PERFORMANCE OF PALM OIL AS MQL FLUID DURING HIGH SPEED DRILLING OF Ti-6Al-4V

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during High Speed Drilling of Ti-6Al-4V

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Abstract:

This paper presents an experimental investigation on the performance of a synthetic ester and palm oil during high speed drilling (HSD) Ti-6Al-4V using minimal quantity of lubricant (MQL) method. Tool wear, wear mechanism, cutting forces and surface integrity were monitored during the machining trials. In order to study the ability of the cutting fluids, temperature was measured during drilling process using a thermocouple wire. Both the synthetic ester and palm oil present comparable performance in terms of tool wear. In addition, palm oil outperformed synthetic ester in terms of cutting forces and workpiece surface integrity due to its ability to reduce the temperature during the drilling process.

Keywords: MQL, High speed drilling, Titanium alloy, Synthetic ester, Palm oil

1. Introduction

It is a fact that the cutting fluid that contains oil, has becomes a huge liability especially in health and environment aspects. Due to increase of health and environmental awareness, industries have begun to eliminating or limiting the amount of the cutting fluid consumption. Minimum quantity of lubricant (MQL) machining is an alternative which minimizing the cutting fluid from machining process. It was found that MQL reduces the friction coefficient and the cutting temperature compared with dry and flood coolant. Drilling had some success with MQL technique and most of the cases were concluded obtaining better or superior performance over conventional method on aluminum silicon alloy [1-3], plain carbon steel [4] and hardened steel [5]. Intention in vegetable oil-based metalworking fluids is growing due to environmental and safety issues. Sources of vegetable oil were mainly from rapeseed, castor, canola, soybean, sunflower, palm, olive, coconut and jojoba. Vegetable based oils such as palm oil, can be processes as a personal care products, food products and bio-fuel production. It contains approximately 60 % of palmatic acid ($C_{15}H_{31}COOH$) which is a form of glycerine and consists of triglycerides, free fatty acids and non-glyceride substances [6]. This oil has substantial lubrication property and better oxidative stability comparable to other high oleic acid oils.

The definition of high speed machining (HSM) depends on workpiece material being machined and type of machining processes. Several sectors such as mold and aerospace industries have implementing HSM to increase their productivity, to achieved good surface finish and it capable to machine complex shape [7]. Despite of the promising performance of HSM, high speed drilling (HSD) process is the weakest process due to poor tool life and tooling cost. HSD was commonly applied on aluminium alloys [8] and carbon reinforced plastic [9]. Recently, Rahim et al. [7] and Li et al. [10]

have conducted a study on HSD of titanium alloys. Rahim et al. [7] reported that peck drilling can be employed with HSD in order to reduced thrust force and torque. Li et al. [10] suggested that the WC-Co spiral point drill gained higher material removal rate, higher tool life and smoother surface finish can be obtained. They also found that spiral point drill design exhibited low thrust force, torque energy and burr size. However, the major concern is there is insufficient data or publication on HSD of titanium alloys with MQL application. Moreover, the use of palm oil as a metal cutting fluid has not been focused. For this purpose, a study was carried out to investigate the effect of different type of oils for MQL applications on tool failure modes, cutting forces, workpiece temperature and surface integrity.

2. Experimental Set Up

A three axis CNC vertical machining center (MAZAK NEXUS-410) was used in this study. The workpiece material was Ti-6Al-4V tested in round bar with a diameter and thickness of 50 mm and 20 mm respectively. The average hardness of bulk material is approximately 320 Hv. The workpiece was mounted on top of the piezoelectric dynamometer (Kistler 9365) which was connected to charge amplifiers to collect the thrust force and torque values.

An AlTiN coated carbide insert (Mitsubishi TAWNH1400T) was mounted on a standard tool shank (TAWSNH1400S16). The diameter, point angle and helix angle were 14 mm, 130° and 30° respectively. The tool shank was collet mounted with a 80 mm overhang. Drilling trials were confined to through holes under the action of external minimal quantity of lubricant (MQL). A commercially available MQL equipment (Kuroda KEP3) was used to deliver a mist spray to the cutting tool and workpiece. Table 1 details the variable operating parameters and conditions employed in this

experiment. Synthetic ester oil and palm oil were used as the MQL oils and the physical characteristics are shown in Table 2.The workpiece temperatures were measured by K type thermocouples at two locations namely TC1 and TC2. These thermocouples were embedded into the workpiece close to the holes wall with a distance approximately 1.25 mm as shown in Figure 1.

