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Performance Evaluation of Chemically Modified Crude Jatropha Oil as a Bio-based Metalworking Fluids for Machining Process

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Abstract

Metalworking fluids (MWFs) acts as cooling and lubrication agent at the cutting zone in the machining process. However, conventional MWFs such as mineral oil gives negative impact on humans and environment. Therefore, the manufacturer tends to substitute mineral oil to bio-based oils such as vegetables and synthetic oil. There is a need to develop environment friendly MWFs as an alternative to the use of lubricant. The aim of this research is to evaluate the performance of chemically modified jatropha oil-based trimethylolpropane (TMP) ester from crude jatropha oil (CJO) as bio-based MWFs. Modified jatropha oil (MJO) was developed by transesterification process with different molar ratios of jatropha methyl ester (JME) to TMP. Afterwards, MJOs were tested on viscosity, density and tribology according to American Society Testing and Materials (ASTM) conditions. Then, the samples were compared with synthetic ester (SE) and CJO on the orthogonal cutting condition. Those lubricants were supplied using minimum quantity lubrication (MQL) technique. The result shows that the viscosity of oils affects the coefficient of friction (COF) and wear scar diameter (WSD). The machining performance of MJO was comparable with SE in terms of cutting force and maximum cutting temperature. It shows that MJO was significantly improved the lubricating effect thus becomes a suitable candidate to substitute SE as a machining lubricant.

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Keywords: Bio-based lubricant; jatropha oil; TMP ester; MQL; orthogonal cutting

1. Introduction

Sustainability has become an important element to be considered in the manufacturing industry. This is due to the increasing consideration on the usage of renewable materials. Besides, conventional MWFs made from petroleum-based oil caused environmental pollution, need high processing cost of recycling processes and caused health problems. Recently, petroleum prices are fluctuated because of the total rate of crude oil output decreased. It was estimated that only 0.1% lubricants in the market are made from vegetable oils[1]. Bio-based oils from vegetable oils are finding their way as an alternative to replace the usage of petroleum-based oil. Bio-based oils offer significant environmental benefits, renewability, biodegradability and have excellent lubricating properties that providing satisfactory performance in machining operation.

Previously, bio-based oils have been used in wide applications such as automotive lubricant, biofuel, hydraulic oil, grease and metalworking fluids. Bio-based oils from soybean, rapeseed, sunflower, palm oil and coconut have been extensively studied for lubricant applications. Erhan et al. [2] studied the lubricant properties of soybean and high oleic sunflower oil. The crucial problem occurred in bio-based oils is low temperature and lack of oxidative stability which can be improved through chemical modification and mix with additives. Similarly, Shashidara and Jayaram[3] showed that soybean, sunflower and rapeseed oil have a potential to be used as MWFs. The authors concluded that oil performances can be improved by additive mixtures, chemical modification of crude oil and genetic modification of the seed oil. This is supported by Wu et al. [4] which reveals that the modified rapeseed oil provides better lubrication properties by reducing friction and extreme pressure ability than the crude oil.

Lawal et al. [5] reported that bio-based oil has been used as MWFs in various material and machining conditions. They
identify that MWFs from palm oil, coconut and sunflower have greater lubricating properties and showed similar performance with mineral oil in terms of cutting force, cutting temperature, surface finish and tool wear. Rahim and Sasahara[6] proved that palm oil outperformed SE via MQL technique of coolant for high speed drilling process. They exposed that the properties of palm oil in terms of viscosity and viscosity index have influenced the machining performance. By using palm oil, cutting force and cutting temperature have reduced. Research findings by Kuram et al. [7] also points viscosity value effect the MWFs efficiency. In addition, Sales et al. [8] highlighted that MWFs formed a thin film between cutting tool and workpiece surface. The presented thin film layer influenced reduction in friction and heat generation. MWFs from vegetable oils offers good boundary lubrication with low coefficient of friction (COF)[9]. Bellaco and Chiffre [10] observed that modified rapeseed oil exhibits excellent performances than the mineral oil in term of cutting force.

In recent years, jatropha oil which is non-edible vegetable oil is currently explored for biofuel industry [11,12]. However, a number of studies have used jatropha oil as lubricant for hydraulic fluid and engine oil [13-15]. Previous research indicated that the modification of jatropha oil with TMP has improved the lubrication properties in terms of pour point, oxidative stability, wear scars and viscosity [14]. Arbain and Salimon [16] added that TMP ester formed complex chains and branches in the fatty acids that improved the lubricant properties.

