PERFORMANCE EVALUATION OF BIODEGRADABLE METALWORKING FLUIDS FOR MACHINING PROCESS

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PERFORMANCE EVALUATION OF BIODEGRADABLE METALWORKING FLUIDS FOR MACHINING PROCESS

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A thesis submitted in fulfillment of the requirement for the award of the Doctor of Philosophy in Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
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NOVEMBER 2017
ACKNOWLEDGEMENT

Alhamdulillah, first of all, all praises is for Allah SWT, the most gracious and the most merciful, who has given me His guidance and blessing in finishing this thesis, entitled “Performance Evaluation of Biodegradable Metalworking Fluids for Machining Process”.

I would like to convey my deepest gratitude to those who have assisted and inspired me in completing this study. I wish to express my sincere thanks to my supervisor Assoc. Prof. Dr. Erween Bin Abd. Rahim and my co-supervisor Dr. Ramdziah binti Md. Nasir for their continuous support, guidance and valuable suggestions throughout the progress of this study. I would also like to express my appreciation to Universiti Tun Hussein Onn Malaysia (UTHM), Johor and the Ministry of Education Malaysia for the financial support given through the Academic Staff Bumiputera Training Scheme (SLAB) during the period of study.

I am grateful and indebted to the academic and laboratory staffs of UTHM who either directly or indirectly helped or supported me in various ways during the experimental stages. Many thanks are also extended to all Precision Machining Research Center (PREMACH) group members, research fellows, and my precious friends.

Finally, I would like to express my deepest gratefulness to my beloved family for their support and understanding throughout the journey. To my parents, Hj. Talib bin Burok and Hjh. Rasidah binti Md. Dawi, thank you for your blessings and prayers, endless love and support, and always cheered me up during the hard times. To the rest of my family, many thanks for your great support and prayers.
ABSTRACT

The widely use of metalworking fluids (MWFs) petroleum-based in the industry have a negative impact to the environment and human. Thus, various initiatives have been undertaken to develop bio-based MWFs especially from crude jatropha oil (CJO). However, the main drawback of CJO is that it has low thermal-oxidative stability. Therefore, the objective of this study is to develop a new formulation of CJO-based MWFs. The newly developed modified jatropha oils (MJOs) were formulated using transesterification process at various molar ratios of jatropha methyl ester to trimethylolpropane (JME:TMP) denoted by MJO1 (3.1:1), MJO3 (3.3:1) and MJO5 (3.5:1). Later, the MJOs were blended with hexagonal boron nitride (hBN) particles at various concentrations (0.05 to 0.5wt.%). MJOs with and without hBN particles were analysed based on the physicochemical properties, tribology behaviour test, orthogonal cutting and turning processes. From the results, MJO5 showed an improvement at thermal (high viscosity index) and oxidative stability (lubricant storage). MJO5c (MJO5+0.5wt.% of hBN particles) showed the optimum physicochemical properties. In the contrary, MJO5a (MJO5+0.05wt.% of hBN particles) exhibited excellent tribological behaviour as reduction of friction and wear, with high tapping torque efficiency. In the orthogonal cutting process, MJO5a recorded the lowest machining force and temperature, thus contributed to the formation of thinner chips, small tool-chip contact length and reduction of the specific energy. MJO5a produced an excellent result in the machinability test by reducing the cutting force, cutting temperature and surface roughness stimulated longer tool life and less tool wear. In conclusion, the MJO5a has a potential impact on the lubricant market as a sustainable MWFs for the machining processes.
ABSTRAK

Penggunaan bendalir kerja logam (MWFs) berasaskan petroleum secara meluas di industri telah memberikan kesan negatif kepada alam sekitar dan manusia. Justeru, pelbagai inisiatif telah dilakukan untuk membangunkan MWFs berasas bio terutamanya daripada minyak jatropha mentah (CJO). Namun begitu, kelemahan utama CJO ialah mempunyai kestabilan terma-oksidatif yang rendah. Oleh itu, objektif kajian ini adalah untuk membangunkan formulasi baharu MWFs berasaskan CJO. Minyak yang baru dibangunkan, minyak jatropha yang dibuahsuai (MJOs) telah diformulasi menggunakan proses transesterifikasi pada pelbagai nisbah molar metil ester jatropha kepada trimetilolpropana (JME:TMP) yang diwakili oleh MJO1 (3.1:1), MJO3 (3.3:1) dan MJO5 (3.5:1). Kemudian, MJOs telah dicampur dengan zarah heksagonal boron nitrida (hBN) pada pelbagai kepekatan (0.05 to 0.5wt.%). MJOs dengan dan tanpa zarah hBN telah dianalisis pada sifat-sifat fizikokimia, ujian kelakuan tribologi, pemotongan ortogonal dan proses pelarikan. Daripada hasil kajian, MJO5 menunjukkan peningkatan terhadap kestabilan termal (index kelikatan yang tinggi) dan oksidatif (penyimpan pelincir). MJO5c (MJO5+0.5wt.% zarah hBN) menunjukkan sifat-sifat fizikokimia yang optimum. Sebaliknya, MJO5a (MJO5+0.05wt.% zarah hBN) mempamerkan tingkah laku tribologi yang sangat baik dengan pengurangan terhadap geseran dan kehausan, serta kecekapan penguliran tork yang tinggi. Di dalam proses pemotongan ortogonal, MJO5a mencatatkan daya dan suhu pemotongan yang rendah, seterusnya menyumbang kepada pembentukan tatal yang nipis, panjang sentuhan mata alat-tatal yang kecil dan pengurangan tenaga spesifik. MJO5a menghasilkan keputusan yang cemerlang dalam ujian kebolehmesinan dengan mengurangkan daya pemotongan, suhu pemotongan dan kekasaran permukaan merangsang jangka hayat mata alat yang lebih panjang dengan kurang kehausan. Kesimpulannya, MJO5a mempunyai potensi di pasaran minyak pelincir sebagai MWFs yang mampun untuk proses pemesinan.
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<td>Flank and rake face of the cutting tool for MJO3a lubricant</td>
<td>239</td>
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<tr>
<td>6.27</td>
<td>Flank and rake face of the cutting tool for MJO1a lubricant</td>
<td>239</td>
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</tbody>
</table>
LIST OF SYMBOLS AND ABBREVIATIONS

