Chapter 3

Tribological Interaction of Bio-Based Metalworking Fluids in Machining Process

Erween Abd. Rahim, Amiril Sahab Abdul Sani and
Norfazillah Talib

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72511

Abstract

Metalworking fluids were applied during the machining process to lubricate and cool the machine tool in order to reduce wear, friction, and heat generated. The increasing attention to the environment and health impacts leads to the formulation of eco-friendly metalworking fluids derived from vegetable oils (Jatropha and palm oils) to substitute the use of mineral-based oil. The present work focuses on the performance of refined bio-based metalworking fluids during tapping torque and orthogonal cutting processes. Bio-based metalworking fluids were formulated using 0.05 wt.% of hexagonal boron nitride (hBN) and 1 wt.% of phosphonium-based ionic liquid $[P_{66614}][(^{i}C_8)_2PO_2]$ in a modified Jatropha and palm olein oils and were examined for their rheological properties in comparison with a commercially obtained synthetic ester (SE)-based cutting fluid. The tapping torque performance of the refined bio-based metalworking fluids was evaluated for their torque and efficiency. In addition, the performance of these bio-based metalworking fluids on orthogonal cutting parameters such as cutting force, cutting temperature, chip thickness, tool-chip contact length, and specific cutting energy was highlighted. The results obtained revealed that the rheological properties of the newly formulated bio-based metalworking fluids were improved. From the tapping torque and orthogonal cutting performances, it was proven that the modified palm and Jatropha oils possess good anti-wear and anti-friction behavior compared to SE. In conclusion, the newly formulated bio-based metalworking fluids are suitable for the use as a new advanced renewable metalworking fluid for machining processes that correspond to the energy-saving benefits and environmental concerns.

Keywords: boron nitride, environmentally adapted metalworking fluid, ionic liquid, renewable sources, sustainable machining

1. Introduction

Sustainability has become an important element to be considered in the manufacturing industry. Sustainable manufacturing has led machining industries to replace petroleum-based lubricants with bio-derived lubricants. Normally, the conventional lubricants consist of the combination of petroleum-based lubricant and additives that are toxic to the environment and difficult to be disposed of after the consumption [1]. The widespread use of petroleum-based lubricant may cause a negative effect to human such as dermatitis, acne, asthma, and a variety of cancers [2]. Hence, lubricants from vegetable oils are favorable as a sustainable alternative to the conventional petroleum-based oil. Vegetable-based lubricant offers significant environmental benefits with respect to resource renewability, biodegradability, as well as providing satisfactory performance in a wide array of applications [3].

In the machining process, metalworking fluids (MWFs) are typically used to separate tool-workpiece interface. MWFs provide lubrication, reduce the friction and wear, cool, and protect metal surfaces against corrosion. Tribology process occurs at the contact area between tool and workpiece, which related to friction, lubrication, and wear of interacting surfaces in a relative motion. Tribology process can be classified as physical, physical-chemical (adsorption), or chemical in nature (tribochemistry) [4]. The absence of MWFs will result in acceleration of tool wear, residual stress, dimensional error, and poor surface finish [5]. Previous researchers have identified that MWFs made of canola/rapeseed, palm, and sunflower oils provided greater lubricating properties and showed comparable performance with currently used petroleum-based MWFs regarding cutting force, cutting temperature, surface finish, tool wear, and tribological behavior [6–8]. Vegetable-based MWFs have high viscosity and viscosity index that significantly influenced the machining performances that provide effective lubricating properties on the tool-chip contact surfaces [8]. Vegetable-based MWFs formed a thin film between tool and workpiece that offers good boundary lubrication condition with a low coefficient of friction [9].

Normally, MWFs contain a combination of base oil and additives. There are various functions of additives being used to enhance the MWFs performance such as antiwear, antifriction, extreme-pressure, antioxidant, and anticorrosion [10]. The addition of additives in base oil could give either beneficial or detrimental effect on the tribological behavior depending on the types of additive, particle size, and concentration. Hence, to have a better understanding on the lubrication and tribology, modified vegetable oils (modified Jatropha oil and modified RBD palm olein) were added with various types of additives (hexagonal boron nitride and phosphonium-based ionic liquid). The effects of various formulations of modified vegetable oils were examined through rheological properties, tapping torque, and orthogonal cutting performances.

1.1. Green solid additive

The green solid particles such as hexagonal boron nitride (hBN), aluminum oxide (Al_2O_3), molybdenum disulfide (MoS_2), carbon nanotube (CNT), and nano-diamond were added in various neat MWFs to increase thermophysical properties and generate a protective film on the contact surfaces [11]. These solid particle additives composed of environmentally benign lamellar powders that have low interlayer friction, ability to form protective boundary layers, and accommodate relative surface velocities [12].

Zhang et al. [13] examined the effect of vegetable-based oils (soybean oil, palm oil, and rapeseed oil) as base lubricants containing nanometer-sized particles as additives and hence, the name nanofluids, during minimum quantity lubrication (MQL) grinding of 45 steel workpiece in comparison with liquid paraffin. The results indicated that palm oil-based nanofluids mixed with MoS_2 nanoparticles produce the best lubricating property in the nanoparticle jet MQL condition due to the high saturated fatty acid and high film-forming property of the carboxyl groups in palm oil. They noted that high viscosity of nanofluids induced good lubricating effect but significantly reduced heat transfer performance. The combination of green solid particles in vegetable oil provided a strong absorption capability and high film strength which enhanced the lubricating property and heat transfer performance. Li et al. [14] performed an experiment on minimum-quantity lubricant cooling (MQLC) grinding of a Ni-based alloy. Palm-based oil was added with different volume fractions of carbon nanotube (CNT) nanoparticles in between 0.5 and 4%. The results found that the volume fraction of 2% of CNT nanoparticles in palm-based oil had achieved the optimal lubrication and heat transfer performance. They initiated that thermal conductivity and viscosity of nanofluids significantly influence the heat transfer properties. Nam et al. [15] conducted an experiment on MQL micro-drilling with the addition of nano-diamond particles in paraffin and vegetable-based oils. The experimental results show that 2 vol. % of nano-diamond particles in the vegetable-based oil significantly reduce the magnitudes of average drilling torques and thrust forces.

At present, the potential of hBN particle as an additive in MWF has been discovered. This solid additive acts as a viscosity, friction, and wear modifiers in many polar and nonpolar oils. Nguyen et al. [16] conducted an experiment on the 3-axis vertical milling center and the lubricant was supplied through MQL method. The results showed that 0.5 wt. % of hBN particles concentration in vegetable-based oil (Unist-Coolube 2210) reduced flank and central wear. A paper by Abdullah et al. [17] has studied the effect of hBN and Al_2O_3 in diesel engine oil by mixing 0.5 vol. % of the solid particles in SAE 15 W40 with the particle size of 70 nm. The results showed that the viscosity index of nano-oil with hBN was improved by 3% compared to nano-oil without additive and nano-oil of Al_2O_3. This finding was due the lower thermal expansion coefficient of hBN (1×10^{-6}/°C). The hBN particles were completely dispersed in the SAE 15 W40 oil and maintained the lubrication properties of the base oil. Furthermore, Talib et al. [18] conducted an experiment on four-ball tribology test of modified Jatropha oil with hBN particles as an application for MQL oil. The modified Jatropha oils were added with the various concentration of hBN particles between 0.05 and 0.5 wt. %. The results revealed that the addition of 0.05 wt. % of hBN particles in the modified Jatropha oil had exhibited excellent tribological performances of the four-ball tribology test in terms of low coefficient of friction, small wear scar diameter, smooth surface roughness, and low volume of wear rate. They indicated that the presence of 0.05 wt. % hBN particles tended to reduce the friction that occurred on the sliding surfaces. The lubrication effect of the MQL oil changed from sliding friction to rolling friction due to the presence of the small amount of hBN particles, which led to the reduction of friction and wear.