The performance of TMP ester outperformed the mineral oils in terms of physical and tribology properties. Therefore, this research work mainly deals with the experimental works with various parameters of tribological testing in order to understand the effectiveness of modified jatropha TMP ester. Furthermore, this study discusses the relation between the properties of MWFs with orthogonal cutting performances. In this study, the performance of modified jatropha TMP ester was analysed in order to discover the potential as a bio-based MWFs.

2. Methodology

2.1. Modification process of crude jatropha oil (CJO)

Chemical modification of the crude jatropha oil (CJO) is needed to improve the oxidation and thermal stability properties. It was converted into jatropha methyl ester (JME) by two steps acid-based catalyst transesterification processes. Then, JME reacted with TMP to produce jatropha oil-based TMP ester as shown in Figure 1. TMP ester which is in polyols groups has the complex and branching structure and a low melting point [15]. The chemical reaction was conducted in three neck flasks with oil bath condition and fitted with condenser by using magnetic hot plate stirrer to provide sufficient heat and stirring conditions. The thermometer was partially immersed in the oil to measure the reaction temperature and this reaction was done via vacuum condition to remove methanol produced.

MJO was produced with two different molar ratios of JME: TMP which are 3:1 (MJO1) and 3:3:1 (MJO3). Both MJOs was compared with SE and CJO. The reaction condition was conducted for 3 hours at the controlled temperature of 120°C. In addition, the catalyst used was set at 1% (w/w) of the oil weight. The methanol produced from the reaction was immediately drawn from the flask via vacuum process. The final product was filtered to remove the substance and impurities. Finally, it was leaved overnight in the drying oven to discard the moisture.

![Figure 1. Transesterification process of TMP with JME](image)

2.2. MWFs properties

MWFs were test accordingly to American Society Testing and Materials (ASTM) procedures as follow;

i. **Density:** MWFs density was measured by using pycnometer. 25 ml of oil was cooled at 15°C. The density value was calculated by the ratio of weight over oil volume.

ii. **Viscosity:** MWFs viscosity was measured by using viscometer. 50 ml of oil was heated at temperature 40°C. The viscometer was immersed in the heated oil to measure the viscosity value.

iii. **Tribology:** The tribology test was carried out by using four balls tribotester machine. The testing was done according to ASTM D4172 to determine the wear and coefficient of friction (COF). The normal load used was at load 392N, with 1200 rpm rotational speed and was regulated at temperature 75°C for 1 hour. The wear scar diameter (WSD) of the bottom three balls was measured by optical microscope and COF was determined from the software.

2.3. Orthogonal Cutting Process

The orthogonal cutting process was carried out on AISI 1045 mild steel disk with the thickness and diameter of 2mm and 150 mm respectively by using NC lathe machine. The set-up is shown in Figure 2. A TiAlN coated tungsten carbide insert was used throughout the experiment. It was mounted on a tool holder. Both insert and the tool holder were fixed on the dynamometer (9257BA). The dynamometer was connected to the charge amplifier and a software to record the cutting force data. The nozzle was placed approximately 4mm to the cutting edge. The temperature during the orthogonal cutting process was measured by using FLIR T640 thermal imager camera. The coolant was supplied via the MQL system to the cutting zone. MJO with two different molar ratios was compared with SE and CJO at various cutting speeds and feed rates as shown in Table 1. SE was chosen due to its physical properties are suitable for the MQL applications [17].
3. Experimental results and Discussion

3.1. MWFs properties

Table 2 shows the properties of CJO, MJO1, MJO3 and SE. From the tribology testing, the viscosity was directly proportional with WSD. While, for COF the CJO had the lowest followed by MJO1, SE and the worst was MJO3. MJO1 provided better COF than SE while WSD of MJO1 was comparable with SE. It indicated that MJO1 was able to replace SE as MWFs in terms of the viscosity and tribology properties.

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Method</th>
<th>CJO</th>
<th>SE</th>
<th>MJO1</th>
<th>MJO3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C, ρ (g/cm³)</td>
<td>ASTM D4052</td>
<td>0.9143</td>
<td>0.95</td>
<td>0.9099</td>
<td>0.9088</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C (mm²/s)</td>
<td>ASTM D445</td>
<td>30.66</td>
<td>19</td>
<td>14.07</td>
<td>12.32</td>
</tr>
<tr>
<td>Wear scar diameter, WSD (mm)</td>
<td>ASTM D4172</td>
<td>0.641</td>
<td>0.693</td>
<td>0.718</td>
<td>0.806</td>
</tr>
<tr>
<td>Coefficient of friction, COF</td>
<td></td>
<td>0.059</td>
<td>0.097</td>
<td>0.086</td>
<td>0.112</td>
</tr>
</tbody>
</table>

