© Universiti Tun Hussein Onn Malaysia Publisher's Office

JAMEA

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/jamea

e-ISSN : 2716-6201

Journal of Advanced Mechanical Engineering Applications

Machinability Evaluation of Nanoparticle Enriched in Vegetable-Based-Nanofluids for Machining Process

Ainaa Mardhiah Sabri[1], Norfazillah Talib[1*], A. Z. Azmi[1], Amiril Sahab Abdul Sani[2]

[1]Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[2]Faculty of Manufacturing and Mechatronic Engineering Technology,
Universiti Malaysia Pahang, 26600 Pekan, Pahang, MALAYSIA

*Corresponding Author

DOI: https://doi.org/10.30880/jamea.2021.02.02.003
Received 27 June 2021; Accepted 16 August 2021; Available online 12 December 2021

Abstract: Vegetable oil had been studying to replace mineral-based oil as metalworking fluids (MWFs) as it is non-toxic, bio-degradable and environmentally friendly. Due to vegetable oil's high viscosity and poor thermal conductivity, some improvements had been applied to a vegetable oil such as chemically modified and the addition of additives. This study aims to evaluate the machining capability of modified jatropha oil (MJO) with nanoparticle additives of 0.025wt% copper oxide (CuO) (MJOc) and 0.025wt% hexagonal boron nitride (hBN) (MJOh) as metalworking fluids. Through the turning process, the machining performance of MJOc and MJOh was compared with commercial synthetic ester (SE) in terms of cutting temperature, surface roughness, tool life, and tool wear. The results indicate that MJOc and MJOh outperformed SE in terms of machining performance. Compared to MJOc, MJOh has better machining performance in terms of cutting temperature and surface roughness. In addition, MJOh had the same tool life performance with SE which is at a cutting length of 6000mm and machining time of 42 minutes. In conclusion, the overall best machining performance is MJOh (MJO+0.025wt% hBN) and has the potential as sustainable MWFs in the lubricant market.

Keywords: Modified jatropha oil, nanofluids, nanoparticles, metalworking fluid, turning, copper oxide, hexagonal boron nitrate, machining performance

1. Introduction

Machining is the removal of material from the surface of a workpiece by moving it around and applying force to it. Chip formation during material removal slides on the tool rake face, subjecting it to severe normal and shear stresses, as well as a high coefficient of friction [1]. During machining, high temperature generated in cutting tools and workpiece interface significantly will affect the tool life, surface roughness of the workpiece and the efficiency of the machining process. Such high cutting temperatures and their negative consequences are often controlled in the industry by careful selection of metalworking fluids, process parameters and cutting tools material [2]. In addition, Metalworking fluids (MWFs) are used as a lubricant in metal removal operations, including grinding, turning, and milling to reduce friction between the workpiece and the cutting tool, enhance tool life, and reduce wear [3]. Machining without using metalworking fluid results in higher power consumption, fast tool wear, and poor surface quality [4].

*Corresponding author: fazillah@uthm.edu.my

Nomenclature			
CuO	Copper oxide	Ra	Surface roughness
C	Carbon	T_t	Total machining time
CJO	Crude Jatropha oil	T_L	Total cutting time
hBN	Hexagonal boron nitride	TMP	Trimethylolpropane
JME	Jatropha methyl ester	$NaOCH_3$	Sodium methoxide
MQL	Minimum quantity lubrication	V_B	Flank wear
MJO	Modified Jatropha Oil	VB_B	Average flank wear
MJOh	MJO + 0.025wt.% hBN	VB_N	Notch wear
MJOc	MJO + 0.025 wt.% CuO	VB_{MAX}	Maximum flank wear

The use of MWF derived from bio-based oil stems from a growing concern about the sustainability of the machining process. Sustainable machining requires environmentally friendly machining, including minimal quantity lubrication (MQL), vegetable-based lubricant, and dry machining [5]. However, mineral-based MWFs have poor biodegradability, non-renewable resources, and high toxicity, which can negatively impact the environment by contaminating soil and causing water and air pollution. Furthermore, skin and respiratory illness increased among workers due to long contact with mineral-based oil [6]. These problems have opened researchers' awareness to explore vegetable oil as a candidate to substitute mineral-based metalworking fluid.

