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EVLUATION OF PALM OIL METHYL ESTER AS LUBRICANT ADDITIVE USING MILLING AND FOUR-BALL TESTS

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ABSTRACT
This paper examines the effectiveness of POME (palm-oil methyl ester) as lubricant additive based on the results obtained in the four-ball and milling tests. The results produced in the four-ball tests showed that small amount of POME as an additive in the mineral oil resulted in shorter running-in period, lower steady-state friction coefficient and degree of adhesion, and higher weld load. The presence of POME enhanced the effectiveness of the mineral oil in suppressing coating delamination and delaying the occurrence of cracking and fracture on the flank face of the tool during milling of stavax® (modified 420 stainless steel). The results obtained in the four-ball tests suggested that this was due to a reduction in the cutting forces and lesser degree of welding of asperities brought about by the presence of POME.

***Keywords*:** machining; lubrication; cutting tools; electron microscopy

1. INTRODUCTION
Various studies showed that attrition, chipping, and cracking and fracture due to impact between the tool and the workpiece were the dominant wear mechanisms at low speeds. At high speeds, the tool wear was governed by thermal cracking and thermo-chemical wear such as diffusion and oxidation (Gu et al., 1999; Sun et al., 1998; Ghani et al., 2004; Dolinsek et al., 2001; Nouari and Molinary, 2005). In milling process, the tool is heated during cutting and cooled when it leaves the cutting zone. Temperature variation can cause periodic expansion and contraction of the tools leading to the formation of thermal cracks which is also known as comb cracks. Thermal cracks are more likely to form at high speeds since the amplitude of the temperature variation increases with increasing speed (Viera et al., 2001; Bhatia et al., 1980). In the past, most of the milling tests were carried out at the cutting speeds of higher than 100 m/min using large tools. It had been widely reported that the optimum speeds for milling steel were in the range of 100-150 m/min. In some cases, milling at speeds below the optimum speeds is inevitable. For example, if a tool with a diameter (D) of 2 mm is used, milling can be performed at speeds (πDN) higher than 100 m/min only if the machine employs a spindle that can be operated at rotational speeds (N) of higher than 16,000 rpm. Small solid end-mills are used to produce small features such as pockets and slots. Recent works carried out in milling stavax® at low speeds (25 and 50 m/min), feedrate (4 mm/tooth) and depth of cut (4 mm) using solid end-mills with diameter of 2 mm showed that the hardness of the steel had significant influence on the tool wear (Liew and Ding, 2008; Liew 2010). In machining stavax® with a hardness of 35 and 40 HRC, the coated tool was predominantly subjected to abrasive wear. During machining stavax® with the hardness of 55 HRC, several distinct stages of tool wear occurred; initial wear by a combination of abrasion, delamination and attrition, followed by cracking and fracture. Small quantity of mineral oil sprayed in mist form was more effective than the conventional flood lubrication in reducing the severity of delamination and abrasive wear, and delaying the occurrence of cracking, fracture and chipping.

In machining where the contact pressure between cutting tool and workpiece is high, the lubrication condition is under boundary lubrication mode. This conditions call for the use of boundary lubricity additive in order to maximize the protection against severe tool wear through the formation of a boundary lubricating films. This film separates the two metal surfaces and thus reduces wear. Ester which could be available as natural product (such as palm oil, canola oil, lard oil, soybean oil etc) or a functionalized molecule (monobasic ester, diester, polyol ester, complex ester etc) are examples of lubrication additives. Masjuki and Maleque (1997) found that with the addition of 5vol% of palm oil methyl ester (POME) in the base-oil lubricant resulted in low wear rate of EN31 steel ball bearing. This suggests that POME can be used as additive in mineral oil in suppressing tool wear in low speed milling application. POME, converted from crude palm oil through transesterification, has very low sulphur content (0.002 wt %), and therefore is more environmental friendly. This work is the extent of the previous works in which (i) the effect of different lubrication conditions (i.e. conventional flood, oil-mist and oil-mist with 5 vol% of POME) on the wear of TiAlN single-layer carbide end-mills in low-speed milling of stavax® and (ii) the effectiveness of POME as additive are investigated.