Vision measuring machine (Mitutoyo) was used for tool wear observation. In addition, scanning electron microscopy (SEM) was employed for further examination of the worn tools. To examine the machined subsurface and microhardness, small specimens were cut from the workpiece using a precision cutter and cleaned using methyl alcohol. The specimens were then mounted, ground using SiC paper and polished with diamond compound. For the examination of subsurface deformation, the samples were then etched by the Krolls reagent for 5 seconds to reveal the microstructure, which is later captured by a confocal scanning laser microscope. Microhardness values were measured using a microhardness tester (Akashi HM-114). A load of 100 g was employed with the distance of 50 μm for each indentation.

Table 1: Cutting conditions.

Workpiece	Ti-6Al-4V
Cutting speed, Vc (m/min)	60, 80, 100
Feed rate, f (mm/rev)	0.1, 0.2
Outlet air pressure (MPa)	0.2
Lubricant flow rate (ml/hour)	10.3
Outlet air flow (l/min)	165

Table 2: Physical characteristic of MQL oil.

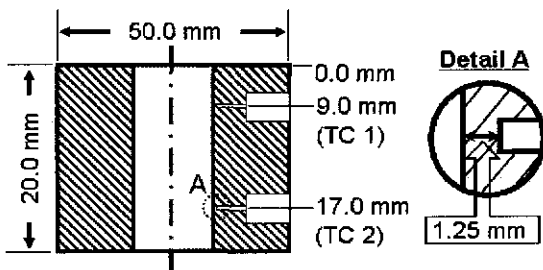| Oil type	Synthetic ester	Palm oil
Density (g cm^{-3})	0.95	0.91
Viscosity at 40°C (mm^2 s^{-1})	19	40
Viscosity index	137	190

Figure 1: Thermocouple locations embedded in the workpiece.

3. Results and Discussions

3.1 Thrust Force and Torque

Thrust force and torque obtained for synthetic ester and palm oil when HSD Ti-6Al-4V are presented in Figures 2 and 3 respectively. Generally, the thrust force and torque decrease with the increase of cutting speed. In contrary, these values were increased when the feed rate increases. In Figure 2, the thrust force results showed a declining trend when the cutting speed increased from 60 m/min to 100 m/min. Both synthetic ester and palm oil recorded a low thrust force of 2318 N and 1954 N at cutting speed of 100 m/min and feed rate 0.1 mm/rev. It shows a reduction of 27 % and 19 % for synthetic ester and palm oil, respectively. Meanwhile, at the cutting speed of 100 m/min and feed rate of 0.2 mm/rev, the recorded thrust force for synthetic ester and palm oil were 3177 N and 2256 N, respectively, thus indicates a reduction of 10 % and 18 %. The effect of feed rate on thrust force can also be seen in Figure 2. Both oils recorded a low thrust force when HSD Ti-6Al-4V at the feed rate of 0.1 mm/rev. For example, at the cutting speed of 100 m/min, synthetic ester and palm oil indicated a reduction of 27 % and 17 %, respectively.

Figure 3 depicts the result of torque at different cutting speed, feed rate and MQL oils. From this figure, it can be readily seen that for a given cutting speed, the torque value are lower for feed rate of 0.1 mm/rev than 0.2 mm/rev. For instance, the torque value for synthetic ester associated with the cutting speed of 100 m/min had reduced significantly i.e., to 9.6 Nm and 13.7 Nm for feed rate of 0.1 mm/rev and 0.2 mm/rev respectively. It shows that the torque value was decreased almost 23 % and 16 % with an increased in cutting speed from 60 m/min to 100 m/min. Palm oil induced the lowest torque at the cutting speed of 100 m/min and feed rate of 0.1 mm/rev, which indicates 32 % reduction when the cutting speed increases form 60 m/min to 100 m/min. Meanwhile, at the feed rate of 0.2 m/min, it exhibited 28 % of the torque reduction.

As mentioned earlier, the values of thrust force and torque decreased as the cutting speed increases. This phenomenon can be explained by the reduction of contact area between tool-workpiece interface and reduction of specific cutting energy [7]. Consequently, the coefficient of friction significantly dropped. In contrary, the thrust force and torque values were significantly increased when the feed rate increases. This can be explained due to the fact that higher feed rate results in a larger cross sectional area of the undeformed chip, greater chip deformation and consequently greater thrust force and torque are produced.