1.2. Ionic liquids

Ionic liquids are chemical compounds composed of cations and anions that have melting points lower than 100°C. The cations are usually organic compounds such as nitrogen or phosphorus, and the anions are the weakly coordinating compounds like bis(trifluoromethylsulfonyl)imide or hexafluorophosphate [19–21]. For many years since the first ionic liquid (IL) was reported in 1982, the research and development of ILs have been rapidly evolving in the research works and in various industrial applications [19, 21–24]. IL lubricants are found in lubricant industries as neat lubricant or lubricant additives for various mechanical lubrication purposes [20, 25, 26].

ILs exhibit remarkable properties such as nonflammable, nonvolatile, low melting point, high thermal stability, highly miscible with organic compound, and better intrinsic properties [27, 28]. Use of ILs as lubricant additives may eliminate further requirements of using detergents, defoamers, antioxidants, or even antiwear and antifriction additives in enhancing the performance of the conventional lubricant in current additive formulation processes [27–29]. Thanks to the abovementioned advanced characteristics of ILs, they have been proven to not only improve the tribological properties (friction and wear) [28–30] of different polar and nonpolar base oils, but also enhanced their physicochemical properties (viscosity, thermal and oxidative stability, pour point) [20, 31].

Pham et al. in 2014 examined the effect of two imidazolium-based ILs ([EMIM] [TFSI] & [BMIM] [I]) as neat lubricants in micro end milling [32]. They suggested the potential use of these ILs as green lubricants that exhibit extremely low volatile organic compounds as well as for the use in MQL systems. A study by Davis et al. in 2015 uses water-based lubricant with an additive of a 0.5 wt. % of [BMIM-PF_6] IL when cutting titanium round bars using MQL system [33]. They found out that the lubricant mixture has effectively reduced the tool wear by 60% when compared to dry cutting and 15% more than MQL without the IL. Goindi et al. [34] have recently proposed the use of imidazolium-based ILs with two different anions in minute quantity being mixed in a canola vegetable oil during orthogonal milling of a plain medium carbon steel via MQL method. They reported that the small quantities of the two imidazolium-based ILs ($[BMIM]^+$ with $[PF_6]^-$ & $[BF_4]^-$) have significantly affected the tribological conditions of the milling process by reducing the peak and mean machining forces in finish as well as rough machining conditions.

Somers et al. [35] tested the application of various imidazolium-, phosphonium-, and pyrrolidinium-based ILs as lubricant additives in different polar and nonpolar base oils including vegetable oil, polyolesters, mineral oil, and polyalphaolefin and found that the miscibility of ILs in these base oils depends highly on the molecular structures of the ILs used. High miscibility in both polar and nonpolar base oils is apparent for ILs that comprise quaternary structures with relatively long hydrocarbon chains of the cations and anions [20, 30]. Several recent studies have confirmed this finding and provided reports on their tribological investigations using lubricant mixtures on different material sliding pairs [36–39].

To date, tailor-made ILs investigated for the application as lubricants and/or lubricant additives have known to play an important role in enhancing tribological interactions between sliding materials. The application of IL-based MQL machining may be explored for other nontoxic, fully miscible, and biocompatible ILs as neat as well as lubricant additives in various base oils for different metalworking applications [20]. Halogen-containing anions such as [PF6] or [BF4] contain rich fluorine compound that is moisture-sensitive [20, 40]. They can cause corrosion on the steel surface under humid conditions, thus may release toxic and corrosive hydrogen halides to the environment. In this work, a biocompatible with low-toxic level of phosphonium-based IL, trihexyl (tetradecyl) phosphonium bis (2,4,4-trimethylpentyl) phosphinate, [P66614][(iC8)2PO2] (PIL) was investigated as an oil-miscible IL in polar base vegetable-based lubricants. The application of 1 wt. % of PIL is anticipated to be adequately sufficient in improving the lubrication performance of the base oil when used on the metal sliding surfaces [30, 31].

2. Methodology

2.1. Lubricant preparation

The crude vegetable oils were modified to enhance certain limitations such as low thermal and oxidative stability due to unsaturation in oil molecule. There are various methods of modification that have been identified by Shashidhara and Jayaram [41] which included reformulation of additives, chemical modification, and genetic modification of oilseed. Prior to this experiment, fatty acid methyl esters (FAMEs) from Jatropha oil and RBD palm olein were chemically modified through transesterification process to develop modified Jatropha oil (MJO) and modified RBD palm olein (MRPO) [18, 31]. They are the product of the transesterification process (ester) between FAMEs from the vegetable oils with a polyol of trimethylolpropane (TMP) and better known as the TMP triester. After the transesterification process, the absence of hydrogen atom at carbon-β in the structure of the ester oil has enhanced the thermal and oxidative stability [42]. Both MJO and MRPO were mixed with two different types of additives; hexagonal boron nitride (hBN) and phosphonium-based ionic liquid (PIL). A small amount of 0.05 wt. % of hBN particles were blended in the base oils using a magnetic follower at a temperature of 60°C for 30 min. Meanwhile, 1 wt. % of PIL was heated at 70°C to reduce its viscosity prior to the mixing procedure with the base oils. Next, the preheated PIL was poured into the base oil and heated at 60°C and stirred rigorously by using the magnetic follower for 30 min. The modified oils were compared with a commercial synthetic ester (SE, Unicut Jinen MQL) as a reference oil.

2.2. Rheological properties

The rheological properties were determined through kinematic viscosity (ASTM D445) and viscosity index, VI (ASTMD2270). The kinematic viscosity was measured using a viscometer at 40 and 100°C. It was calculated from the ratio of dynamic viscosity over density at the same temperature. The correlation between viscosity and temperature was further associated with VI. The testing was repeated for three times and the average value was recorded.

2.3. Tapping torque test

Tapping torque tests (ASTM D5619) were carried out on a CNC machine, installed with a tapping torque set up, as shown in **Figure 1**. The tests were conducted using AISI 1215 cylindrical low carbon steels at the machining speed of 400 rpm as shown in **Table 1**. The workpieces

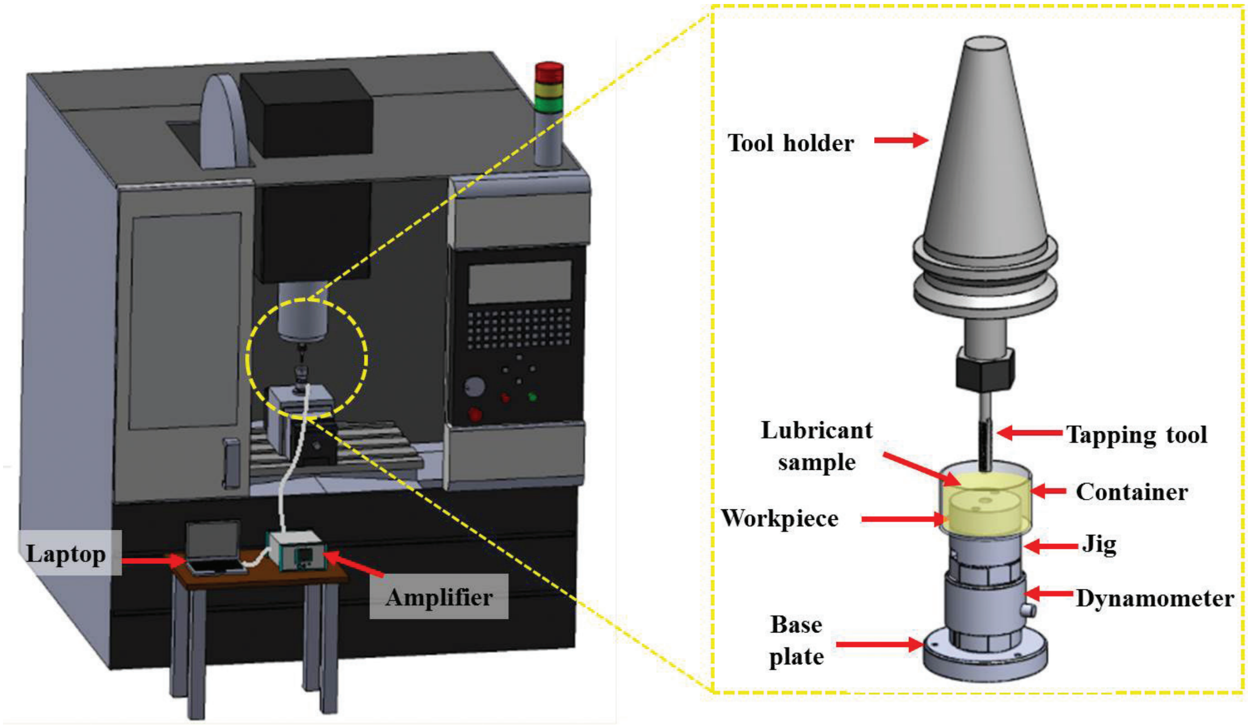

Figure 1. Tapping torque set-up [18].