% - Percent, efficiency
µ - Micro
µ - Coefficient of friction
µm - Micrometer
a - Radius of wear scar diameter
ADDC - Antimony dialkyldithiocarbamate
Al - Aluminium
Al₂O₃ - Aluminium oxide
AOCS - American Oil Chemist’s Society
ASTM - American Society for Testing and Material
AW - Anti-wear
B - Boron
BHA - Butylated hydroxy anisole
BHT - Butylated hydroxyl toluene
BSTFA - N,O-Bis(trimethylsilyl)tri-fluoroacetamide
BUE - Built-up-edge
C - Carbon
C₃H₈O - 2-propanol
CAN - Canola oil
CC - Coconut oil
CH₃O - Methanol
CJO - Crude jatropha oil
cm - Centimeter
CNT - Carbon nanotube
Co - Cobalt
COF - Coefficient of friction
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>CPO</td>
<td>Crude palm oil</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>CSt</td>
<td>Centistoke</td>
</tr>
<tr>
<td>CTAB</td>
<td>Cetyltrimethylammonium bromide</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical vapour deposition</td>
</tr>
<tr>
<td>d</td>
<td>Depth of cut</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data-acquisition</td>
</tr>
<tr>
<td>DBDS</td>
<td>Dibenzyldisulfide</td>
</tr>
<tr>
<td>DBP</td>
<td>Dibutyl 3,5-di-t-butyl-hydroxy</td>
</tr>
<tr>
<td>DE</td>
<td>Diester</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
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<tr>
<td>DTC</td>
<td>Dithiocarbamates</td>
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<tr>
<td>DTP</td>
<td>Zincdithiophosphates</td>
</tr>
<tr>
<td>E</td>
<td>Elastic modulus</td>
</tr>
<tr>
<td>EDS</td>
<td>X-ray spectrometer</td>
</tr>
<tr>
<td>EHD</td>
<td>Elastohydrodynamic</td>
</tr>
<tr>
<td>EJME</td>
<td>Epoxidized jatropha methyl ester</td>
</tr>
<tr>
<td>EJO</td>
<td>Esterified jatropha oil</td>
</tr>
<tr>
<td>EJRO</td>
<td>Epoxidized jatropha raw oil</td>
</tr>
<tr>
<td>emf</td>
<td>Electro motive force</td>
</tr>
<tr>
<td>EP</td>
<td>Extreme pressure</td>
</tr>
<tr>
<td>EPME</td>
<td>Epoxidized pongam methyl ester</td>
</tr>
<tr>
<td>EPRO</td>
<td>Epoxidized pongam raw oil</td>
</tr>
<tr>
<td>F</td>
<td>Friction force</td>
</tr>
<tr>
<td>FAME</td>
<td>Fatty acid methyl ester</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Cutting force</td>
</tr>
<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>FESEM</td>
<td>Field emission scanning microscope</td>
</tr>
<tr>
<td>FFA</td>
<td>Free fatty acid</td>
</tr>
<tr>
<td>$F_n$</td>
<td>Normal force to friction</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Feed rate</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Shear force</td>
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</table>
$F_t$ - Thrust force
$g$ - Gram
GC - Gas chromatography
G-ratio - Grinding ratio
H - Hydrogen
h - Hour
$H_2SO_4$ - Sulfuric acid
$H_3PO_4$ - Ortho-phosphoric acid
hBN - Hexagonal boron nitride
HOSBO - High oleic soybean oil
J - Joule
JME - Jatropha methyl ester
k - Volume wear rate
KOH - Potassium hydroxide
l - Litre
$L$ - Evaluation length
$L_c$ - Total contact length
$\lambda_c$ - Cut-off length
LCA - Life cycle analysis
LN - Liquid nitrogen
$L_s$ - Sliding length
m - Meter
Mbar - Megabar
ME - Monoester
mg - Milligram
min - Minute
MJO1 - Modified jatropha oil (3.1:1)
MJO1a - Modified jatropha oil (3.1:1) with 0.05wt.% of hBN particles
MJO1b - Modified jatropha oil (3.1:1) with 0.1wt.% of hBN particles
MJO1c - Modified jatropha oil (3.1:1) with 0.5wt.% of hBN particles
MJO3 - Modified jatropha oil (3.3:1)
MJO3a - Modified jatropha oil (3.3:1) with 0.05wt.% of hBN particles
MJO3b - Modified jatropha oil (3.3:1) with 0.1wt.% of hBN particles
MJO3c - Modified jatropha oil (3.3:1) with 0.5wt.% of hBN particles
MJO5  - Modified jatropha oil (3.5:1)
MJO5a - Modified jatropha oil (3.5:1) with 0.05wt.% of hBN particles
MJO5b - Modified jatropha oil (3.5:1) with 0.1wt.% of hBN particles
MJO5c - Modified jatropha oil (3.5:1) with 0.5wt.% of hBN particles
MJOs  - Modified jatropha oil
MI    - Millilitre
mm    - Millimeter
Mn    - Manganese
MoS$_2$ - Molybdenum disulphide
MPa   - Megapascal
MQL   - Minimum quantity lubrication
MQLPO - MQL palm oil
MQLSE - MQL synthetic ester
MWF   - Metalworking fluid
MWSD  - Mean wear scar diameter
N     - Newton, nitride, normality (strength of alkali)
$N$   - Normal force to friction
NaOCH$_3$ - Sodium methoxide
NaOH  - Sodium hydroxide
nm    - Nanometer
NPG   - Neopentylglycol
npi   - Nanoparticle inclusions
O     - Oxygen
$\phi$ - Shear angle
$\phi$ - Diameter
$^\circ$ - Degree of angle
$^\circ$C - Degree celsius
OL    - Ordinary lubricant
P     - Phosphorous
PAO   - Polyalphaolefins
PCR   - Poly-merase chain reaction
PE    - Pentaerythritol
PG    - Propyl gallate
POME  - Palm oil methyl ester
PVD - Physically vapour deposited
\( r \) - Distance from the centre of the contact surface, \( r = 3.67 \text{mm} \)
\( R \) - Radius of the ball, resultant force
\( \rho \) - Density
\( r_a \) - Chip thickness ratio
\( R_a \) - Surface roughness value
RBD - Refined, bleached and deodorised
rev - Revolution
rpm - Revolution per minute
RR - Roundup Ready
\( r_{tip} \) - Maximum stylus tip radius
\( s \) - Second
S - Sulphur
SBO - Soybean oil
SCCO\textsubscript{2} - Supercritical carbon dioxide
SE - Synthetic ester
SEM - Scanning electron machine
Si - Silicon
SS - Sesame oil
T - Friction torque
\( t \) - Sliding time, thickness of cutting tool
TAN - Total acid number
TBHQ - Mon-\text{tert}-butyl-hydroquinone
\( t_c \) - Deformed chip thickness
TE - Triester
Ti - Titanium
\( \text{TiO}_2 \) - Titanium dioxide
TMP - Trimethylolpropane
TMPE - Synthetic lubricant
TMPTO - Trimethylolpropanetrioleate
\( t_o \) - Undeformed chip thickness
\( \nu \) - Poisson ratio
U - Specific energy
UFA - Unsaturated fatty acids
v - Kinematic viscosity
V - Vanadium
VB - Average flank wear
VB_{max} - Maximum flank wear
VB_{N} - Maximum notch wear
V_{c} - Cutting speed
VI - Viscosity index
vol. - Volume
vol.% - Percentage based on volume of oil
W - Applied load
W - Tungsten
w - Width of cut
W_{f} - Weight pycnometer with sample
WC - Tungsten carbide
W_{o} - Weight of dried pycnometer
WSD - Wear scar diameter
wt. - Weight
wt.% - Percentage based on weight of oil
xGnPs - Exfoliated graphite nano-platelet
ZDDP - Zinc dialkyldithiophosphates
\alpha - Rake angle
\beta - Beta, clearance or relief angle
# LIST OF APPENDICES