Generally, synthetic ester produces higher thrust force and torque compared to the forces produced by palm oil. The increase in thrust force and torque can be attributed to the reduction of lubrication and cooling effect which in turn leads to a further increase in the cutting temperature. Palm oil contains more than 50 of palmatic acid ($C_{15}H_{31}COOH$) which consists of triglyceride structures that provide desirable lubricant [6].In contrary, Wakabayashi et al. [11] reported that synthetic ester outperformed vegetable oil in terms of coefficient of friction due to the formation of lubricating film on the cutting tool and on the machined surface. Palm oil has an ability to form a thin film of intermolecular layer which promotes boundary lubrication hence helps to reduce the rate of heat generation and friction between tool-chip

interface. The higher viscosity index of palm oil ensures that it will provide more stable lubricity across the operating conditions range. Moreover, the low content of polyunsaturated fatty acids in palm oil makes it less prone to oxidative polymerization.
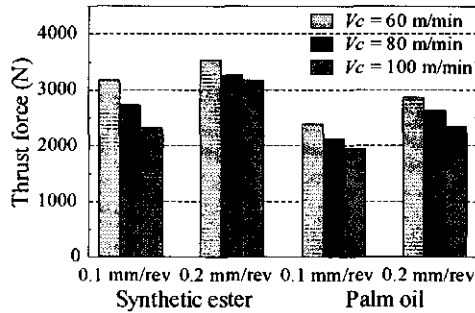

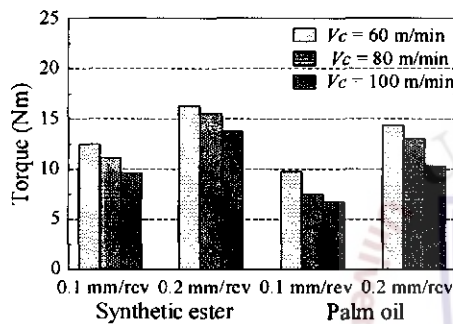Figure 2: Thrust force as a function of cutting speed for various feed rate and MQL oils.

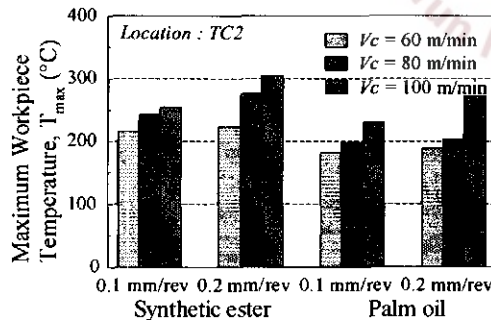Figure 3: Torque as a function of cutting speed for various feed rate and MQL oils.

Figure 4: Maximum workpiece temperature as a function of cutting speed for various feed rate and MQL oils.

3.2 Workpiece Temperature

The effect of cutting speed, feed rate and MQL oils on maximum workpiece temperature at location TC2 when HSD Ti-6Al-4V is shown in Figure 4. It can be seen that the maximum workpiece temperature increases with cutting speed, feed rate and MQL oils. Synthetic ester recorded an increment of 18 % (f=0.1 mm/rev) and 36 % (f=0.2 mm/rev) when the cutting speed increases from 60 to 100 m/min. Moreover, as the feed rate increases from 0.1 to 0.2 mm/rev, it recorded an increment of 4 %, 14 % and 20 % for the cutting speed of 60, 80 and 100 m/min, respectively. Furthermore, an increment of maximum

workpiece temperature by about 27 % (f = 0.1 mm/rev) and 44 % (f = 0.2 mm/rev) can be achieved by palm oil when the cutting speed increases from 60 to 100 m/min. The increase of the maximum workpiece temperature with the feed rate of 0.2 mm/rev is more noticeable than that when the feed rate of 0.1 mm/rev is used.

The described results reveal that the changes of cutting speed and feed rate have a significant effect on the workpiece temperature. This phenomenon is due to the fact that as the cutting speed increases, the strain rates in primary and secondary shear zones also increase. An increase in cutting speed is always accompanied by a reduction of the chip thickness, thus increasing the strain rate of plastic deformation and cutting energy. Machining at high feed rate has produced more stress and increased workpiece temperature. An increase in temperature generated was due to an increased in contact time between the chip and the tool, hence increased the friction at the tool-chip interface. Figure 4 also compares the MQL oil effects on the maximum workpiece temperature. It is interesting that the values of temperature exhibited by the palm oil were relatively lower than the synthetic ester. This observation indicates that palm oil enhances heat dissipation in cutting tool. Furthermore, high viscosity of palm oil helps to flow easily to the cutting zone at minimal quantity. This enables the reduction of friction between the tool and workpiece and subsequently reduced the heat. As the machining temperature increases, the viscosity of palm oil gradually dropped thus it remains more fluids to facilitating a better drainage and cooling from chip and workpiece.