were predrilled with 5 mm diameter drill bit size. Tapping was performed using an uncoated high-speed steel tapping tool with the size of M6x1.0. The workpiece attached on the jig was later mounted on a dynamometer, Kistler 9345A. The dynamometer was amplified via a multichannel amplifier, Kistler 5070. Approximately, 20 ml of the lubricant sample was poured into the container to lubricate the tools during the tapping process. The result of the torque was recorded using the Dynoware software. Each tapping process was repeated five times for each lubricant sample, prior to averaging the torque values. The efficiency of tapping torque was calculated according to Eq. (1).

$$\text{Efficiency (\%)} = \frac{\text{Average torque of reference oil}}{\text{Average torque of lubricant sample}} \tag{1}$$

Description	Value
Spindle speed (rpm)	400
Feed rate, f_r(mm/rev)	1
Hole depth (mm)	12 (through hole)
Tapping tool	High speed steel, M6
Lubricant volume (ml)	30
Workpiece material	AISI 1215 steel
Workpiece dimension (mm)	Ø37×12

Table 1. Tapping torque test parameter.

2.4. Orthogonal cutting

Orthogonal turning process was conducted on an NC lathe machine (Alpha Harrison 400) to cut a steel disk of AISI 1045 plain medium carbon steel. The tool used was a square shape insert with a positive rake angle of 5°, clearance angle of 11°, and a model number of SPGN120308. The tool insert was fixed on a modified tool holder of CSDPN 2525 M12 in a way that the chip will flow freely without any hindrance on the rake surface of the cutting insert during the chip formation process. The steel disk has an initial diameter and width of 150 and 2 mm respectively. The complete cutting parameter is shown in **Table 2**.

The cutting tool was fixed on a dynamometer, Kistler 9275BA in order to measure the cutting forces. The forces measured were amplified by using the Kistler 5070 amplifier and were recorded on a PC for data analysis. The lubricants were supplied via an MQL system directly to the cutting edge at the tool-workpiece interfaces. The air supply pressure was fixed at 4 bar and the flow rate was set at 0.16 l/hr. The MQL nozzle with an outlet diameter of 2.5 mm was located at a distance of 8 mm between the nozzle outlet and the tool-workpiece interfaces and inclined at 45° to the cutting edge plane. The maximum cutting temperature was captured by using an infrared thermal camera (FLIR T640) within a temperature range of 0–1000°C. The camera was located parallel to the axial direction of the lathe machine facing toward the cutting zone. The schematic diagram of the complete setup assembly on the lathe machine is shown in **Figure 2**.

Each cutting test was conducted twice using each of the lubricant sample and new cutting edge to reduce measurement error during the results analysis. At the end of each cutting operation, the cutting forces were recorded and the chips were collected for cutting force evaluation and chip thickness measurement analysis respectively. The cutting force was determined in the Z-axis during the chip formation process. At least 10 chips were measured for their thickness by using a digital micrometer. The specific cutting energy, U, was calculated using Eq. (2), where F_c is the cutting force, w is the cutting depth, and t_o is the undeformed chip thickness [43].

$$U = \frac{F_c}{t_o \cdot w} \tag{2}$$

Description	Value
Cutting speed, v_c (m/min)	350
Feed, f (mm/rev)	0.12
Cutting depth, w (mm)	2
Disk diameter (mm)	150
Disk thickness, d (mm)	2
MQL lubricants	SE; MJO + hBN0.05%; MJO + PIL1; MRPO + hBN0.05%; MRPO + PIL1%
MQL supply pressure (MPa)	0.4
MQL flow rate (l/hr)	0.16
Nozzle inner diameter (mm)	2.5
Nozzle distance (mm)	8

Table 2. Cutting parameter of the orthogonal lathe machining.

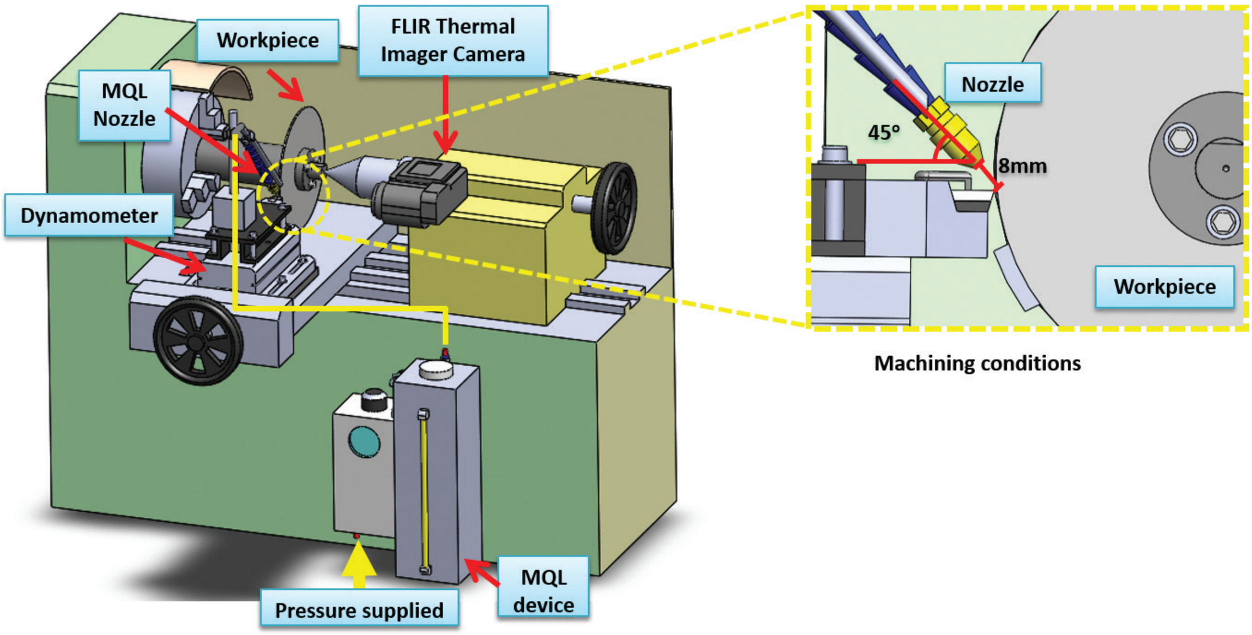

Figure 2. Orthogonal lathe cutting set-up.

Finally, the sliding region on the tool insert's rake face was analyzed under an optical microscope and the tool-chip contact length was measured for data analysis. Scanning electron microscope (SEM) was used to further analyze the surface morphology of the sliding regions.