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<td>B</td>
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CHAPTER 1

INTRODUCTION

1.1 Background of study

Sustainability has become an important element to be considered in manufacturing industry. Sustainability is commonly divided into three main pillars which are social, environment and economic. There are six factors that significantly affect the sustainable manufacturing; energy consumption, manufacturing cost, environmental effect, operational safety, personal health and waste reduction (Jawahir et al., 2013). It has enlightened the manufacturers in machining industries to shift their trend towards other potential alternative solutions that can replace the petroleum-based lubricant. Petroleum-based lubricants possess poor biodegradability, need high processing cost of recycling processes and cause environmental pollution and health problems. Recently, petroleum prices are fluctuating due to the decrease in total rate of crude oil output.

This scenario triggers an interest in finding alternatives to petroleum-based lubricant. The vegetable oils such as the soybean oil, sunflower oil and canola oil are promising natural sources to be developed as lubricants for industrial applications. It was estimated that only 0.1% lubricants in the market are made from vegetable oils (Erhan et al., 2006). From the recent research by Lawal et al. (2012), it seems that vegetable oil was the suitable replacements of the petroleum-based lubricant. These oils indeed could offer significant environmental benefits with respect to resource renewability, biodegradability, as well as providing satisfactory performance in a wide array of applications. However, the usage of vegetable oil as lubricant also faced some problems such as low thermal and oxidation stability that caused the oil to become thick and sticky (Abdalla and Patel, 2006; Akbar et al., 2009; Arbain and
Salimon, 2011a). The aforementioned problems result in restraints for vegetable oil to be used as an industrial lubricant. Therefore, the modification of vegetable oil is crucially important in order to improve the crude oil efficiency. There are three types of modification that have been identified by Shashidhara & Jayaram (2010) which include reformulation of additives, chemical modification and genetic modification of oil seed.

In the machining process, metalworking fluids (MWFs) is used for machining purposes, stamping processes and manufacturing of automotive components as shown in Figure 1.1. The absence of MWFs will result in acceleration of tool wear, residual stress, dimensional error and poor surface finish (Skerlos et al., 2008). The utilization of MWFs is more than 100 million gallons annually and the current worldwide consumption is approximately 640 million gallons (Marksberry & Jawahir, 2008). However, the usage of vegetable oil as MWF is still not widespread due to its limitation as mentioned earlier. Previous researchers have identified that MWFs made of rapeseed, palm, coconut and sunflower oils provided greater lubricating properties and showed comparable performance with currently used petroleum-based lubricant with regards to cutting force, cutting temperature, surface finish, tool wear and tribological behaviour (Belluco and Chiffre, 2004; Jayadas et al., 2007; Kuram et al., 2013c; Rahim and Sasahara, 2011a).

Figure 1.1: Metalworking fluids usage (Marksberry and Jawahir, 2008)
Rahim and Sasahara (2011b) proved that vegetable oil outperformed synthetic ester (SE) in terms of force, temperature, energy and power. They exposed that the properties of palm oil based on viscosity and viscosity index have influenced the machining performances. Research finding by Kuram et al. (2013a) also pointed out that the viscosity value affected the MWFs efficiency. Besides, MWFs made of vegetable oils offers good boundary lubrication with low coefficient of friction (COF) (Jayadas et al., 2007). In addition, Sales et al. (2006) highlighted that MWFs formed a thin film between cutting tool and workpiece surface that influenced reduction in friction and heat generation.

Hence, the development of new modification of vegetable oil is crucially needed to be applied as MWF. From the modification process, the oil’s properties can be enhanced and related to the machining performances outcomes. In this study, modified jatropha oils (MJOs) were selected to be used as sustainable MWFs for the machining process. In order to explore the reliability of these newly developed MWFs, the properties of MJOs on tribological behaviour and the machining performances were evaluated.