3.3 Tool Wear and Wear Mechanism

Figures 5 and 6 show the effect of different type of MQL oils on tool wear pattern when HSD of Ti-6Al-4V. In general, an increase in cutting speed or feed rate will increase the tool wear rate. Uniform flank wear was the dominant failure mode under most cutting conditions for both MQL oils. Excessive fracture and flaking on the flank, corner and margin area of the drill can be observed for both MQL oils at all tested cutting conditions. This occurs due to the contact or friction between the drill surface to the bottom and hole wall surfaces. In overall, the results suggested that palm oil exhibited comparable performance with synthetic ester in terms of flank wear rate. This can be attributed to the ability of palm oil in reducing the temperature at the tool-workpiece interface thus the flank wear rate was reduced. Palm oil has higher viscosity index than synthetic ester. The higher viscosity index of palm oil can be explained due to the fact that the vegetable oil contains triglycerides that maintain stronger intermolecular interactions with increasing temperature [6]. In addition, the fatty acid in palm oil contains a thicker molecular layer of lube oils. These factors could contributed to the better lubricating hence could reduce the tool wear rate.

SEM was used for detail examination of the worn tools and to obtain better understanding on tool wear development. As mentioned earlier, flank wear was the dominant wear mode. As a consequence, chipping,

adhesion, attrition and abrasion were occurred as its wear mechanisms. The rate of flank wear was rapid at high cutting conditions in both oils. When the worn tools were close examined, the tools were found to be fully or partially covered by the workpiece material as shown in Figures 7 to 9.
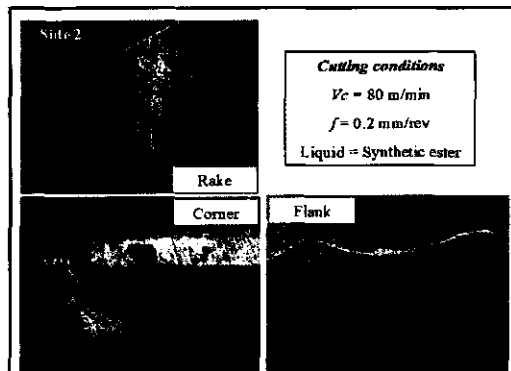

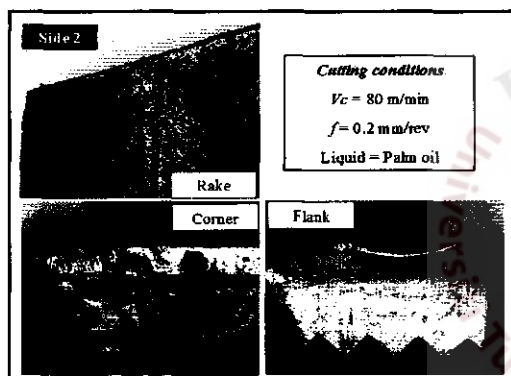Figure 5: Typical wear pattern when HSD Ti-6Al-4V using synthetic ester.

Figure 6: Typical wear pattern when HSD Ti-6Al-4V using palm oil.

The existence of the adhered material by synthetic ester is more pronounced than the case using palm oil. In the early stage of the process, the adhered material protects the cutting edge from wear but after prolonged machining it became unstable, broke away and bringing along the tool particles hence resulted in flaking and micro-chipping of the cutting tool. Mechanical and thermal loading may contributed to this wear mechanism. Furthermore, micro-chipping is more severe on the outer corner of the drill where high local flank wear and stress concentration were dominated prior to chip. High cutting temperature near the cutting edge of the tool which caused the workpiece material to weld to the tool and subsequently pulled apart resulting in the loss of cutting edge. The strong bonding between the adhered material on the tool may cause attrition wear mechanism as shown in Figure 7 and 8. This can be explained by the results of broken away and removing the substrate materials from the cutting tool. The adhered material on the tool became weaker with increasing cutting temperature and its strength is not sufficient to withstand the forces acted during drilling process. As a result, the substrate material

was removed by adhered material and a rough surface on the cutting tool was formed.