Vegetable oils are favoured as a sustainable substitute due to their high biodegradability, low toxicity to humans and the environment, and the fact that they are derived from renewable resources that may be produced constantly [7]. There are three types of sustainability: environmental, economic, and social. In terms of the environment, vegetable oil waste has no negative impact, particularly soil, where the fluid is transformed to a lower molecular weight component over time [8]. While economically beneficial, vegetable oils in the industry contribute to the global concern for green technology. Vegetable oils, such as canola and rapeseed, are more viable candidates for biodegradable lubricant base stocks [9]. Biodegradable base stocks are less expensive than synthetic base stocks [10]. For social sustainability, Because vegetable oil is non-toxic, workers are less likely to contract illnesses while using it in machining [11]. The triglyceride structure in vegetable oil consists of fatty acids, it offers lower volatility, higher lubricity, flash point, and higher viscosity index and rapid biodegradation [12]. However, the major part of vegetable oils is a triglyceride, which consists of free fatty acids (FFA) and glycerol, which causes the limitation in vegetable oils usage owing to their poor thermal-oxidative stability qualities [6]. Vegetable oil's properties can be enhanced in various ways, such as chemical modification and the addition of nanoparticles to vegetable-based oil.

The addition of nanoparticles to MWFs such as mineral Oil cutting fluid strengthen with various filler fractions of nanoparticles of copper oxide (CuO) and titanium dioxide (TiO2) has also revealed an improvement in surface finish and tool life of products [13]. Increase in lubricating characteristics and thermal of the fluids due to the particles. Since solid particles have greater thermal conductivity due to the higher surface area of the nanofluids, thermal conductivity is enhanced [14]. Obtaining wear reduction of up to 66% is due to the spreading of hexagonal boron nitride (hBN), WS2, and MoS2 nanoparticles in MWFs. This was assigned to nanoparticles shearing of trapped nanoparticles and filling surface valleys at the interface of touching surfaces [15].

Therefore, this study mainly concerns the experimental works through the turning process to investigate the tool life, cutting temperature, tool wear, and surface roughness using modified jatropha-based nanofluids. The additive uses are CuO and hBN at 0.025 wt% concentration ratios.

2. Methodology

2.1 Preparation of Vegetable oil-based Nanofluid Lubricant

In the production of MJO, CJO undergoes a chemical modification process. First, crude Jatropha Oil (CJO) undergoes a two-step acid-based catalyst esterification process to produced Jatropha methyl ester (JME), as shown in the schematic diagram in Figure 1(a). Figure 1(b) shows the transesterification process where JME will react with trimethylolpropane (TMP) with the presence of sodium methoxide ($NaOCH_3$) and produced modified Jatropha oil (MJO). For the preparation lubricant sample, MJO was mixed with the additives to formulate the nanofluids. The additives used was copper oxide nanoparticle (CuO) and hexagonal boron nitride (hBN). The concentrations of additives were 0.025 wt.%. The size of additives ranging from 90 nm to 100nm. The additives were blended with MJO using a magnetic stirrer at 700 rpm and temperature 60°C for 30 minutes. Table 1 shows the MJOs used in this experiment and were compared with the synthetic ester (SE, Unicut Jinen MQL) as benchmark oil.