2. EXPERIMENTAL

2.1 Four-ball wear tests

The tribological behavior of lubricants was examined using a four ball test machine, conforms to ASTM IP239. Three steel balls were secured and placed in a triangular pattern within a bath of the test lubricant. A fourth ball was pressed and rotated on the top of the three balls at a nominal load between 300 to 1500N at 1500 rev/min for a duration of 1 minute. G40 steel balls with a diameter of 12.7mm were used. The test lubricants used in this study were (i) 100 vol% of liquid paraffin oil and cyclomethicone, (ii) mixture of 5 vol% of POME and 95 vol% liquid paraffin oil and cyclomethicone, and (iii) emulsified water-based coolant of 91 vol% water and 9 vol% SDBL (Shell Dormous BL) oil. The weld load i.e. the normal load causing the balls to weld was determined for each lubrication condition. The coefficient of friction was continuously measured throughout the tests. After the tests, the diameters of the wear scars were measured.

2.2 Cutting Tests

The machining tests were performed on an Okuma CNC milling machine which can be operated up to 14000 rpm (*N*). Since the cutting tools used in this study have a diameter (*D*) of 2 mm, the maximum speed that (πDN) can be achieved with this tool is 88 m/min i.e. when the spindle is operated at the maximum rotation speed of 14000 rpm. Machining was conducted at combinations of cutting speed of 50 m/min and feed rate of 0.6 mm/tooth in the presence of lubricant.

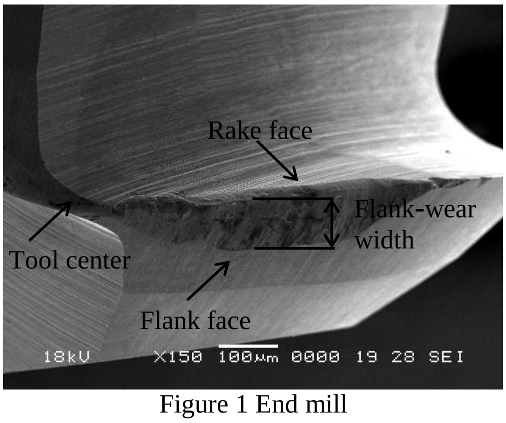


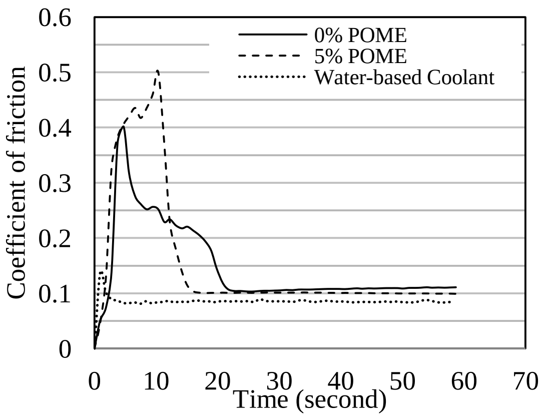
Figure 1 End mill

Three types of lubricants i.e. (i) a solution containing 100 vol% mixture of liquid paraffin oil and cyclomethicone sprayed in mist form using compressed air at a flow rate and pressure of 0.2 liter/hour and 0.2 MPa, respectively (ii) a solution containing 5 vol% of POME and 95 vol% mixture of liquid paraffin oil and cyclomethicone sprayed in mist form using compressed air at a flow rate and pressure of 0.2 liter/hour and 0.2 MPa, respectively and (iii) emulsified water-based coolant (91 vol% water and 9 vol% SDBL oil) flooded over the chip and the tool rake face, were used. The depth of cut and width of cut were kept constant at 0.2 mm and 0.4 mm respectively. The wear mechanism occurring on the cutting tool was monitored up to the cutting distance of 24 m. After machining the wear on the rake and flank faces (Figure 1) were examined using a scanning electron microscope (SEM). All experiments were performed with workpieces of stavax® (modified AISI 420 stainless steel with composition by wt% 0.38% C, 0.9% Si, 0.5% Mn, 13.6% Cr, 0.3% V, balance Fe) with a hardness of 55 HRC. This alloy is widely used as the moulding tool material on account of its high strength, corrosion resistance and machinability. The carbide end mills PVD-coated with a single layer TiAlN (5 µm thick) had two flutes, a flank width of 200 µm, a diameter of 2 mm and a helix angle of 30^0. The cutting tools were obtained from Sumitomo Electric.