The heat generation at the region near periphery is higher that other location of the drill. As a result, the hardness of the cutting tool decreases. For this reason, the abrasion wear mechanism was formed and more severe at this location for both MQL oils as shown in Figures 9 and 10. According to Gu et al. [12], the ability of the cutting edge to resist the abrasive wear is related to its hardness. A typical sliding wear of the cutting tool is revealed indicating grooves parallel to the contact direction. The development of the grooves on the flank face was due mainly to the cobalt used as a binder in the cutting tool.

3.4 Surface Integrity

Figures 11 and 12 show the microstructures of the machined surface produced when HSD with synthetic ester and palm oil. The microstructures were deformed toward to spindle rotation direction. It was found that a very thin disturbed layer or plastically deformed layer was formed underneath the machined surface. It became more severe when machining at high cutting speed and feed rate as a result of high cutting temperature at the cutting zone. It was due to the localized heating on the machined surface together with high stresses produced during machining process. In addition, the high temperature generated during drilling is enough to cause a softening effect on the machined surface thus leads to severe plastic deformation. It was found that the thickness of plastically deformed layer reduced when Ti-6Al-4V was drilled using palm oil. The average thickness for synthetic ester was 15 μm at the cutting speed of 100 m/min and feed rate of 0.1 mm/rev. Meanwhile, palm oil recorded an average thickness of 8 μm at the same condition. This could be due to the fact that less temperature was generated when drilling was carried out by palm oil. Palm oil enables to reduce the friction between the tool and workpiece which in turn reduces the cutting temperature.

The measurements of microhardness underneath the machined surface indicated that various cutting conditions produced similar trend in the microhardness variations as shown in Figures 13 and 14. It can be seen that the hardness beneath the machined surface (below 0.05 mm) was lower than the average hardness of bulk material when HSD with synthetic ester and palm oil. This indicated that the surface experienced a thermal softening effect due to localized heating during drilling process. In addition, it can be suggested that strength of the material decreases due to overaging process [13]. Furthermore, the hardness values beneath the surface recorded by palm oil were slightly higher than synthetic. Such results were directly associated with low cutting temperature generated during drilling process as discussed earlier. Increase in hardness values were recorded at the range of 0.05 to 0.3 mm beneath the machined surface. This can be associated by the compressive residual stresses induced during the machining process. After reaching the peak values, the hardness reduced gradually until it reaches the average

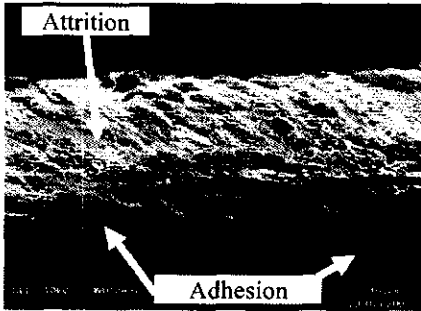hardness of bulk material further away from the machined surface.

Figure 7: SEM micrograph showing micro-chipping, adhesion and attrition at cutting speed of 80 m/min and feed rate of 0.2 mm/rev using synthetic ester.
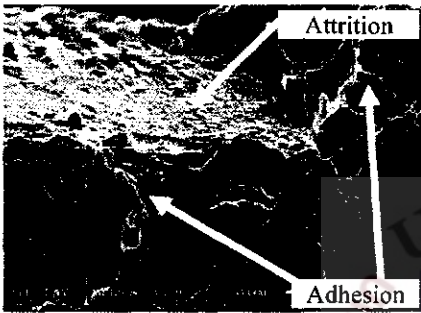

Figure 8: SEM micrograph showing micro-chipping, adhesion and attrition at cutting speed of 100 m/min and feed rate of 0.1 mm/rev using palm oil.
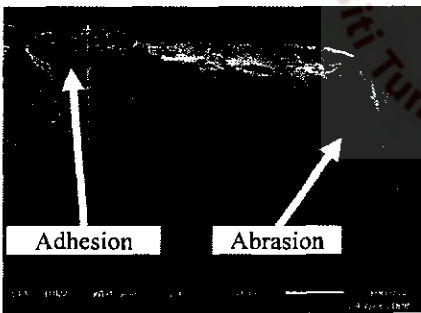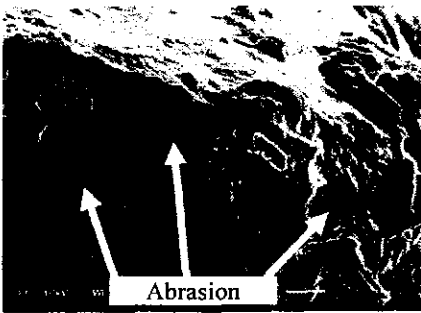

Figure 9: SEM micrograph showing micro-chipping, adhesion and abrasion at cutting speed of 100 m/min and feed rate of 0.1 mm/rev using synthetic ester.