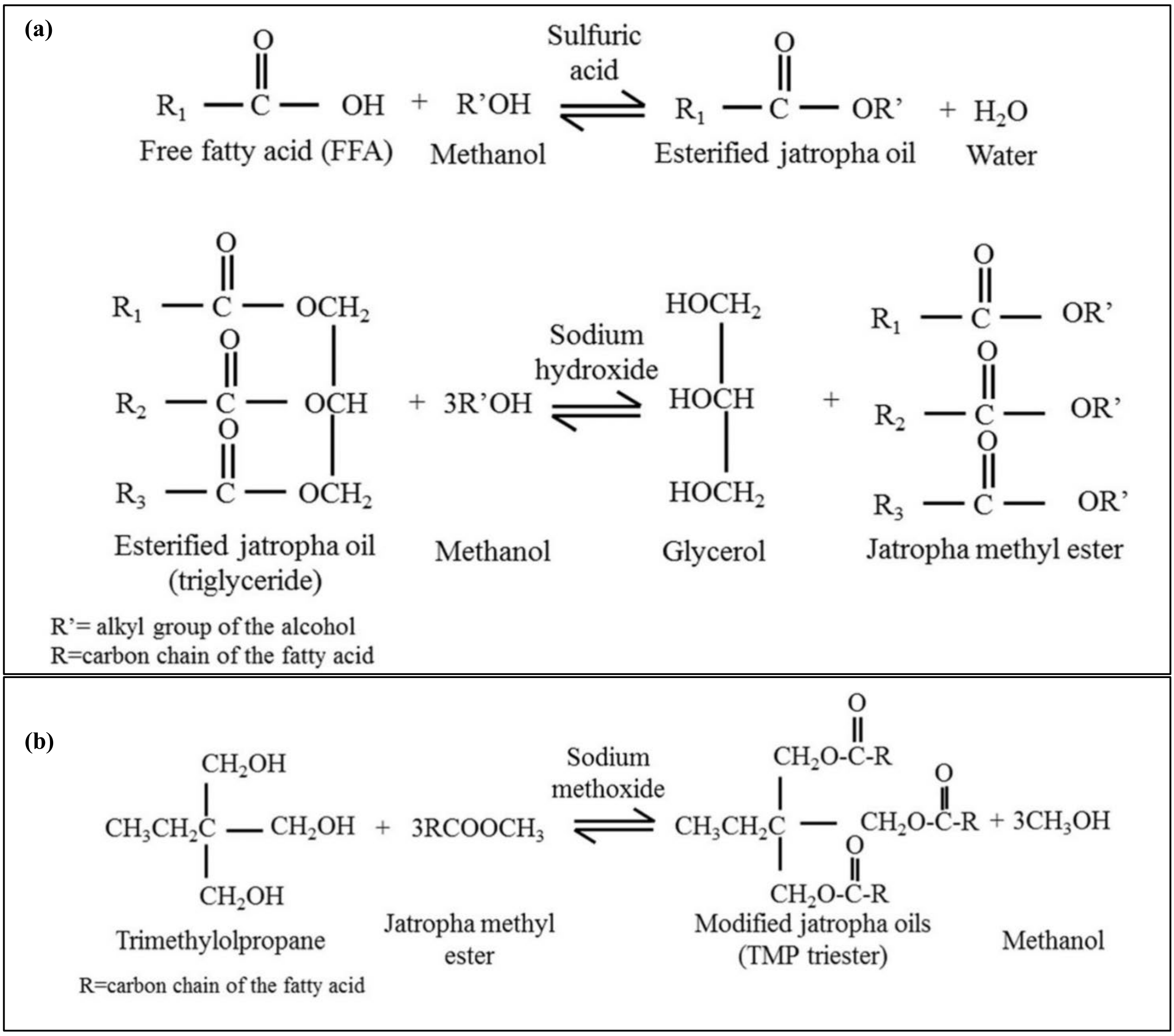

Fig. 1 - (a) Two-step acid base catalyst transesterification process and (b) transesterification process for reaction of JME with TMP [16]

Table 1 - Oil samples

Modified Jatropha oil (MJO)	Benchmark oil
MJO + CuO (MJOc)	Synthetic ester (SE)
MJO + hBN (MJOh)	

