces and its influence on friction and wear, *Tribol. Int., 22* (2) (1989) 111–119.
[16] H.H. Masjuki and M.A. Maleque, The effect of palm oil diesel fuel contaminated lubricant on sliding wear of cast irons against mild steel, *Wear, 198* (1996) 293–299.
[17] Extreme pressure properties: friction and wear tests for lubricants, four-ball machine, *Standard IP-239*, Vol. 1, Part 1, 1986, 45th annual education Manual for analysis and testing, pp. 239.1–239.16.
[18] C.Y. May, M.A. Ngan and Y. Basiron, Palm oil methyl ester as fuel: palm diesel, *PORIM Information Series*, ISSN 0128-5726, October, 1993, p. 17.
[19] T.B. Lane, The flash temperature parameter: a criterion for assessing E.P. performance in the four-ball machine, *J. Inst. Petrol, 43* (1957) 181.
[20] T. Ren, Q. Xue and H. Wang, A study of the tribological properties of S-(1H-benzotriazol-1-yl)-methyl, O,O′-dialkyldithiophosphates as additives in liquid paraffin, *Wear, 173* (1994) 167–170.

Biographies

Masjuki Hassan obtained his BSc (Hons) (Mech. Eng.), MSc (Tribology) and PhD (Mech. Eng.) from Leeds University in 1977, 1978 and 1982 respectively. He then joined the Department of Mechanical Engineering, University of Malaya, Malaysia as a lecturer, was promoted to associate professor, and is currently the head of the department. His interests include alternative fuels for automobile engines, engine tribology and energy conservation in building. He has published many papers in international and national journals and is a member of SAE, STLE and IMechE.

M.A. Maleque received his BSc Eng. degree in metallurgy from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 1992. He holds a masters degree in metallurgical engineering and is continuing a doctoral programme in tribology at the University of Malaya. He is at present a lecturer at the Department of Mechanical Engineering, University of Malaya. He is a member of STLE. His research interests are broad, including modelling of wear, better lubricating additives and the use of POME to lower the friction and wear of ferrous and non-ferrous materials, and heat treatment of new materials.