3. Results and discussions

3.1. Rheological properties

Figure 3 displays the kinematic viscosity values and the calculated viscosity index (VI). The kinematic viscosity of the reference oil (SE) at 40 and 100°C are 21.5 and 5.6 mm^2/s, respectively. It can be seen that MRPO + hBN0.05% shows the highest kinematic viscosity values of 22.2 mm^2/s at 40°C and 6.35 mm^2/s at 100°C. The addition of hBN particles in MRPO-based oil improves the viscosity values due to lower thermal expansion coefficient of hBN particles (1×10^{-6}/°C), thus enhanced the thermal stability [17]. Meanwhile, MRPO + PIL1% recorded the kinematic viscosity values of 22.21 mm^2/s at 40°C and 6.25 mm^2/s at 100°C. Both MRPO-based oils demonstrated the highest kinematic viscosity value compared to MJO-based oils and SE due to the high saturation of fatty acids in the MRPO-based oil. MRPO-based oil contains high composition of saturated fatty acid (palmitic acid, $C_{15}H_{31}COOH$) at 50–70% [44]. Meanwhile, both MJO-based oils had the lowest kinematic viscosity values at both temperatures. This can be explained by the presence of unsaturated fatty acids (oleic acid, $C_{17}H_{33}COOH$ and linoleic acid, $C_{17}H_{31}COOH$) in MJO-based oil [45]. Moreover, MRPO + PIL1% demonstrates the highest VI value of 259 which was 17% higher than SE. The high VI is desirable as it indicates little changes in viscosity across a wide range of operating temperature. Both MJO-based oils had the lowest VI values which had 5% reduction compared to SE.

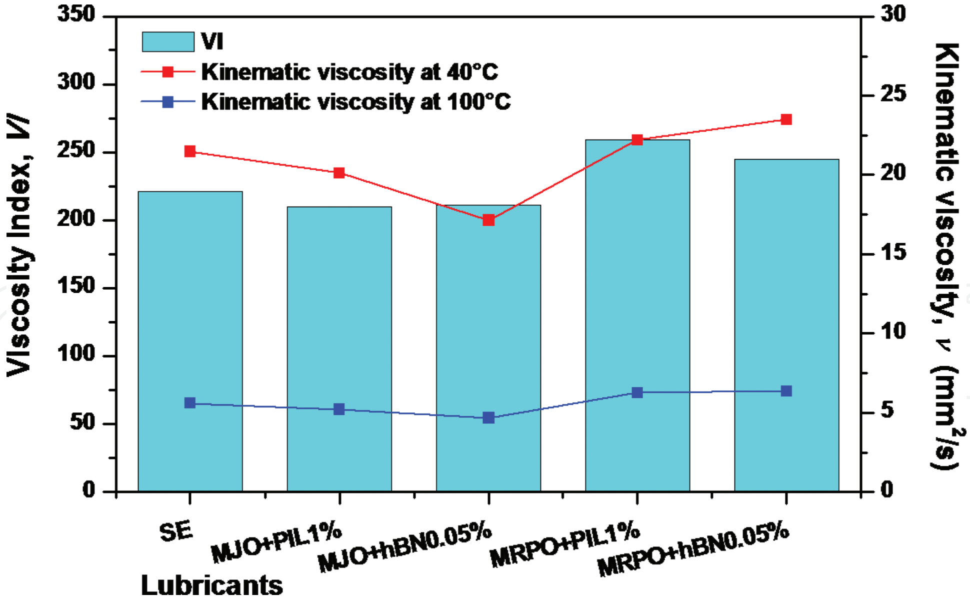

Figure 3. The kinematic viscosity values at 40 and 100°C and the calculated viscosity index value.

3.2. Tapping torque performance

Figure 4 shows the tapping torque and efficiency for all lubricant samples. The reference oil (SE) had the highest tapping torque at 129 Nm. The results reveal that the tapping torque for all modified vegetable oils exceeded the tapping torque of SE. MJO + PIL1% had the lowest tapping torque of 104 Nm correlated with the highest tapping torque efficiency of 124%. The presence of PIL as an additive improves the tapping torque performance. This is because of the addition of PIL in MJO-based oil, which is thermally more stable than SE. The alkyl chain length and hydrogen bonding between the cation and the anion seem to influence the tribofilm formation of PIL [29]. Meanwhile, MJO + hBN0.05% recorded tapping torque of 117 Nm with the tapping torque efficiency of 110%. The presence of hBN particles provided a thin lubrication film that allows the particles to change from sliding friction to the rolling friction [18]. Moreover, the presence of long carbon chain length of MJO-based oil and MRPO-based oil which is between 16 and 18 carbon number had enhanced the adsorption ability of the fatty acids on the metal surfaces, thus exhibited better tapping torque performance. MRPO + hBN0.05% and MRPO + PIL1% had tapping torque efficiency of 107 and 106%. It can be seen that the addition of PIL and hBN particles as the additive in MRPO-based oil did not significantly affect the tapping torque performance compared to the MJO-based oils. This scenario is due to the weak tribo-chemical reactions of additives with the MRPO-based oil, thus reduced the adsorption ability of the lubricant molecules on the metal surface [46].

3.3. Orthogonal cutting performance

The orthogonal lathe cutting operations were conducted at a constant speed and feed. The cutting force, cutting temperature, chip thickness, specific cutting energy, and tool-chip contact length are the main outputs of this experimental section analysis. The results for each lubricant mixture were compared with the conventional cutting fluid, synthetic ester (SE).

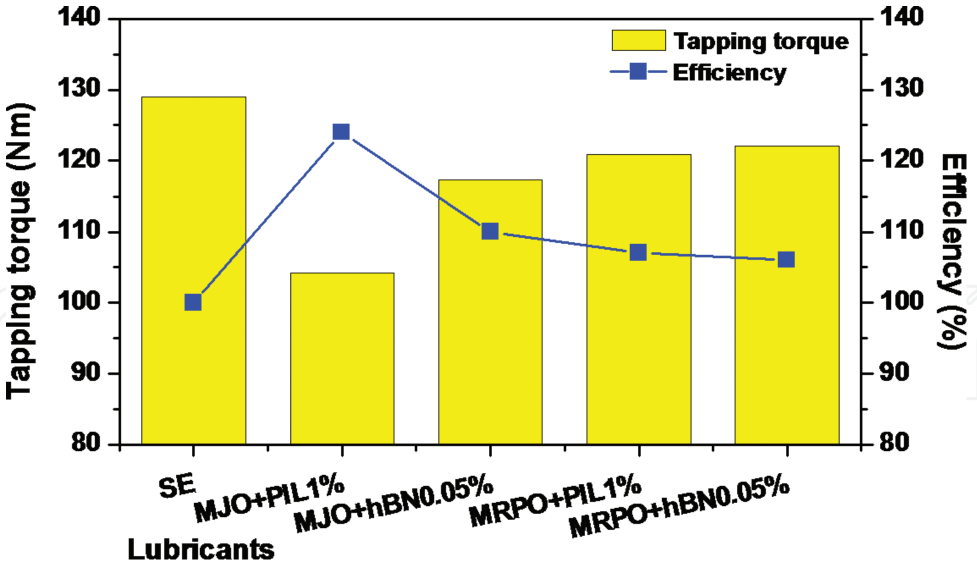

Figure 4. Tapping torque and torque efficiency value of all lubricant samples.

3.3.1. *Cutting force and temperature analysis*

Figure 5 shows the results of cutting force, F_c measured in the Z-axis and the maximum cutting temperature results after the orthogonal cutting operations. It is shown that SE produced the highest cutting force and cutting temperature at ca. 612 N and 308°C respectively. SE generated poor lubrication condition on the cutting zone as compared to the other lubricant samples. MJO + PIL1% produces the greatest reduction of cutting force (2% reduction) as well as the cutting temperature (10% reduction) compared to the SE which corresponds to the good lubrication ability of the PIL additive contained in the base oil, MJO. The addition of 0.05 wt. % hBN solid particles also improved the lubrication ability of the MJO base oil. It is anticipated that the different type of lubricant used with the addition of the same additive did