2.2 Machining Setup

The workpiece used in the experiment was AISI 1045 Steel with a diameter of 100mm and length of 200mm as shown in Figure 2(a). The cutting tool used was uncoated cermet (TNGG220408R-UM) with a relief angle and a nose radius of 0° and 0.8mm, mounted on the tool holder MTQNR2525M22N. The turning process was performed using a Numerically Controlled (NC) lathe machine (Alpha Harrison 400) with the machining parameter listed in Table 2. The lubricant supplied using MQL along the cutting edge of the workpiece with input pressure of 0.4 MPa and high-velocity flow at 0.16 l/hr. The nozzle with an inner diameter of 0.25mm was placed about 8mm to the cutting edge with a 45° angle, as shown in Figure 2(b).

The maximum cutting temperature was measured using thermal image camera FLIR T640 placed opposite the workpiece. The data was analyzed on the laptop using FLIR Tool software. Surface roughness, Ra was measured using Mitutoyo Surface Roughness Tester (model SJ-400). The measurement procedure was conducted according to

ISO4288:1996. Progression of VB_B, VB_{max}, and VB_N was observed at the cutting edge of the flank face using a tool maker microscope (Nikon MM60). The tool life was recorded based on the total machining time, T_t and total cutting length, T_L. The tool wear was inspected through a tool maker microscope (Nikon MM60) at rake face, flank face and nose face.

Table 2 - Machining parameter

Description	Values
Cutting speed, VC (m/min)	300
Feed rate, fr (mm/rev)	0.2
Depth of cut (mm)	1
Oil flow rate (1/hour)	0.16
Workpiece material	AISI 1045
Cutting tool	Uncoated cermet