1.2 Problem statement

MWFs are used to reduce the generation of heat and friction at the tool-workpiece interfaces during the machining process. The conventional MWFs which consist of the combination of petroleum-based lubricant and additives are toxic to the environment and difficult to be disposed after the consumption (Erhan et al., 2006). The petroleum-based lubricant exhibited poor biodegradability and required high processing cost for recycling process. The widespread use of MWFs caused significant health and environmental hazards through their life cycle. As MWFs are complex in their composition, they may cause irritation or allergy to the skin, lungs, eyes, nose and throat. Moreover MWFs lead to more severe conditions such as dermatitis, acne, asthma, and a variety of cancers. Nicol & Hurrell (2008) reported that all occupational diseases of workers are due to skin contact with MWFs as shown Figure 1.2.

To overcome these problems, various alternatives to petroleum-based lubricant have currently been explored by researchers which include the
developments of synthetics oils, vegetable based-oil and solid lubricants (Lawal, 2013; Nguyen et al., 2012; Suhane, 2012). The growing demand for biodegradable materials opened an opportunity for using vegetable oil as a replacement to petroleum-based oils. This condition is due to the increasing awareness on sustainable elements in machining process that identified majority of the lubricant oil consists of non-sustainable elements (Pusavec et al., 2010).

Therefore, MWFs made of vegetables oil are favourable as sustainable alternative to the conventional MWF. MWFs from vegetables oil served as an anti-wear and anti-friction medium due to strong interactions with the lubricant at the contact surfaces (Quinchia et al., 2014). Previous researchers indicated that vegetable oil exhibited higher lubricity, lower volatility as well as higher viscosity index and flash point when compared to mineral and synthetic oils (Lovell et al., 2006). MWFs from edible vegetable oils such as soybean, canola and sunflower oil have been widely studied by previous researches (Clarens et al., 2004; Erhan and Asadauskas, 2000; Kuram et al., 2010). Hence, aforementioned oils are planted in the four seasons countries such as United State and European. They are readily biodegradable and less costly than synthetic base-stocks. They also showed a considerably acceptable performance as lubricants and have been commercialized. However, the feedstock used from edible vegetable oils for biolubricant production may compete with the feedstock used for the food production thus contributes in high rising cost of

Figure 1.2: Description of health effects on experts and workers due to MWF’s exposure (Nicol and Hurrell, 2008)
food (Gashaw and Teshita, 2014; Shamsuddin et al., 2015; Umaru and Aberuagba, 2012). Yet, the used of non-edible jatropha oil is preferable to substitute the petroleum base oil. Jatropha oil has extensively been studied for the usage as biofuel (Chhetri et al., 2008; Kombe et al., 2012; Okullo et al., 2012) and bio-lubricants such as for hydraulic fluids and engine oil (Resul et al., 2012; Imran et al., 2013; Zulkifli et al., 2014). Jatropha oil is a clean and renewable source of lubricant that cannot be used for the nutritional purposes. A main drawback found in crude jatropha oil (CJO) is that it has poor thermal-oxidative stability due to unsaturation in molecule that leads to oxidation reaction (Arbain and Salimon, 2011b). Therefore, it is crucially needed to chemically modify the CJO to improve the oil’s property. In addition, the use of jatropha oil as MWF is still not widespread and because of issue, further research relate to the development of bio-based MWFs is needed in investigating the potential properties of jatropha oil as MWF.

Moreover, MWF-based oils can be strengthened by the addition of various functions of additives. Previous studies used sulphur and phosphorous compounds as additives in vegetable oil lubricant (Belluco and Chiffre, 2004; Minami et al., 2007; Waara et al., 2001; Yan et al., 2012; Zeng et al., 2007). Eventhough, these compound influenced the machining performances by reducing friction and wear, there were poisonous to environment (Ji et al., 2012; Johnson and Hils, 2013). Therefore, boron and nitrite compounds have been found in numerous industrial applications because they are safe to be handled, non-toxic, no limitations on its operational uses, good thermal stability and high thermal conductivity (Reeves et al., 2013; Wan et al., 2015). The presence of boron and nitride compound in lubricant also enhanced the lubrication and tribological behaviours (Abdullah et al., 2013; Nguyen et al., 2012). However, there is limited study that discussed the effects of the boron and nitride compounds in tribological behaviours and machining performances.

An appropriate MWF’s properties significantly affect the machining performances. Therefore, new formulations of bio-based MWFs made of non-edible jatropha oil and boron and nitride compounds are desirable in order to develop sustainable MWF with enhanced lubrication and tribological behaviour. In discovering a suitability of bio-based MWF, the effects of lubrication properties and additives concentrations are needed to be studied.
1.3 Aim and objectives

The aim of this research was to study the performance of newly formulation of MJOs as bio-based MWFs. The main focus was emphasized on preparing the bio-based MJOs, analysing the properties of MJOs, examining the tribological behaviours and evaluating the machining performances. The specific objectives of this study are:

i. To study the application of vegetable-based oils as MWFs in machining process. (Related to Chapter 2)

ii. To develop a new formulation of MJO-based MWFs and to analyse the physicochemical properties at various molar ratios (jatropha methyl ester and trimethylolpropane) and addition with various concentrations of additive. (Related to Chapter 3)

iii. To examine the tribological behaviour of newly developed MJOs through four ball and tapping torque tests. (Related to Chapter 4)

iv. To evaluate the performances of newly developed MJOs in the orthogonal cutting process under minimum quantity lubrication method in terms of cutting force, cutting temperature, chip thickness, tool-chip contact length and specific energy. (Related to Chapter 5)

v. To justify the machinability criteria of the newly developed MJOs under minimum quantity lubrication method in terms of tool life, tools wear mechanism, cutting force, cutting temperature and surface roughness through turning process. (Related to Chapter 6)

1.4 Scopes of the research

Figure 1.3 demonstrates the flow chart of the current research scopes. This study involved a development of newly formulation of bio-based MWFs denoted as MJOs by chemical modification and mixed with additive. Two step acid-based catalysed transesterification process was carried out to develop jatropha methyl ester (JME). Then, the desired JME which achieved the required properties according to ASTM D6751 was reacted with trimethylolpropane by varying the molar ratio by transesterification to develop MJOs. The entire products were compared with commercial SE and CJO. Physicochemical properties include density, viscosity, flash
Figure 1.3: The flow chart of the research scopes

point, water content and acid value were analysed. The tribological behaviours of the products were examined through four ball test and tapping torque test. Both physicochemical test and tribology test were performed according to ASTM standard testing procedure. The evaluation of machining performances were carried out by using orthogonal cutting process at three level of feed rates (0.08, 0.1 and 0.12 mm/rev) and three level of cutting speeds (350, 450 and 550 m/min) in terms of cutting force, cutting temperature, chip thickness, tool chip contact length and specific energy. Finally, the machinability test was conducted by turning process at
constant machining parameter to investigate the tool life, tool wear, cutting force, cutting temperature and surface roughness.