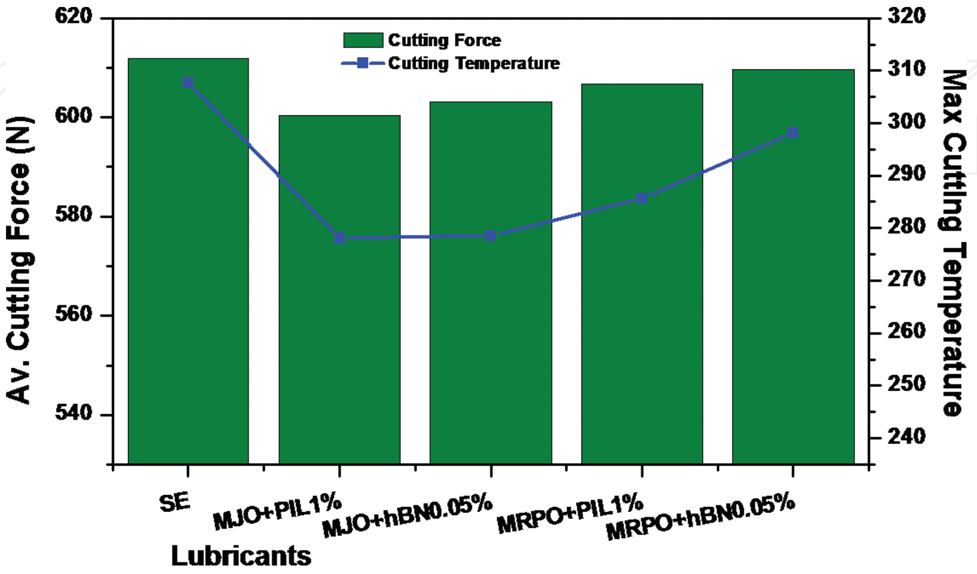

Figure 5. Cutting force and temperature results.

give similar improvement effect as shown by the results of MRPO base oil. MRPO + PIL1% and MRPO + hBN0.05% show a reduction in both cutting force and cutting temperature when compared to the SE in a range between 0.4 and 8% decrement respectively.

The addition of 1 wt. % PIL has enhanced the antifriction and antiwear properties of the base oil by reducing the scuffing effect and the abrasive wear mechanism [25]. The polarity of the phosphonium-based IL additive has resulted in the increased adsorption rate of the additive molecules on the metal surface. The result is also corroborated by the tapping torque and efficiency values reported in the previous section. The tribofilm formed helps lower the frictional torque of the base oil corresponding to the reduction of friction coefficient. It acts as a separation layer between the metal asperities and kept them apart from direct contact, thus reduces the cutting force and generates less heat.

The addition of 0.05 wt. % hBN solid particles in the base oil reduces the average cutting force as well as the heat generated within the cutting zone by separating the metal asperities contacts during the sliding processes. However, the ability of the particles in reducing the frictional force and the heat generation is greatly affected by the particles filling rate in the asperity valleys which enabled them to align in parallel to the relative sliding motion, thus reducing the stress concentration on the contact surfaces [31]. Therefore, the high polarity of the PIL and the ability of its anionic moieties that can quickly adsorb on the sliding metal surfaces via strong electrostatic interactions even at high temperature and load working conditions has become the most attractive contribution of the PIL additive toward the formation of tenacious lubricant films on the metal surface that greatly reduces friction and wear [20]. This type of lubricant additive has successfully improved the tribological performance of the polar oil of MJO- and MRPO-based lubricant samples during the machining of the plain medium carbon steel of AISI 1045 [47].

3.3.2. Chip thickness analysis

The average chip thickness after the machining processes is exhibited in **Figure 6**. During the material removal process, the chip is formed due to the elastic, elastic-plastic, and plastic deformation processes of the workpiece material. It is mainly influenced by the heat generation under high stresses and temperature arisen due to the high deformation resistance between the cutting insert and the workpiece material being cut [48]. The chip thickness is one of the parameters that affected the chip formation mechanisms with the shearing angle between the uncut chip thickness and the cutting forces required during the material removal process [39].

An effective surface lubrication on the cutting zone has helped reduce the chip thickness produced after the machining operations by reducing the thermal stresses that occurred on the sliding surfaces. As presented in the previous subsection, the reduced friction due to high lubrication effect of MJO + PIL1% compared to the SE has successfully decreased 20% of the chip size which indicates the reduced tensile strain on the outer surface of the chip during bending. The specific thermal effects were reduced due to the adequate lubricant being sprayed and penetrated the sliding interfaces [49]. In addition, the fast and strong electrostatic interactions between the lubricant and additive molecules with the metal substrates had formed the tenacious lubricant film that reduced the contact area at the shear zone, thus resulting in the reduction of frictional force [20, 30, 38]. Furthermore, this phenomenon also contributed to thinner chips being cut with large shear angle and low cutting energy. These results were

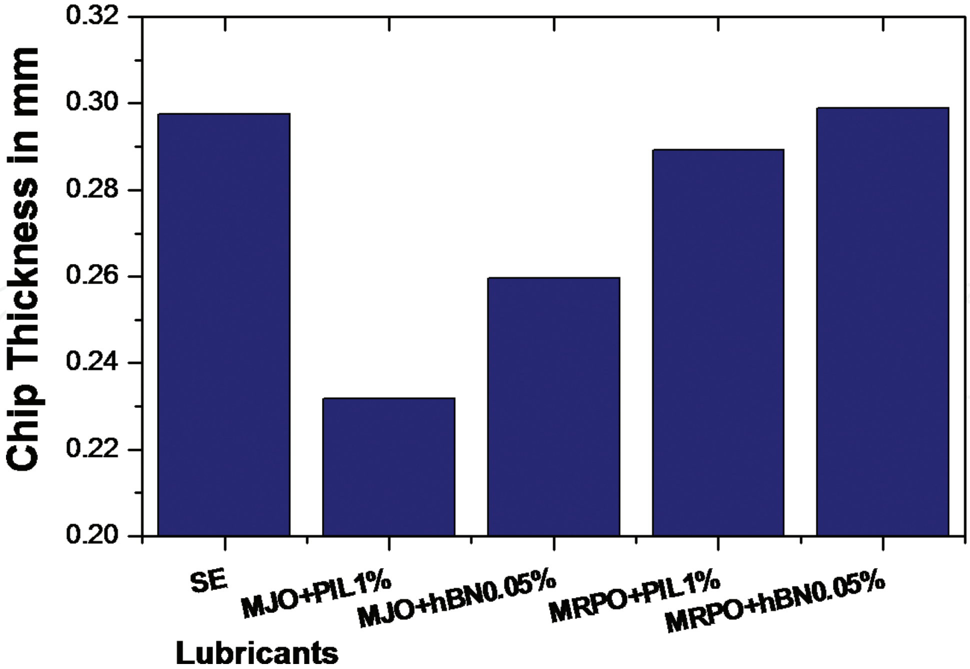

Figure 6. Result of the measured chip thickness.

comparable to the findings reported by Somers et al. [35]. They identified that the more polar IL additive has improved the properties of the polar vegetable oil. They also indicated that the ILs can form low-shear layers of anions and cations when adsorbed onto the metal surface and they can also break down to form a protective tribolayer by reacting with the exposed metal. The more polar ILs induced physical and chemical interactions with the metallic surface by adsorption at the sliding contact, thus contributing to the reduction of friction.

3.3.3. Evaluation of specific cutting energy

The calculated specific cutting energy following Eq. (2) of the orthogonal lathe machining is presented in **Figure 7**. Specific cutting energy is correlated with the energy during plastic deformation and friction [43, 48]. It indicates the amount of energy required to perform plastic deformation and overcome friction in the machining process [39]. Specific cutting energy decreases with temperature as the shear stress of the material in the shear plane decreases with the reduction of the chip thickness compression ratio [48].

It is clearly seen from **Figure 7** that the SE poses the highest cutting energy which correlates with the production of high shear stresses in the shear plane. The shear angle is also a predominant factor controlling the distribution of stresses together with the chip compression ratio and the rake angle. The lubrication characteristics of the lubricant mixtures have considerably reduced the shear stresses between metal surfaces when they were in relative motions by providing adequate lubrication film with high load carrying capacity, thus reducing the requirement of the cutting energy [43]. As mentioned earlier, the formation of tribofilm by the active end of the lubricant molecules and the additives on the metal surfaces has directly enhanced the lubrication properties on the contact zone. The complex and branched chain of TMP triester and the additive molecules caused a superior lubricity behavior and a high thermal stability which offered better tribological behavior regarding friction reduction and lower the generated thermal stresses.