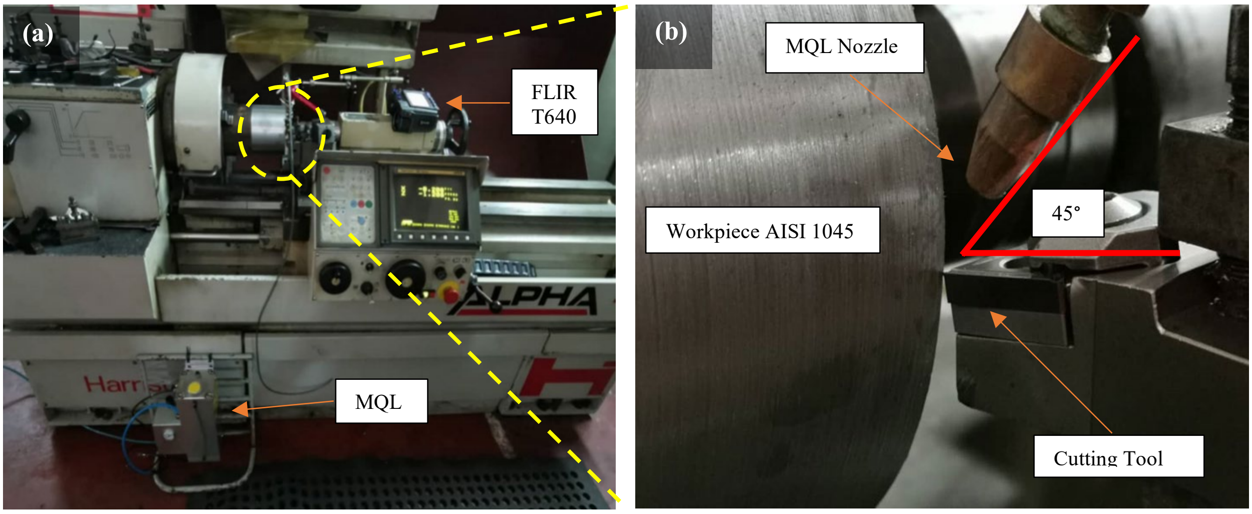

Fig. 2 - Turning process setup

3. Results and Discussion

3.1 Cutting Temperature

Figure 3 shows the result of the maximum cutting temperature of MJOh, MJOc and SE. From the graph, it is shown that the highest temperature between the three oil samples is SE with 198.8°C follow by MJOc, which is 160°C and lastly MJOh with 154.6°C. The cutting temperature of MJOc and MJOh decreased by 20% and 22% respectively than the cutting temperature of SE. When compared to SE with carbon chains ranging from C8 to C10, MJOs with carbon chains ranging from C16 to C20 exhibited a higher adsorption capacity. In addition, MJOs also generated TMP triester branches in oil molecules, which contributed to the high molecular weight and more polar structure [17]. Moreover, good adsorption of acid promoted by fatty acid content in MJO could generate lubrication film resulting in low friction between the cutting tools and workpiece interfaces [16,18]. This is also due to the low viscosity index of SE (139) which leads to insufficient formation lubrication film thus cause higher friction. The heat generated during machining also increased due to an increased in friction [12].

The cutting temperature of MJOh is recorded 4% lowered than cutting temperature MJOc. This is because the thermal expansion coefficient of hBN nanoparticles is lower which is 1 X 10^{-6}/°C [19] compared to the thermal expansion coefficient of CuO 1.9 X 10^{-6}/°C [20]. The cutting temperature is influenced by the thermal expansion coefficient of additives.The cutting temperature drops due to the material's a high thermal expansion coefficient [21]. The presence of hBN particles in MJOs enhanced thermal conductivity and heat transfer coefficient, resulting in higher heat dissipation capacity [17]. Furthermore, the hexagonal crystalline form of hBN nanoparticles in which boron and nitrogen atoms located on the same layer were densely packed and securely linked together demonstrated exceptional thermal stability [22].

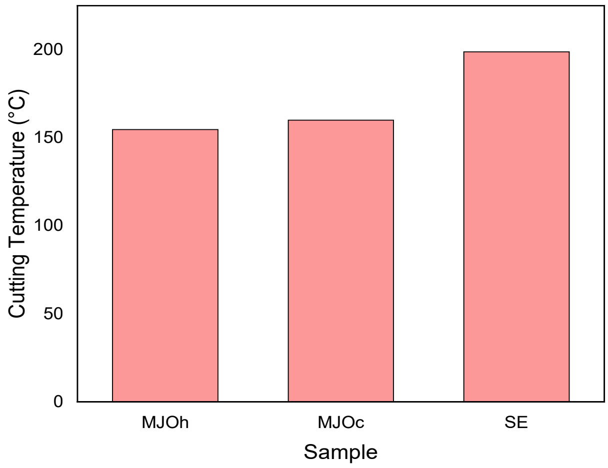

Fig. 3 - Cutting temperature

3.2 Surface Roughness

Figure 4 shows the surface roughness values for MJOh, MJOc, and SE. From the graph, the surface roughness of SE is 2.86 µm, the highest value compared to MJOh and MJOc. The flow resistance is higher as the viscosity of SE is high at 19 mm^2/s compared with MJOs (<19 mm^2/s) thus resulting in higher energy losses [17]. Due to higher flow resistance, the lubrication capability worsened and cause surface quality deterioration.

In addition, MJOc and MJOh exhibit lower surface roughness than SE because of the addition of additives in the MJOs. The increase in surface quality was more noticeable when nanofluid was used. Nano-solid lubricants are considered to penetrate better to the tool-chip and tool-work-piece interfaces, while nano-additives are better able to remove heat from the cutting zone by improving the cutting liquid's thermal conductivity. In addition, oil particles are retained by nano-additives, which prevent the cutting oil from being released immediately from the cutting zone, resulting in greater lubrication [23]. Thus, reduce friction and improve the surface quality of the workpiece. Besides that, Copper nanoparticles have gained prominence because of their ability to reduce material wear and friction through a recovery mechanism, as well as their ability to build a long-lasting sustainable protective layer [24].