1.5 Organization of thesis

The inscription of this thesis is divided into seven chapters. Chapter 1 provides a brief introduction to the research topic, including the problems and related issues. Based on this, aim and objectives were developed. Chapter 2 presents a review of the literature in creating the aims study by considering constrains and limitations of current researches. Topics reviewed include types, sources and application methods of MWFs, modification of vegetable oils, MWFs properties and application of vegetable oils in the machining process. Chapter 3 presents the whole experiment procedure on the developing of the MJOs, including the material preparation, chemical modification process and physicochemical testing. The effect on the various molar ratios and various additives concentrations are briefly discussed. Chapter 4 presents the experiment procedures and analysis method to examine the tribological behaviour of the newly developed MJOs through four ball test and tapping torque test. Chapter 5 presents the evaluation of machining performances through the orthogonal cutting process of the newly developed MJOs by considering cutting force, cutting temperature, chip thickness, tool-chip contact length and specific energy consumption. Further, Chapter 6 discusses the investigation on machinability criteria of the newly developed MJOs through turning process regarding to the tool life, tool wear, cutting force, cutting temperature and surface roughness. Finally, conclusions and recommendations are presented in Chapter 7.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter consists of reviews on literature related to the development and application of bio-based oils as metalworking fluids for machining process. The reviews can be organized into eleven main sections; i.e. sustainable manufacturing, metalworking fluids in machining process, metal cutting, lubricant sources, modification method for vegetable-based metalworking fluids, physicochemical properties, tribological behaviour, applications of vegetables-based metalworking fluids in machining process, effect of additive particles in metalworking fluids for machining processes, jatropha oil as potential bio-based metalworking fluid and hexagonal boron nitride (hBN) as an additive in metalworking fluid.

2.2 Sustainable manufacturing

Sustainability provides an understanding regarding the basic theories and applications of sustainability science about product life cycle engineering with the implementation of sustainable in social, economy and environment aspects (Jawahir et al., 2013). Sustainable manufacturing can be expressed as providing goods and services for costumer satisfying while accelerating economic growth and decelerating the environmental damage. The sustainability is aiming a quality level of product, process and system that allows preserving, keeping and maintaining something (Molamohamadi and Ismail, 2013). Sustainable manufacturing delivers product and process that affect the quality of human life and contribute to the world economy.
There are six elements which contribute in the sustainability of product include environmental effect, social impact (in terms of health, safety and ethics), functionality, resource utilization and economy, manufacturability and product’s recyclability and remanufacturability (Jawahir et al., 2013). In addition, Jawahir et al. (2013) also revealed that there are six elements affect the sustainability in manufacturing process; i.e. energy consumption, manufacturing cost, environmental impact, operational safety, personal health and reduction of waste material. Both sustainability elements in product and process were implemented in the blueprint for model-based sustainable manufacturing as shown in Figure 2.1. The concept of “6R” (reduce, reuse, recycle, recover, redesign and remanufacture) was introduced in sustainable manufacturing as the innovation based transformation from an open-loop, single life-cycle paradigm to a closed-loop, multiple life-cycle paradigm (Jawahir and Jayal, 2011). The implementation of sustainability principles in machining process encourages the industry to save money and improve the environmental and social performance. In this way, Jawahir and Jayal (2011) defined that sustainable machining techniques use less quantity of metalworking fluid, liquid nitrogen, vegetable oil or compressed air as a cooling-lubrication medium. The lubricants used in sustainable machining methods are totally biodegradable and eco-friendly. Chetan et al. (2015) defined the various characteristics of sustainable machining techniques which increased awareness of the sustainability issues in machining as shown in Figure 2.2.

Skerlos et al. (2008) initiated that metalworking fluid (MWF) systems are excellent candidate to implement sustainable machining since simultaneous improvements of economic, environmental and health dimensions are possible and critically necessary. They suggested the development of gas-based minimum quantity lubrication (MQL) systems such as the development supercritical carbon dioxide (SCCO₂) MWF. On the other hand, Kuram et al. (2013b) have suggested three methods that contributes to the sustainable machining were dry cutting, MQL and implement of vegetable oil. Further, Lawal et al. (2013) identified another alternative to the conventional lubricant to be applied in the machining process. They initiated the conventional lubricant that was normally produced from the petroleum-based oil can be replaced using high-pressure coolant technique, cryogenic cooling, solid lubricant and air or gas or vapour coolant.
The implementation of MWF in the machining process increases the quality and productivity of the products. However, the conventional cooling method by delivering with a huge amount of coolant (flood cooling technique) required a high machining cost (Pusavec et al., 2010). Berchmans & Hirata (2008) recognized that inexpensive feedstock such as non-edible oils, animal fat and waste cooking oil could reduce the machining cost. Therefore, this study focused on the implementation of vegetable oil and green solid lubricant would be applied for MQL methods in machining process.
2.3 Metalworking fluid in machining process

An increasing awareness with regards to sustainable aspect in the manufacturing industry leads to the consideration for renewable and biodegradable-based oils. Biodegradability shows the ability of MWF to be decomposed by microorganisms (Anand and Chhibber, 2006). Table 2.1 displays the biodegradability of some base lubricants. This property ensures the environmentally friendly of vegetable-based oil and modified vegetable-based oil, thus enhances the commercial value. Abdalla et al. (2007) indicated a huge total of 320,000 tons of MWF had to be disposed every year, which acquires a high recycling cost. The complex formulation of MWFs generated fungi and bacteria which cause irritation or allergy upon skin contact (Bakalova et al., 2007). Furthermore, a long exposure to MWF causes serious health problems, such as lung infection, eye irritation and cancer (Nicol and Hurrell, 2008).