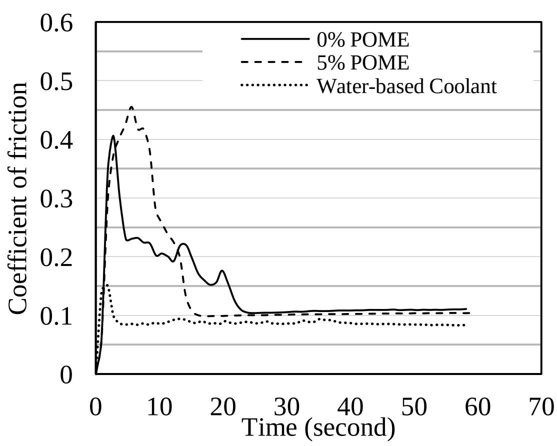
3. RESULT AND DISCUSSION

3.1 Four-ball wear tests

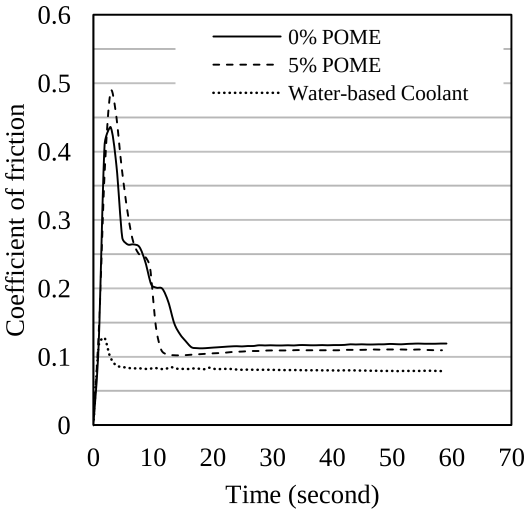
Figure 2 shows the change in the friction coefficient with time for different lubrication conditions. A notable feature of the results obtained at the nominal loads of 600, 700 and 800 N was the sharp increase followed by a rapid drop of the frictional coefficient to a low prevailing steady-state value in the initial stage of the tests.



(a)



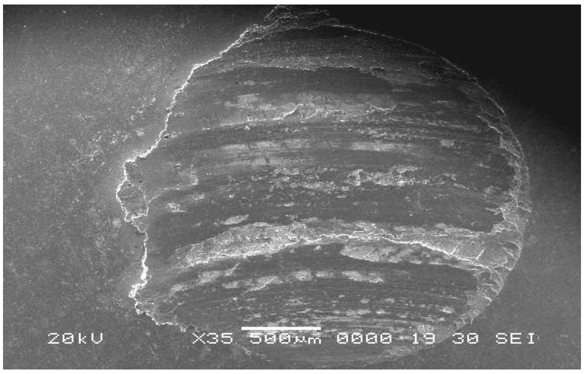
(b)



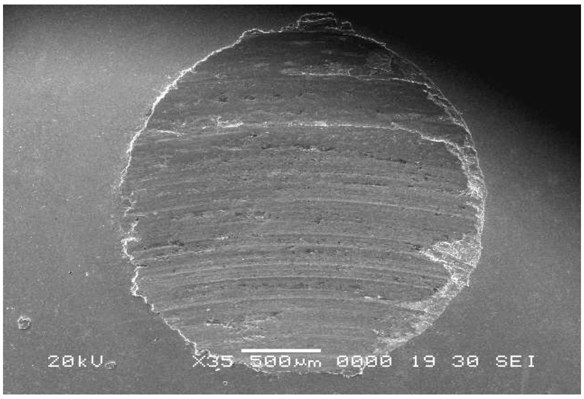
(c)

Figure 2 The change in friction coefficient in mineral oil, mineral oil blended with POME and emulsified water-based coolant at the nominal loads of (a) 600, (b) 700, and (c) 800N.