MJOh records the lowest surface roughness with a reduction of 62% compared to SE. By occupying the valleys at the sliding interfaces with the least amount of hBN particles (0.05 w.%), hBN particles minimize interfacial interaction at tool-workpiece interfaces while forming a thin powder lubrication layer [17]. In addition, the hBN particles in lamellar powder formed a boundary layer that attached to the contact surfaces and slid over each other to reduce friction [25].

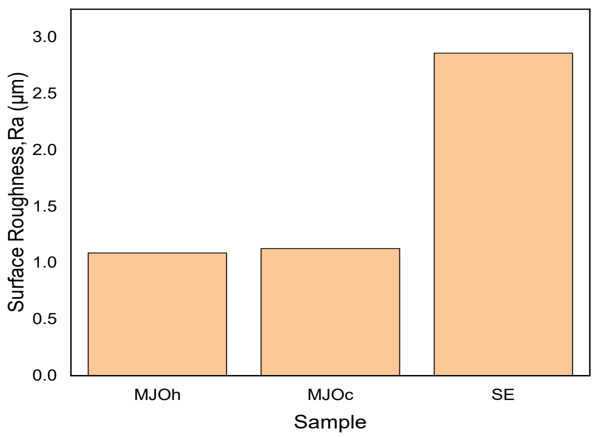

Fig. 4 - Surface roughness

3.3 Tool Life

Tool life value is observed until it exceeds the tool wear criteria base on ISO 3685:1993. In this experiment, the progression of wear, machining time and cutting distance for MJOh and SE only are observed. This is because from cutting temperature and surface and roughness testing, MJOh shows better results compared to MJOc. Thus, only MJOh undergoes this testing and is compared with benchmark oil, SE.

From Figures 5,6, and 7 the maximum flank wear (VB_B max), average flank wear (VB_B) and notch wear (VB_B) have been recorded for SE and MJO+hBN oil samples. The tool lubricated with SE, reach 0.6mm for notch wear, VB_N could be seen as a tool failure due to the maximum value of notch wear in tool life criteria and it took 6000mm of cutting length with 42 minutes of machining time for the tool fail. Low tool life of SE can be attributed to lower carbon chain length and poor absorption endurance at tool-chip contacts. SE was burnt during the machining process due to increased heat production before it was lubricated [17].

Meanwhile, the tool lubricated with MJO+hBN reach 0.3mm for average flank wear, VB_B could be seen as a tool failure, follow the tool life criteria and took 6000mm of cutting length with 42 minutes of machining time for the tool to fail. A previous study stated that the correct mixture is that low concentration (0.5 vol%) of hBN particles, in terms of tool life and reduce friction in the tool-chip interface [23].