Figure 10: SEM micrograph showing abrasion at cutting speed of 100 m/min and feed rate of 0.2 mm/rev using palm oil.
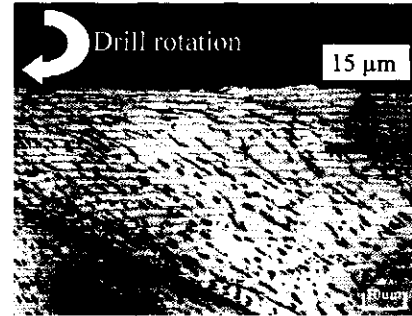

Figure 11: Microstructure of Ti-6Al-4V showing plastic deformation after HSD using synthetic ester (Vc=100 m/min, f=0.1 mm/rev).
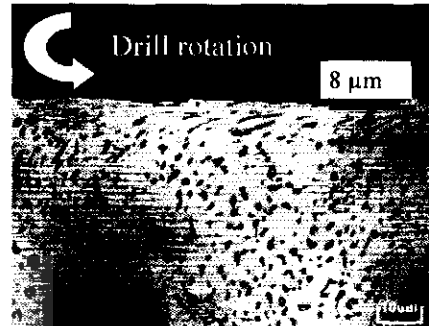

Figure 12: Microstructure of Ti-6Al-4V showing plastic deformation after HSD using palm oil (Vc=100 m/min, f=0.1 mm/rev).
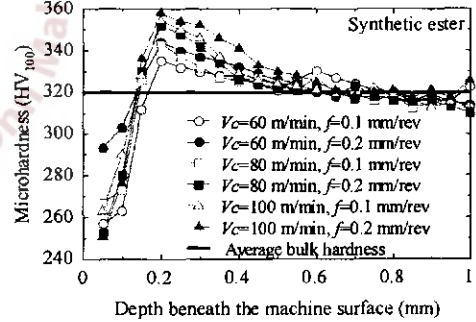

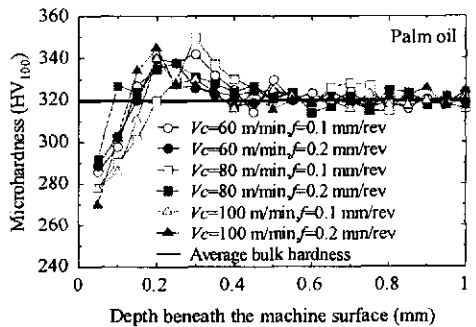Figure 13: Microhardness value of Ti-6Al-4V after HSD using synthetic ester.

Figure 14: Microhardness value of Ti-6Al-4V after HSD using palm oil.

4. Conclusions

The following conclusions are drawn on HSD with synthetic ester and palm oil on Ti-6Al-4V under various cutting conditions.

i. Palm oil exhibited lower thrust force and torque compared to synthetic ester due to its ability to reduce the rate of heat generation and friction between tool-chip interface.

ii. The values of maximum workpiece temperature exhibited by the palm oil were relatively lower than the synthetic ester. This observation indicates that palm oil enhances heat dissipation in the cutting tool.

iii. The results suggested that palm oil exhibited comparable performance with synthetic ester in terms of flank wear rate mainly due to the ability of palm oil in reducing the temperature at the tool-workpiece interface thus reduced the flank wear rate.

iv. Chipping, adhesion, attrition and abrasion were the dominant tool wear mechanisms were responsible for the tool failure under most cutting conditions used.

v. Severe plastic deformation of the machined surface can be observed especially when HSD with synthetic ester compared to palm oil. This could be due to the fact that less temperature was generated when drilling was carried out by palm oil.

vi. The top layer of the machined surface is softer than bulk material due to thermal softening and overaging effect due to localized heating during drilling process.

Acknowledgement

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