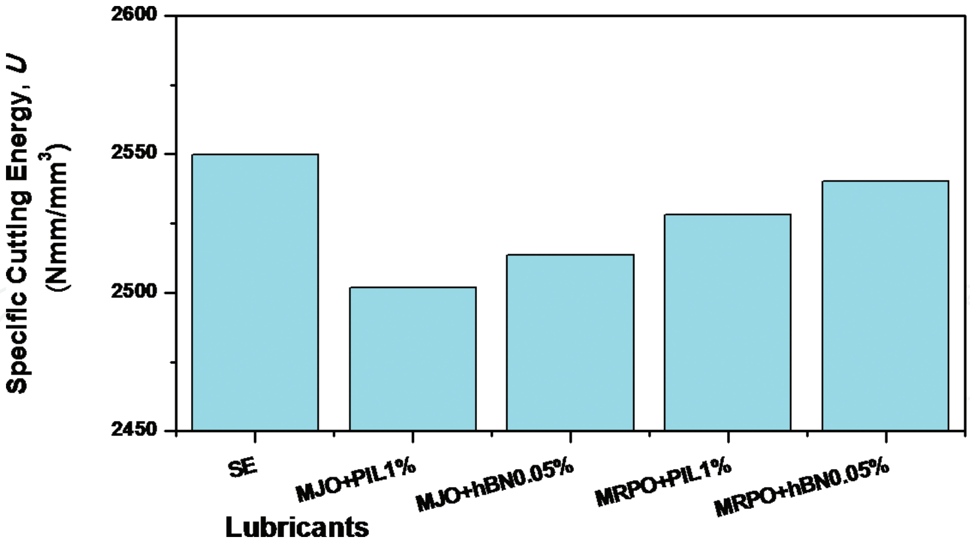

Figure 7. Specific energy of the orthogonal cutting process lubricated with all lubricant samples.

3.3.4. Evaluation of tool-chip contact length

The tool-chip contact region was analyzed underneath an optical microscope and the average contact length was measured and presented in **Figure 8**. The interaction between the metal chip and the tool rake face produces two contact regions of sticking and sliding friction during the orthogonal cutting process [43, 48]. The contact length and cutting forces are greatly influenced by the cutting lubricants applied on the cutting zone. The total contact length, L_c has been reported to depend most strongly on the deformed chip thickness h_c and proportional to the product of the chip thickness and the effective friction coefficient. Here, the lubrication effect by using different MQL lubricant mixtures had improved the tool/chip contact

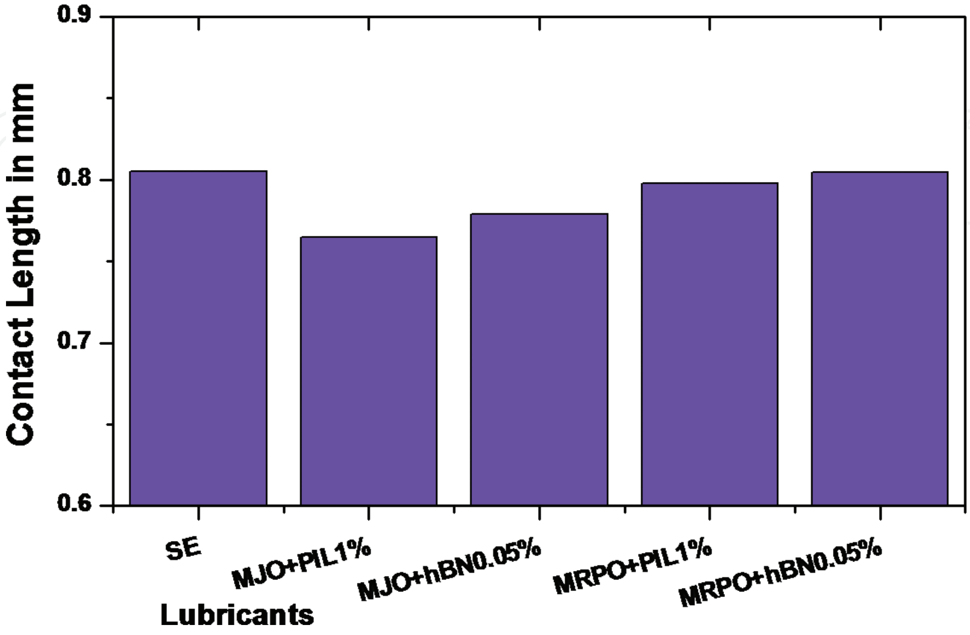

Figure 8. Results of the measured tool-chip contact length.

length compared to the surface lubricated with SE. It was clearly seen that the various types of the metalworking fluids clearly affected the tool-chip contact length. The poor lubrication effect of the SE has resulted in the high frictional sticking contact with the workpiece material and produces high shear and strain stress on the cutting edge, which leads to the high frictional stress and longer contact length [39, 49].

The lubricant forms an intrinsically hydraulic wedge between the chip and the rake face of the tool insert, which may prevent seizure between the tool-chip interfaces and thus greatly lower the cutting force [48]. The addition of additives has successfully reduced the total stresses on the sticking and sliding regions during the chip formation processes [26, 36]. The tribofilm formed on the sliding surfaces acts as a wear-protected film and the lubricant spray mist penetrates to the tool cutting edge. It reduces the friction stress and subsequently shortens the tool/chip contact length and improved chip control [43, 48]. Sticking or seizure occurs at the tool edge interface and the chip then slides beyond the sticking region. The occurrence of material transfer or adhesion on the rake face indicates the material wear mechanism and the lubrication effects of different lubricant samples during the material removal process. The surface topography of the sliding region is presented in **Figure 9**.