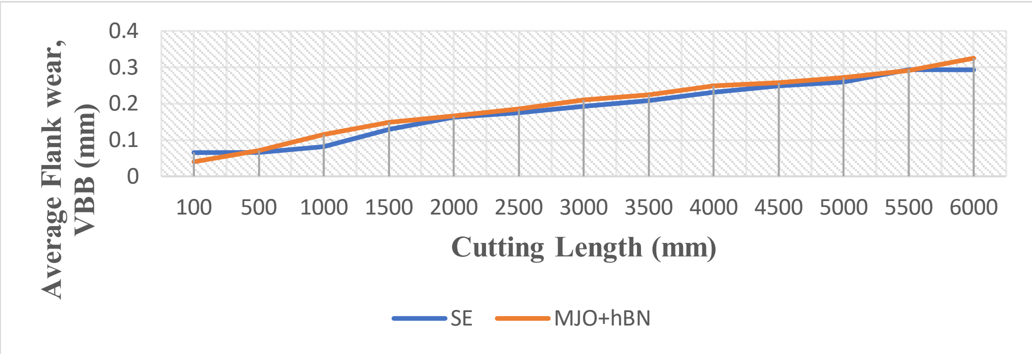

Fig. 5 - Progression of average flank wear, VBB of SE and MJOh

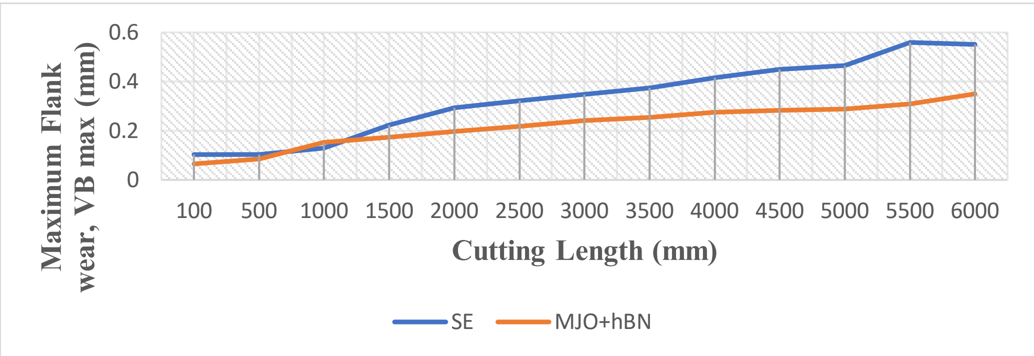

Fig. 6 - Progression of maximum flank wear, VB_{max} of SE and MJOh

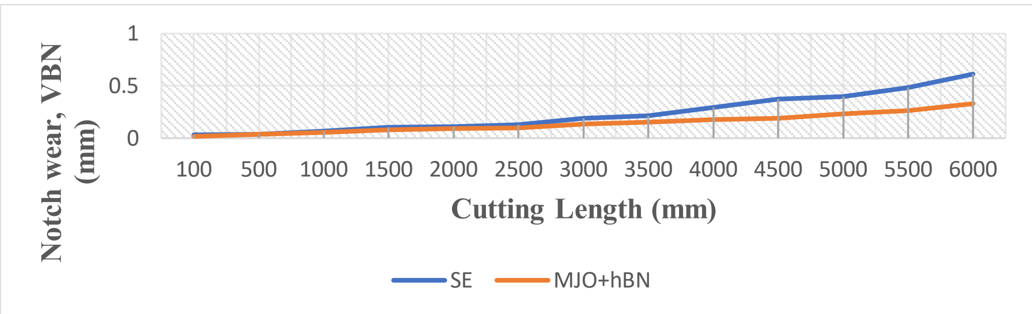

Fig. 7 - Progression of notch wear, VB_N of SE and MJOh

3.4 Tool Wear

The micrograph of the cutting tool lubricated by MJOh oil samples is shown in Figure 8 after the machining process at the end of the tool life. From the observation, the cutting tool failed because of the notch formation, flank, and crater wear. Crater wear happened by abrasion, adhesion (attrition) and diffusion, while, flank wear happened by abrasion and microchipping. The progression of wear influences the growth of friction and temperature at the tool-workpiece interfaces [2]. Constant movement and touching of the workpiece and chips surfaces cause great friction that leads to material removal [26]. Meanwhile, abrasion wear happens mostly when a hard rough surface peeled off the tool material, between the tool-chip interfaces, or emerging from workpiece or cutting tool material [27].

Both oxidation and chemical wear cause notch wear, where the thermo-mechanical stress gradient was high [2]. The basic wear types, notch and flank wear were found on the line of chipping and cutting depth. The main type of wear that harms cutting tools in the machining of nickel-based superalloys, especially at low cutting speeds, was reported to be notch wear at the tool's tip and depth of cut [28].