In addition, previous study indicated that 85% of the global lubricant consumption are petroleum-based oil (Pop et al., 2008). Further, Lukoil (2013) reported that, a global demand for liquid hydrocarbon would grow annually by 1.2%, and the quantity would reach 105 million barrels oil per day in 2025. The high demand of petroleum-based oils in the industry led to the research and development of environmentally friendly lubricants. Therefore, the bio-based MWF from vegetable oil has become crucial to be explored and developed as it is a safe and environmentally friendly type of oil. In addition, several methods have been developed for controlling the temperature and to reduce the friction in the cutting zone in order to increase the machining efficiency such as flood coolant, dry machining, minimum quantity lubrication method (MQL) and cryogenic coolant.

During the machining process, MWFs penetrated into the cutting zone to provide sufficient lubrication and cooling effect. They reduced the friction between the tool-chip interfaces and adsorbed the heat generated associated with the reduction

<table>
<thead>
<tr>
<th>Types of lubricants</th>
<th>Biodegradability (%)</th>
<th>CEC-L-33-A-94 method</th>
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<tbody>
<tr>
<td>Mineral oil</td>
<td>20-40</td>
<td></td>
</tr>
<tr>
<td>Vegetable oil</td>
<td>90-98</td>
<td></td>
</tr>
<tr>
<td>Ester</td>
<td>75-100</td>
<td></td>
</tr>
<tr>
<td>Polyol</td>
<td>70-100</td>
<td></td>
</tr>
</tbody>
</table>
of power consumption. They removed debris or swarf from the work surfaces (Brinksmeier et al., 2015). MWFs are used as lubricant in machining processes to increase tool life, enhance machining efficiency and provide excellent surface quality and accuracy. There are two major components in MWFs which are basic fluid and an additive package as shown in Figure 2.3 (Winter et al., 2012). In general, conventional-based MWF (straight or neat oil) are mostly from petroleum-based oil. Synthetic ester and vegetable oil are currently used as a replacement of mineral oil. Furthermore, the addition of various types of additives is to improve the specific oil characteristic.

MWF can be classified as straight oil, soluble oil, synthetic, semi-synthetic and vegetable-based oil as shown in Table 2.2. Semi-synthetic and fully-synthetic oils have been recently used due to their good lubrication and cooling behaviours. The semi-synthetic oil contains a combination of petroleum-based oil with additives that mixed with water and the fully-synthetic oil contains a combination of chemicals and additives that mixed with water (Rudnick and Erhan, 2013). Both petroleum-based oil and synthetic oil with the combination of various additives can be harmful to human and the environment due to their high toxicity, non-renewability and high disposal cost.

![Figure 2.3: Component of metalworking fluids (Winter et al., 2012)](image-url)
Table 2.2: Advantages and disadvantages of MWFs (Rudnick and Erhan, 2013)

<table>
<thead>
<tr>
<th>Types</th>
<th>Descriptions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight oils</td>
<td>These products derived primarily from petroleum oils or animal and vegetable oils are occasionally used. These oils contain no water and used singly or in combination with or without additives. These oils are not diluted with water and offer excellent lubricants but having limited cooling capacity.</td>
<td>Excellent lubricity and rust control</td>
<td>Low cooling, fire hazard, create a mist/smoke, limited to low speed and heavy cutting operation</td>
</tr>
<tr>
<td>Soluble oils</td>
<td>There are actually oil-in-water emulsions which are combinations of 30%-85% severely petroleum oils and emulsifiers that may include other additive.</td>
<td>Good lubricity and cooling</td>
<td>Rust control problems, bacteria growth and evaporation losses</td>
</tr>
<tr>
<td>Semi-synthetics</td>
<td>These products concentrate contains water-soluble additive, emulsifiers and less than 20% petroleum oil</td>
<td>Good cooling, rust control and microbial control</td>
<td>Easily foam and contaminated by other machine fluids, stability is affected by water hardness Poor lubricity and easily contaminated by other machine fluids</td>
</tr>
<tr>
<td>Synthetics</td>
<td>There are contains no petroleum oil and form true solutions when diluted with water.</td>
<td>Excellent cooling, and microbial control, non-flammable, non-smoking, good corrosion control, reduced misting and foaming problems</td>
<td>Poor lubricity and easily contaminated by other machine fluids</td>
</tr>
</tbody>
</table>

2.3.1 Flood coolant

In regular machining operation, MWF is supplied through conventional lubrication by flood coolant to the cutting zone. In this method, large amount of MWF is continuously delivered to the cutting zone by pipe, hose or nozzle. The MWF is cumulated in a reservoir, filtered and pumped back to the delivery nozzle. The use of flood coolant method has increased the overall machining cost especially in disposal matter (Sharma et al., 2009). Madhukar et al. (2016) pointed that 22% of the MWF costs in machining process come from disposal cost. Moreover, as flood coolant is used for several times, the MWFs may become dirty and contaminated as it continuously in contact to the machined particles. Furthermore, the physical and chemical properties of MWFs changed adversely, thus affected the machining efficiency and induced adversely impacts on the environment and human health (Tazehkandi et al., 2015a). Normally, the flood coolants are mainly made from water-based oil. Hence, the presence of water led the growth of various bacteria and
microbes which can endanger the human health (Kuram et al., 2013b). Therefore, several methods such as dry machining, MQL and cryogenic cooling are finding their ways as an alternative to the flood cooling.

### 2.3.2 Dry machining

Dry machining is a machining process without the presence of MWFs. This method offers several beneficial aspects with regard to environment and human health. Dry machining confirms workers’ health and a clean work environment. Moreover, dry machining reduces the machining cost cutting down the cost of purchasing the MWFs, reduces the disposal cost and provides less hazardous impact to environment. However, this method is not suitable to cut very hard materials and it highly dependent on the selection of appropriate cutting tools, cutting parameters, and types of workpiece material (Ghani et al., 2014).