3.2. Cutting Forces

Figure 3 (a), (b) and (c) showed the results of cutting forces values at various cutting speeds, feed rates and MWFs. It can be observed from the trend that cutting force decreases with the increasing of cutting speed. Furthermore, the value of cutting force increases with the increasing of feed rate. This is due to increases in material removal of the workpiece that required more energy to the
cutting zone and led to the increasing of cutting force [18]. It was interesting to highlight that the reduction of cutting force also depends on the lubricant properties. Viscosity plays a significant role in lubricant performance. As mentioned earlier, SE poses highest viscosity than MJO1 and MJO3 as shown in Table 2. Therefore, SE recorded the lowest cutting force value at all tested conditions. The viscosity demonstrated the significant effect on cutting force values and it determined the effectiveness of the lubricant itself [7].

At the feed rate of 0.08 mm/rev, there was a deviation of cutting force values between MJO1 and MJO3 when compare to SE. At the cutting speed of 350 m/min, the value of cutting force for SE was reduced to 16% and 18% when compared with MJO1 and MJO3 respectively. This is due to the approximate viscosity value of MJO1 and MJO3. Meanwhile, at the feed rate of 0.10 mm/rev, MJO3 recorded the lowest value of cutting force. It was proving that the performance of MJO was comparable with SE. Furthermore, at the feed rate of 0.12 mm/rev, the cutting force significantly increases as the viscosity of MWFs decreased. It revealed that the less viscous oil will affect the effectiveness as a lubricating agent at the cutting zone and caused high cutting force.

Besides, the WSD and COF also significantly affect the cutting force. It shows that the WSD increased as the viscosity decreases. The different of WSD of MJO1 and SE only 3% while the COF of SE was slightly higher than MJO1. It verified that the performances of MJO1 were comparable with SE. Even though CJO has the lowest WSD and COF values with high viscosity, but it recorded high cutting force compared to SE at all feed rates. It’s due to the present of double bonds in the crude oil. The crude oils have low thernals and oxidative stability [15] that affect the oil properties and influence the machining performances.

3.3. Maximum Cutting Temperature

Figure 4(a), (b) and (c) present the results of maximum cutting temperature at different cutting speeds, feed rates and MWFs. Cutting temperature increases as the cutting speed and feed rate increased. The heat was generated due to shear and plastic deformation at the primary shear zone at workpiece, the tool-chip interface at secondary shear zone at the sliding zone and at the workpiece and tool interface at the tertiary shear zone [19].

Overall result showed that SE recorded slightly lower cutting temperature compared to MJO1 and MJO3. It is due to the high viscosity and lowest WSD value of SE. At the feed rate of 0.08 mm/rev, the SE recorded 2.37% and 5.57 % reduction compared to MJO1 and MJO3 respectively. The trends were consistent for all feed rates. The reduction of percentage values was too small due to the lubricating film layer provided from MJO was strong and subsequently improved the machining performance by reducing the friction and machining temperature. In addition, the lower value of COF tends to improve the machining performance especially on the reduction of cutting temperature.
Cenkachorn indicated that the value of viscosity influenced the reductions of COF [20]. The lubricant with low viscosity will increase the temperature. However, the result of this study shows that the CJO with lower COF recorded high cutting temperature. It can be explained by the fact that the present of unsaturated fatty acids in the carbon chain affects the lubricant performance. Unsaturated fatty acids contain double bonds which are easily broken with high temperature. The lack of oil properties, have to be overcome by chemical modification. The existing of double bonds structure of the crude oil has to be changed to the branched of polyol ester (TMP ester) in order to improve the lubrication properties.

4. Conclusions

The performance evaluation of MWFs with respect to cutting force and cutting temperature was determined and obtained. The results of MJO were compared with SE and CJO. Therefore, it can be concluded from the analysis that;

i. The highest WSD and COF generated high cutting force and maximum cutting temperature due to reduction in thin lubrication film in the tool-chip interface.

ii. The lubricant viscosity gave a significant effect on the machining performance. As the lubricant viscosity decreases, the cutting force and maximum cutting temperature increased.

iii. Even though CJO has better tribology properties, however due to the lack of oxidation and thermal stability, it was not recommended to be applied as a lubricant for machining processes.

iv. MJO1 recorded comparable performances in terms of lubricant properties and machining performance. MJO1 improves the COF compared to SE. The machining performance of MJO1 slightly not much different with SE. MJO1 was able to substitute SE as a sustainable MWFs in the machining operation.

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