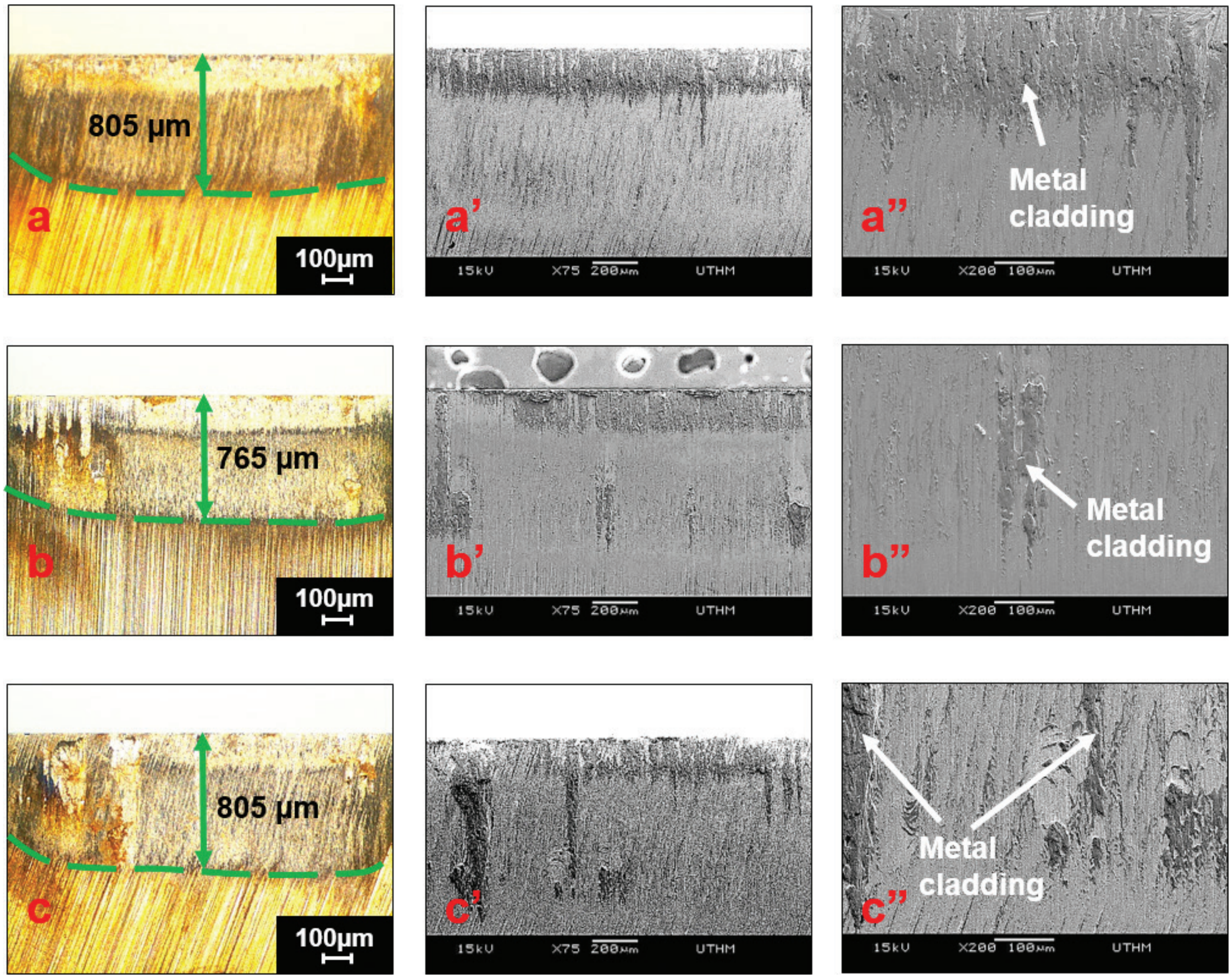

Figure 9. Optical and SEM images of the selected surface morphology on the cutting tools rake face at 50×, 75×, and 200× magnifications respectively; (a, a′, a″) SE; (b, b′, b″) MJO + PIL1% and (c, c′, c″) MRPO + hBN0.05.

The lubrication characteristics of metalworking fluids considerably reduced the friction between surfaces when they were in relative motions, thus reducing the requirement of cutting energy [48]. SE contributed to poor lubrication behavior where oxidization at high operation temperature could easily take place [18]. MRPO + hBN0.05% shows a decrement of 0.4% in specific cutting energy under the given cutting condition, while MJO + PIL1% shows superior performance with 2% improvement compared to the SE. The presence of solid additive of boron nitride particles in the vegetable base oils did help to increase the base oil performance, however, the higher adsorption rate of PIL than the hBN particles are seen to impose better lubrication effect. The poor lubrication film of the SE and MRPO + hBN0.05% was contributed by a low formation of protective layers on the contacting surfaces and also corresponds to the decreased of spray penetration into the cutting zone which leads to the direct contact of metal asperities that produces high friction between the tool and workpiece surfaces. In conclusion, the low energy required posed by the lubricant mixtures clearly proved the ability of these lubricant additives to be used as new formulations for an advanced renewable bio-based MWF from Jatropha and palm olein oils. They may become an attractive alternative to the world dominating mineral-based MWFs.

4. Conclusions

From the experimental data analyzed in this work, the following conclusions are obtained:

- The presence of polyol ester and fatty acids in the newly refined biodegradable lubricants from Jatropha and palm olein oils plays a significant importance to the tribological behavior on the metal sliding pairs in terms of wear and friction reduction. The presence of alkyl groups affects the good tribological behavior posed by the vegetable-based oils, MJO & MRPO.
- The MJO & MRPO lubricants proved to be more effective in enhancing their machining performances during the tapping torque tests and the orthogonal cutting experiments with the addition of a small quantity of an oil-miscible ionic liquid and hBN solid particles as lubricant additives.
- Good synergistic effect on the tribological and machining performance of the lubricant mixtures was shown by enhanced machining performances with improved physical properties and lubrication effects. All lubricant mixtures have shown reduced tapping torque, improved tapping efficiency, low cutting force and cutting temperature, reduced specific cutting energy and tool-chip contact length compared to the conventional synthetic ester, SE.
- The addition of phosphonium-based ionic liquid (1 wt. % PIL) into the MJO and MRPO is found to impose better lubrication ability than the addition of hBN solid particles (0.05 wt. %) in improving the tribological and machining performances of the base oils.
- The low amount of the additives used in the MJO & MRPO has great potential to be used as lubricant additives in the bio-based cutting fluids for metalworking applications.
- 'Greener' manufacturing activities by using renewable sources and low amount of biocompatible additives resulted in good energy efficiency and cleaner environment. In terms of sustainable machining operation, MJO + PIL1% & MJO + hBN0.05% are found to be a good alternative as reference for replacing the industrial dominating mineral oil-based lubricants.

Acknowledgements

The authors would like to thank the Ministry of Education Malaysia and University Tun Hussein Onn Malaysia for the financial support via Fundamental Research Grant Scheme (Vot. 1467 and Vot. 1591).

Author details

Erween Abd. Rahim*, Amiril Sahab Abdul Sani and Norfazillah Talib

*Address all correspondence to: erween@uthm.edu.my

Precision Machining Research Center (PREMACH), Faculty of Mechanical and
Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor,
Malaysia

References

[1] Erhan SZ, Sharma BK, Perez JM. Oxidation and low temperature stability of vegetable oil-based lubricants. Industrial Crops and Products. 2006;**24**:292-299

[2] Nicol A, Hurrell AC. Exploring knowledge translation in occupational health using the mental models approach: A case study of machine shops. Proceedings of the European Safety and Reliability Conference. 2008;**1**:749-756

[3] Lawal SA, Choudhury IA, Nukman Y. Application of vegetable oil-based metalworking fluids in machining ferrous metals–A review. International Journal of Machine Tools and Manufacture. 2012;**52**:1-12

[4] Mang T, Dresel W. Lubricants and Lubrication. 2nd ed. Weinheim, Germany: WILEY-VCH Verlag GmbH & Co. KGaA; 2007. 890 p

[5] Skerlos SJ, Hayes KF, Clarens AF. Current advances in sustainable metalworking fluids research. International Journal of Sustainable Manufacturing. 2008;**1**:180-202

[6] Belluco W, Chiffre L. Performance evaluation of vegetable-based oils in drilling austenitic stainless steel. Journal of Materials Processing Technology. 2004;**148**:171-176

[7] Kuram E, Ozcelik B, Simsek BT, Demirbas E. The effect of extreme pressure added vegetable based cutting fluids on cutting performance in milling. Industrial Lubrication and Tribology. 2013;**65**(3):181-193. DOI: 10.1108/00368791311311187

[8] Rahim EA, Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. Tribology International. 2011;**44**:309-317

[9] Jayadas NH, Nair KP, Ajithkumar G. Tribological evaluation of coconut oil as an environment-friendly lubricant. Tribology International. 2007;**40**:350-354

[10] Brinksmeier E, Meyer D, Huesmann-Cordes AG, Herrmann C. Metalworking fluids–Mechanisms and performance. CIRP Annals–Manufacturing Technology. 2015;**64**:605-628

[11] Vasu V, Reddy PKG. Effect of minimum quantity lubrication with Al2O3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems. 2011;**225**:3-16

[12] Reeves CJ, Menezes PL. Advancements in eco-friendly lubricants for tribological applications: Past, present, and future. In: Davim JP, editor. Ecotribology. Switzerland: Springer International Publishing; 2016. p. 41-61

[13] Zhang Y, Li C, Jia D, Zhang D, Zhang X. Experimental evaluation of MoS_2 nanoparticles in jet MQL grinding with different types of vegetable oil as base oil. Journal of Cleaner Production. 2015;**87**:930-940

[14] Li B, Li C, Zhang Y, Wang Y, Yang M, Jia D, Zhang N, Wu Q. Effect of the physical properties of different vegetable oil-based nanofluids on MQLC grinding temperature of Ni-based alloy. International Journal of Advanced Manufacturing Technology. 2016;**89**:3459-3474

[15] Nam JS, Lee PH, Lee SW. Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication. International Journal of Machine Tools and Manufacture. 2011;**51**:649-652

[16] Nguyen TK, Do I, Kwon P. A tribological study of vegetable oil enhanced by nano-platelets and implication in MQL machining. International Journal of Precision Engineering and Manufacturing. 2012;**13**:1077-1083

[17] Abdullah MIHC, Abdollah MF, Amiruddin H, Tamaldin N, Nuri NRM, Hassan M, Rafeq SA. Improving engine oil properties by dispersion of hBN/Al_2O_3 nanoparticles. Applied Mechanics and Materials. 2014;**607**:70-73