Dry machining process indicates high friction at tool-workpiece interface, thus increases cutting temperature at the cutting zone stimulated with excessive tool wear and decreases tool life. Furthermore, the chips produced during machining cannot be carried away and deteriorating the machined surface. Tasdelen et al. (2008) investigated the influenced of MQL compared with dry cutting in machining 100Cr6 through orthogonal turning test in terms of tool–chip contact and chip morphology. They found that the contact length decreased using MQL methods as compared to dry cutting for both short and long engagement time of the section at intermittent turning. This scenario was mainly due to cooling effect from air constituent in the aerosol flow. Furthermore, it can be seen that the chips produced in dry machining were wider than the chips produced in cutting using MQL.

The performances of dry machining can be enhanced by developing cutting tool coating materials, developing tool materials with lower COF and high heat resistance and appropriate tool geometries (Kuram et al., 2013). In this way, MQL and cryogenic cooling methods during machining may offer a solution to overcome some drawbacks of the dry machining.
2.3.3 Minimum quantity lubrication

Due to the negative effects of the flood coolant on environment and human health and limited material to cut in dry machining, the MQL or near dry machining (NDM) has shown greater effect in the machining process. In MQL, a combination of high pressure and oil are transported in the form of an aerosol (mist) to the cutting zone. Aerosols are generated by atomization process, which is the conversion of a bulk MWFs into a mist through the nozzle (Astakhov, 2008). Two types of MWF are typically used for MQL included vegetable oils and synthetic ester (Khan and Dhar, 2006; Suda et al., 2002). The reasons are these two types of MWF have high biodegradability and less toxic which lead to the environmental compatibility. The synthetic ester is commonly made from chemically modified vegetable oil has high boiling temperature and flash point and a low viscosity that promoted a thin lubrication film on the tool-workpiece interface to reduce friction and heat generation. Meanwhile, fatty acids alcohol synthesized from long-chained alcohols are made from natural raw materials or from mineral oils have lower flash point and high viscosity. The lubricating effects is very moderate, but they have better heat removal due to evaporation of heat (Weinert et al., 2004).

In recent times, nanofluids such as molybdenum disulphide (MoS$_2$), carbon nanotube (CNT), titanium dioxide (TiO$_2$) and aluminium oxide (Al$_2$O$_3$) have been used in MQL systems. The addition of nanofluid in MQL showed an improvement on thermal conductivity and heat transfer coefficient (Dixit et al., 2012). Zhang et al. (2015) applied nanofluid containing MoS$_2$ with a diameter of 50 nm in several types of oil-based (liquid paraffin, palm oil, rapeseed oil, and soybean oil) for grinding process. The grinding performances were compared in terms of cutting force, particle size, viscosity of nanofluids, and workpiece surface roughness. The experimental results revealed that the addition of MoS$_2$ in soybean-based oil increased the nanoparticle concentration and the nanofluid viscosity which corresponded to better lubricating property. However, the addition of MoS$_2$ more than 6% deteriorated the grinding performance due to nanoparticle agglomeration that reduced the lubricating property.
2.3.4 Cryogenic cooling

During cryogenic cooling, the liquid nitrogen (LN) at 196° is applied to the cutting zone. Nitrogen is odourless, colourless, non-toxic gas and evaporates into the air, which there is no MWF used to be disposed. Tazehkandi et al. (2015a) studied the machining of Inconel 740 using the application of LN and spray mode of biodegradable vegetable cutting fluid through turning process. The result showed that use of LN in a combination with spray mode of the cutting fluid and compressed air was more efficient that the flood mode in terms of cutting force and tool tip temperature. There was a reduction in the amount of tool wear which prevented the formation of built-up-edge. Moreover, by employing this method the consumption of the cutting fluid during turning process can be significantly reduced.

Furthermore Rahim et al. (2016) promoted supercritical carbon dioxide technique (SCCO$_2$) of coolant in order to replace the usage of LN. They investigated the cutting temperature, cutting force, chip thickness, tool-chip contact length and specific energy in orthogonal cutting of AISI 1045 using the approach of SCCO$_2$ method of coolant. They revealed that using SCCO$_2$, cutting temperature, cutting force, chip thickness, tool-chip contact length and specific energy can be decreased significantly when compared to MQL method. They initiated that the carbon dioxide is a non-toxic gas and has excellent solubility with vegetable oils above its critical point (critical temperature = 31.2 °C, critical pressure = 7.38 MPa), much cheaper and easily availed as compared to LN. The carbon dioxide offers rapid expansion of supercritical solutions for coating and spraying applications. The SCCO$_2$ produces a homogenous and finely dispersed spray of dry ice and frozen oil particles at a few microns in size, thus provides sufficient heat removal and lubrication to the cutting zone.

It can be seen that, the cryogenic machining is a recommendable alternative to flood coolant and MQL. However, Deiab et al. (2014) stated that the machining cost of cryogenic machining is still undoubted and need to be further investigated. Moreover, overcooling during the cryogenic machining induces to embrittlement of workpiece and hence increases the cutting force (Chetan et al., 2015).
2.4 Metal cutting

Metal cutting is the process of removing unwanted material from workpiece to obtain a part with a certain desired shape and size with high dimensional accuracy and high quality surface finish. Machining performances are influenced by various machining parameters as shown in Figure 2.4. It can be divided into five main categories namely cutting fluid, cutting tool, machine tool, workpiece and machine conditions.

![Machining parameters diagram](image)

**Figure 2.4: Machining parameters**

### 2.4.1 Orthogonal cutting mechanism

Orthogonal cutting uses a wedge-shaped tool in which cutting edge is perpendicular to the direction of cutting speed. The orthogonal cutting models are shown in Figures 2.5 and 2.6. The surface along the chip flows is known as rake face and the surface ground back to clear the new or machined workpiece surface known as flank. The tool used in orthogonal cutting only has two elements of geometry which are rake angle (α) and relief angle or clearance angle (β). The rake angle determines the direction of chip formation, meanwhile the relief angle is made to avoid the tool from touching the newly cut workpiece surface as it passes the workpiece. During the cutting process, there are forces generated between the workpiece and cutting tool. The depth of the individual layer of material which have
been removed by the action of the tool is known as undeformed chip thickness, $t_o$ (Groover, 2007).