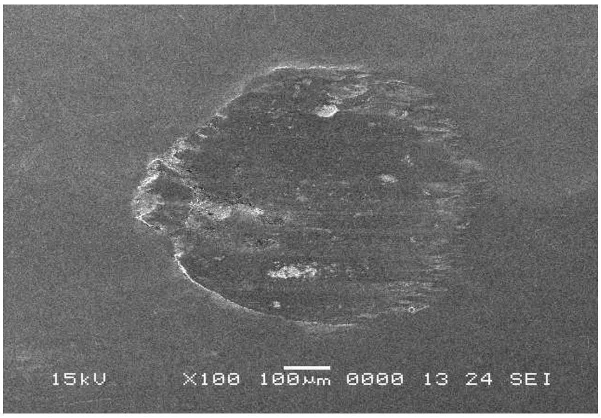
This reflects the nature of the running-in process. During the running-in process, the hardness of the material increased until it was able to support a lubricant film (Welsh, 1963; Tyfour et al., 1995). Once this had been achieved, the friction coefficient would drop to a low prevailing steady-state value. Under oil lubrication, the presence of POME resulted in shorter running-in period and lower steady-state frictional coefficient. The presence of POME in the mineral oil resulted in smoother worn scars. These results are in accord with the lower steady-state coefficient measured during the tests. The worn surfaces produced in mineral oil without POME appeared to be rougher than those produced in mineral oil blended with POME and emulsified water-based coolant (Figure 3). SEM examination at higher magnification revealed that the rough surfaces had numerous amounts of cavities, indicating that severe adhesive wear occurred (Figure 4). Adhesive wear easily occurs on nascent surfaces or surfaces lack of effective lubricant film and this phenomenon normally gives rise to high frictional force (Wang and Lei, 1996). The incidences of welding and rupture of asperities occurred in this wear mechanism result in the liberation of small debris and the formation of fine cavities on the worn surface. Under emulsified water-based coolant, the low prevailing friction coefficient could be attributed to the formation of interfacial layers due to the reaction between the additives, oil and water with the worn surface. It has been reported that steel can react with the small amount of water vapour in air to form iron hydroxide and ferri-oxide-hydrates resulting in low frictional force and mild wear in the sliding of steel (Baets et al., 1998; Goto and Amamoto, 2003). Works carried out by Cholakov and Rowe (1992) using a four-ball tribometer showed that water-based lubricants had higher ability to disperse heat and one of the important factor that governed the effectiveness of a fluid in reducing wear was its ability to disperse heat from the contact surfaces. Water-based fluids, because of their inherent cooling ability, dissipate heat from the contact surfaces at a faster rate.



(a)



(b)



(c)

Figure 3 SEM images of the worn surfaces of the steel balls produced at 800 N in (a) mineral oil without POME, (b) mineral oil blended with 5vol% POME and (c) emulsified water-based coolant. The worn surface produced in mineral oil without POME appeared to be rougher.

This in turn causes lesser degree of softening of the material, and thus welding of asperities and adhesive wear. Therefore, the smooth surface and low friction coefficient produced in emulsified water based-coolant was not solely due to the inhibition of adhesive wear by the formation of interfacial films.

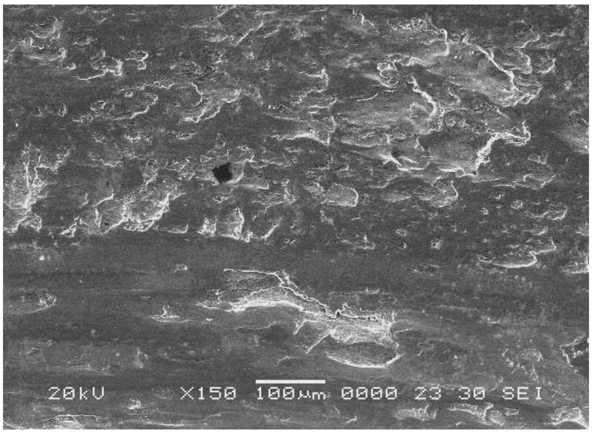


Figure 4 Examination of the steel balls tested at 800 N in mineral oil without POME at higher magnification shows that the worn surface has numerous cavities, indicating of adhesive wear.