[18] Talib N, Nasir RM, Rahim EA. Tribological behaviour of modified jatropha oil by mixing hexagonal boron nitride nanoparticles as a bio-based lubricant for machining. Journal of Cleaner Production. 2017;**147**:360-378

[19] Bermudez M-D. Introduction to the ionic liquids special issue. Tribology Letters. 2010; **40**(2):213. DOI: 10.1007/s11249-010-9707-0

[20] Amiril SAS, Rahim EA, Syahrullail S. A review on ionic liquids as sustainable lubricants in manufacturing and engineering: Recent research, performance, and applications. Journal of Cleaner Production. 2017;**168**:1571-1589. DOI: 10.1016/j.jclepro.2017.03.197

[21] Chetan SGP, Rao V. Application of sustainable techniques in metal cutting for enhanced machinability: A review. Journal of Cleaner Production. 2015;**100**:17-34. DOI: 10.1016/j.jclepro.2015.03.039

[22] Zhang L, Feng D, Bin X. Tribological characteristics of alkylimidazolium diethyl phosphates ionic liquids as lubricants for steel–steel contact. Tribology Letters. 2009;**34**(2): 95-101. DOI: 10.1007/s11249-009-9412-z

[23] Cai Z-b, Meyer HM, Ma C, Chi M, Luo H, Jun Q. Comparison of the tribological behavior of steel–steel and Si3N4–steel contacts in lubricants with ZDDP or ionic liquid. Wear 2014;**319**(1-2):172-183. DOI: 10.1016/j.wear.2014.08.002

[24] Hernández Battez A, Blanco D, Fernández-González A, Mallada MT, González R, Viesca JL. Friction, wear and tribofilm formation with a [NTf2] anion-based ionic liquid as neat lubricant. Tribology International. 2016; **103**(November 2016):73-86. DOI: 10.1016/j.triboint.2016.06.038

[25] Anand M, Hadfield M, Viesca JL, Thomas B, Hernández Battez A, Austen S. Austen. Ionic liquids as tribological performance improving additive for in-service and used fully-formulated diesel engine lubricants. Wear 2015;**334-335**:67-74. DOI: 10.1016/j.wear.2015.01.055

[26] Zhu L, Zhao Q, Wu X, Zhao G, Wang X. A novel phosphate ionic liquid plays dual role in synthetic ester oil: From synthetic catalyst to anti-wear additive. Tribology International. 2016;**97**(May 2016):192-199. DOI: 10.1016/j.triboint.2015.12.047

[27] Qu J, Truhan JJ, Dai S, Luo H, Blau PJ. Ionic liquids with ammonium cations as lubricants or additives. Tribology Letters. 2006;**22**(3):207-214. DOI: 10.1007/s11249-006-9081-0

[28] Palacio BB. A review of ionic liquids for green molecular lubrication in nanotechnology. Tribology Letters. 2010;**40**(2):247-268. DOI: 10.1007/s11249-010-9671-8

[29] Yu B, Bansal DG, Qu J, Sun X, Luo H, Dai S, Blau PJ, Bunting BG, Mordukhovich G, Smolenski DJ. Oil-miscible and non-corrosive phosphonium-based ionic liquids as candidate lubricant additives. Wear 2012;**289**:58-64. DOI: 10.1016/j.wear.2012.04.015

[30] González R, Bartolomé M, Blanco D, Viesca JL, Fernández-González A, Hernández Battez A. Effectiveness of phosphonium cation-based ionic liquids as lubricant additive. Tribology International. 2016;**98**:82-93. DOI: 10.1016/j.triboint.2016.02.016

[31] Amiril SAS, Rahim EA, Talib N, Kamdani K, Rahim MZ, Syahrullail S. Performance evaluation of palm- olein TMP ester containing hexagonal boron nitride and an oil miscible ionic liquid as bio-based metalworking fluids. Journal of Mechanical Engineering. 2017;**SI 4**(1):223-234

[32] Pham M-Q, Yoon H-S, Khare V, Ahn S-H. Evaluation of ionic liquids as lubricants in micro milling–Process capability and sustainability. Journal of Cleaner Production. 2014;**76**:167-173. DOI: 10.1016/j.jclepro.2014.04.055

[33] Davis B, Schueller JK, Huang Y. Study of ionic liquid as effective additive for minimum quantity lubrication during titanium machining. Manufacturing Letters. 2015;**5**:1-6. DOI: 10.1016/j.mfglet.2015.04.001

[34] Goindi GS, Sarka P, Jaya AD, Chavan SN, Mandal D. Investigation of ionic liquids as additives to canola oil in minimum quantity lubrication milling of plain medium carbon steel. International Journal of Advanced Manufacturing Technology. 2017. DOI: 10.1007/s00170-017-0970-1

[35] Somers AE, Khemchandani B, Howlett PC, Sun J, MacFarlane DR, Forsyth M. Ionic liquids as anti-wear additives in base oils: Influence of structure on miscibility and wear

performance for steel on aluminium. ACS Applied Materials & Interfaces. 2013;**5**(22): 11544-11553. DOI: 10.1021/am4037614

[36] Zhu L, Zhao G, Wang X. Investigation on three oil-miscible ionic liquids as antiwear additives for polyol esters at elevated temperature. Tribology International. 2017;**109** (May 2017):336-345. DOI: 10.1016/j.triboint.2016.10.032

[37] Zhou Y, Jun Q. Ionic liquids as lubricant additives: A review. ACS Applied Materials & Interfaces. 2017;**9**(4):3209-3222. DOI: 10.1021/acsami.6b12489

[38] Hernández Battez A, Bartolomé M, Blanco D, Viesca JL, Fernández-González A, González R. González. Phosphonium cation-based ionic liquids as neat lubricants: Physicochemical and tribological performance. Tribology International. 2016;**95**:118-131. DOI: 10.1016/j.triboint.2015.11.015

[39] DeVries WR. Analysis of Material Removal Processes. 1st ed. USA: Springer-Verlag; 1992. 254 p. DOI: 10.1007/978-1-4612-4408-0

[40] Bart JCJ, Gucciardi E, Cavallaro S. Advanced lubricant fluids. In: Bart JCJ, Gucciardi E, Cavallaro S, editors. Biolubricants: Science and Technology. Cambridge: Woodhead Publishing Limited; 2013. pp. 824-846

[41] Shashidhara YM, Jayaram SR. Vegetable oils as a potential cutting fluid—An evolution. Tribology International. 2010;**43**:1073-1081

[42] Arbain NH, Salimon J. The effects of various acid catalyst on the esterification of jatropha curcas oil based trimethylolpropane ester as biolubricant base stock. Journal of Chemistry. 2011;**8**:33-40

[43] Stephenson DA, Agapiou JS. Metal Cutting Theory and Practice. 3rd ed. USA: CRC Press; 2016. p. 947

[44] Syahrullail S, Izhan MI. Tribological investigation of RBD palm olein in different sliding speeds using pin-on-disk tribotester. Scientia Iranica. 2014;**21**:162-170

[45] Salimon J, Abdullah BM, Yusop RM, Salih N. Synthesis, reactivity and application studies for different biolubricants. Chemistry Central Journal. 2014;**8**:1-11

[46] Minami I. Molecular science of lubricant additives. Applied Sciences. 2017;**7**:1-33

[47] Qu J, Bansal DG, Yu B, Howe JY, Luo H, Dai S, Li H, Blau PJ, Bunting BG, Mordukhovich G, Smolenski DJ. Antiwear performance and mechanism of an oil-miscible ionic liquid as a lubricant additive. ACS Applied Materials & Interfaces. 2012;**4**(2):997-1002. DOI: 10.1021/am201646k

[48] Grzesik W. Advanced Machining Processes of Metallic Materials–Theory, Modelling and Applications. 1st ed. Amsterdam, Netherlands: Elsevier; 2008. 472 p

[49] Trent EM, Wright PK. Metal Cutting. 4th ed. Oxford, United Kingdom: Elsevier Science & Technology; 2000. 464 p