As shown in Figures 2.5 and 2.6, the cutting tool penetrates into the workpiece and forces to form the chips that fly along the rake face of the tool. High pressure and plastic deformation occur in front of the cutting edge where the elastic limits of workpiece materials are exceeded. The chip deformation is dependent on the cutting conditions (cutting speed, feed, depth of cut), tool geometry and material properties. From Figure 2.5, the uncut chip thickness ($t_o$) is known as the feed while
the deformed chip has a different chip thickness \((t_c)\). The friction that occurs between the chip and the tool significantly affects the cutting process. The huge amount of heat energy produces from this process will be transferred into the workpiece. The shearing action will takes place along the shear plane when the cutting tool is forced into the workpiece material. The chip is formed by shear deformation along a thin shear plan, oriented at shear angle \((\phi)\) with the surface of the workpiece as shown in Figure 2.6. The relationship between shear angle and rake angle is expressed in Equation 2.1.

\[
\text{Shear angle, } \phi (\text{o}) = \tan^{-1} \left( \frac{r_a \cos \alpha}{1 - r_a \sin \alpha} \right)
\]  
\[(2.1)\]

where,
- \(r_a\) = Chip thickness ratio, \(r_a = \frac{t_o}{t_c}\)
- \(t_o\) = Undeformed chip thickness
- \(t_c\) = Deformed chip thickness
- \(\alpha\) = Rake angle

The optimization of cutting tool geometry, cutting tool material, cutting speed, rake angle and cutting fluid are needed to reduce or minimize the friction. In the metal cutting operation, there are three locations of deformation, namely primary shear zone, secondary shear zone and tertiary shear zone, as shown in Figure 2.7 (Kiliçaslan, 2009).

**Primary shear zone (A-B):** The chip formation takes place firstly and mainly in this zone as the edge of the tool penetrates into the work-piece. Material in this zone has been deformed by a concentrated shearing process.

**Secondary shear zone (A-C):** The chip and the rake face of the tool are in contact from A to C. When the frictional stress on the rake face reaches a value that is equal to the shear yield stress of the work-piece material, material flow also occur on this zone.

**Tertiary shear zone (A-D):** When a clearance face of the tool rubs the newly machined surface deformation can occur on this zone.
2.4.2 Cutting force

Cutting forces can be defined as the forces generated by friction in machining. The generated forces can be used to estimate the lubrication efficiency of the metalworking fluid. The generated friction is the resisting force of a workpiece material while it slides over the cutting tool and acts oppositely to the relative motion (cutting speed, \(V_c\)) of the surface. Figure 2.8 shows Merchant’s force diagram which the forces acts on the chip during orthogonal cutting process. The cutting force (\(F_c\)) is in the direction of cutting which in the same direction as the cutting speed and the thrust force (\(F_t\)) is perpendicular to the cutting force. Both, cutting force and thrust force can be directly measured through force measuring device called dynamometer during the machining operation. Meanwhile, the other four forces components; friction force (\(F\)), normal force to friction (\(N\)), shear force (\(F_s\)) and normal force to shear (\(F_n\)) can be calculated by Equations 2.2 to 2.5 (Groover, 2007);

\[
F = F_c \sin \alpha + F_t \cos \alpha \tag{2.2}
\]
\[
N = F_c \cos \alpha - F_t \sin \alpha \tag{2.3}
\]
\[
F_s = F_c \cos \phi - F_t \sin \phi \tag{2.4}
\]
\[
F_n = F_c \sin \phi + F_t \cos \phi \tag{2.5}
\]

The cutting forces were influenced by machining parameters such as feed rate, depth of cut, cutting speed and types of lubricant used. Rahim and Sasahara (2011b) reported that the cutting force significantly decreased as the cutting speed...
increased. The reduction of cutting force is due to the reduction of contact area at tool-chip interfaces which reduces the specific cutting energy. In addition, cutting force increases with the increase in feed rate. The reason is due to the increased chip load as the feed has been increased during the cutting process. Thicker chips formed as the feed rate increases which substantially increases the cutting force.

Moreover, Khan and Dhar (2006) stated that the cutting force significantly decreased using MQL method using vegetable-based oil. The usage of vegetable oil beneficially improves the workpiece quality and reduces friction and heat generation. The vegetable oil’s molecules have high absorption ability due to the long, heavy and dipolar in nature, create a strong lubrication film. Furthermore, greater molecular weight of vegetable oil stimulates less loss from vaporization and misting. Liu et al. (2011) found that the usage of MQL method significantly reduced the cutting force. The oil’s droplets easily penetrated into the contact zone of the chip-tool-workpiece interface, led to the friction reduction.

2.4.3 Cutting temperature

There are various methods to measure the cutting temperature under different conditions and on different types of machines as shown in Figure 2.9 (Longbottom and Lanham, 2005). The tool-workpiece thermocouple (Figure 2.10) and embedded
Figure 2.9: Temperature measurement methods

Figure 2.10: Tool-workpiece thermocouple method (Leshock and Shin, 1997)
thermocouple (Figure 2.11) are regularly used methods to measure the cutting temperature. The tools and/or workpieces have to be insulated in order to avoid short-circuit in the system during using the tool-workpiece thermocouple method. Here the cutting temperature is associated to the electro motive force (emf) generated across the hot interface between tool and workpiece. Meanwhile, the embedded thermocouple is placed in a hole drilled in the tool in the case of turning or in the workpiece for milling. The holes have to be placed close to the cutting edge at very precise locations. This method can be used to identify the temperature distribution within the tool or workpiece but not for determining the surface temperature. Another approached method is physically vapour deposited (PVD) film (Figure 2.12). The PVD film method requires the workpiece to be cut into two parts and the
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