The smallest wear scar diameter was obtained in emulsified water-based coolant (Table 1) due to the combination of the shortest running in period and lowest prevailing steady-state wear. Running-in process is the stage where large amount of material loss occurs (So and Lin, 1999). Under oil lubrication, the presence of POME resulted in smaller worn scars and higher values of weld load in comparison to the oil without POME. Under such high loads when the possibility of seizure is high, oil lubricant reduces the contact between the two contacting surfaces through the formation of a lubrication film. The film formation is typically caused by the adsorption of the additive on the contacting metal interface through chemical reactions. The high chemical affinity at the contact surface region is caused by the synergistic effect of a very high surface energy and active sites from the freshly abraded surfaces (nascent) and flash temperature generated from the collision of asperities from one surface to the other sliding surface (Hsu and Gates, 2005). The protective role of the film is further improved with the presence of POME. The characteristics of the friction coefficient at a lower load of 300 N appeared to be different from those obtained at the higher loads. At 300 N, no drop in the coefficient of friction was observed in the running-in process and the steady-state friction coefficient obtained in oil without POME, oil with 5% POME and emulsified water-based coolant was essentially the same (Figure 5). Under this condition, hydrodynamic lubrication prevails whereby a hydrodynamic lift generated by the liquid pressure of the lubricant is great enough to keep the contacting surfaces to be separated. Under this lubrication condition, the only friction involved in the system was the viscous shear of the lubricant (Avitzur, 1990). The coefficient of friction produced in plain mineral oil and mineral oil with POME additive was essentially the same due to their similar viscosity characteristics.

Table 1 Weld load and wear scar diameter for different lubrication conditions

Lubrication condition	Weld load (N)	Average diameter scar (mm) produced at the nominal loads of			
		300N	600N	700N	800N
Emulsified water-based coolant	1050	0.30	0.59	0.65	0.73
Mineral Oil (without POME)	1200	0.28	1.97	2.30	2.60
Mineral Oil with 5vol% POME	1400	0.29	1.79	2.20	2.30

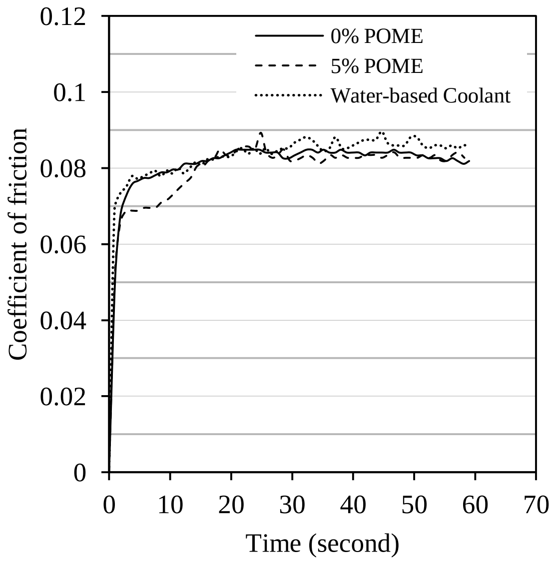


Figure 5 The change in friction coefficient in different lubrication conditions at nominal load of 300N.

3.2 Effect of lubrication on the tool wear progression

Figure 6 shows the change in the maximum flank-wear width V_B with cutting distance in milling stavax® under flood and oil mist (with and without POME) lubrications. Three distinct stages of tool wear occurred. In this initial stage of machining, delamination, attrition and abrasion were the dominant wear mechanisms. Removal of coating by the combination of these wear mechanisms exposed the substrate. Cracks were then formed on the carbide substrate exposed on the flank face. This was followed by the formation of individual surface fracture at the cracks which would then enlarge and coalesce to form a large fracture surface. These cracks propagated in a direction parallel to the cutting edge are often referred as mechanical or fatigue cracks. SEM images of the worn surfaces showing evidences of delamination wear, cracking and fracture can be seen in the works published by Liew and Ding (2008) and Liew (2010). Oil-mist lubrication was more effective in delaying the occurrence of cracking and fracture. The effectiveness of water-based and oil-based lubricants in reducing the frictional forces and wear depends on the frictional condition. In high-speed machining, the high temperature generated is the primary concern because it causes excessive adhesive wear and softening of the material leading to high wear. Under such circumstances, water-based lubricants are likely to perform better as they are better coolants than oil-based lubricants. However, in low-speed machining where the heat gave beneficial effects (i.e. reducing the hardness of the work material, and hence the cutting force and the severity of abrasion) and mechanical wear (such as abrasion, delamination, cracking and fracture) occurred, the use of lubricant with higher viscosity and lower cooling ability such as oil-based lubricant resulted in lower wear rate.

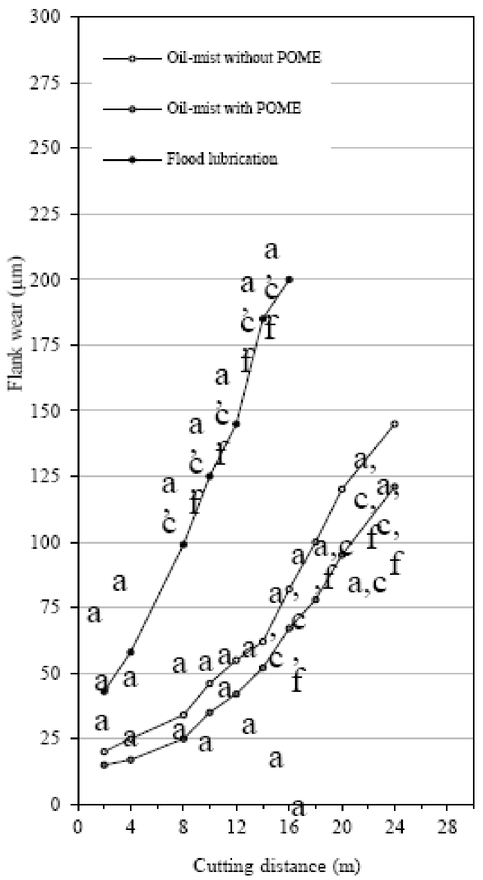


Figure 6 The change in dominant wear mechanism and the flank wear under flood and oil-mist (with and without POME) lubrications. The alphabets indicate the operating wear mechanism on the flank face. a:abrasion and attrition, c:cracking, f:fracture. Coating delamination took place in all cutting conditions.

It was found that the presence of POME in the oil-mist lubricant further delayed the occurrence of cracking and fracture. This could be a direct result of a reduction in the cutting forces and the degree of welding of asperities brought about by the POME (as demonstrated in the four-ball tests) which in turn reduced (i) the severity of the impact of the tool on the work material and (ii) the removal rate of the coating in the initial stage of machining, giving the tool substrate greater suppression of fatigue crack initiation (Toudt et al., 2000; Lackner et al., 2006; Hogmark et al., 2000; Liew, 2010).

4. CONCLUSION

The results obtained in the four-ball tests showed that small amount of POME as an additive in the mineral oil resulted in shorter running-in period, lower steady-state friction coefficient and degree of adhesion, and higher weld load. Compare to the flood lubrication, small quantity of mineral oil sprayed in mist form was more effective in reducing the coating delamination and delaying the occurrence of cracking and fracture. The presence of POME in the oil-mist lubricant further delayed the occurrence of cracking and fracture. This could be due to a reduction in the cutting forces and lesser degree of welding of asperities brought about by the POME POME (as demonstrated in the four-ball tests) which in turn reduced (i) the severity of the impact of the tool on the work material and (ii) the removal rate of the coating in the initial stage of machining, giving the tool substrate greater suppression of fatigue crack initiation.

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