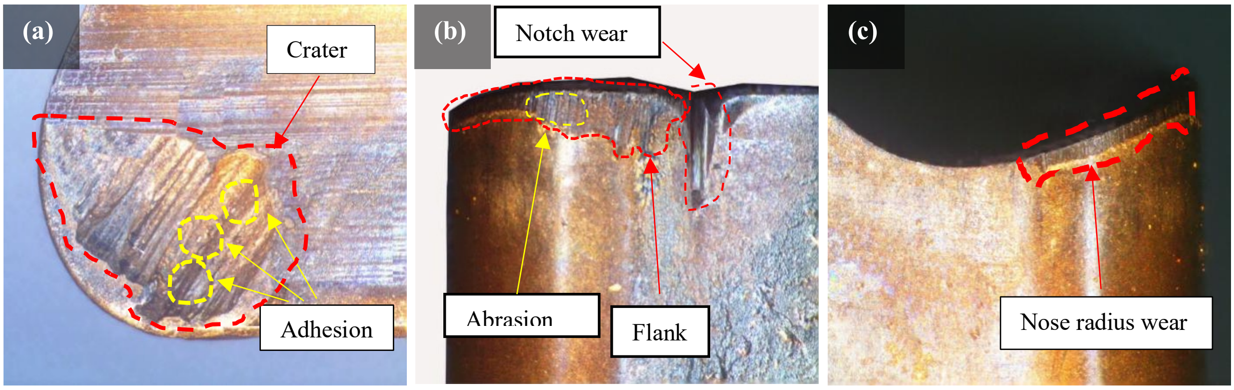

Fig. 8 - (a) rake face; (b) flank face; (c) nose face of the cutting tool for MJOh sample at total machining time of 42 minutes

4. Conclusion

In this study, the new formulations of modified jatropha oil (MJOs) were successfully developed with CuO and hBN as additives at concentrations of 0.025wt%. The turning performances of MJOh and MJOc were investigated in comparison with SE. Overall, the turning performances of the MJO samples with both additives (CuO and hBN) were better compared to SE. The addition of additives enhances the lubrication performance. It can be observed that MJOh has the best machining performance in terms of cutting temperature and surface roughness. The addition of hBN particles gives greater thermal conductivity, improves heat transfer rate, and reduces the cutting temperature.

Further, the result recorded that MJOh and SE have the same tool life (6000mm, 42 min). Maximum notch wear (VB_N) was shown as a tool failure mode for SE while average flank wear (VB_B) was shown as a tool failure mode for MJOh. Abrasion and adhesion were found as the dominant wear mechanism at the flank and rake faces of the tool lubricated using MJOh. In conclusion, the results showed that the modified jatropha oils with the addition of 0.025wt.% of hBN nanoparticles additives depicted excellent machining performances. Thus, modified Jatropha oil +hBN can be a potentially sustainable and environmentally friendly metalworking fluid.

Acknowledgement

The authors would like to thank the Ministry of Higher Education (MOHE) and Universiti Tun Hussein Onn Malaysia for the financial support through the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2018/TK03/UTHM/03/10).

References

[1] B. Ackroyd *et al.*, "Exploration of contact conditions in machining," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 215, no. 4, pp. 493–507, 2001

[2] N. R. Dhar and M. Kamruzzaman, "Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition," *Int. J. Mach. Tools Manuf.*, vol. 47, no. 5 SPEC. ISS., pp. 754–759, 2007

[3] E. Brinksmeier, D. Meyer, A. G. Huesmann-Cordes, and C. Herrmann, "Metalworking fluids - Mechanisms and performance," *CIRP Ann. - Manuf. Technol.*, vol. 64, no. 2, pp. 605–628, 2015

[4] R. Katna, M. Suhaib, and N. Agrawal, "Nonedible vegetable oil-based cutting fluids for machining processes–a review," *Mater. Manuf. Process.*, vol. 35, no. 1, pp. 1–32, 2020

[5] E. Kuram, B. Ozcelik, E. Demirbas, E. Şik, and I. N. Tansel, "Evaluation of new vegetable-based cutting fluids on thrust force and surface roughness in drilling of AISI 304 using Taguchi method," *Mater. Manuf. Process.*, vol. 26, no. 9, pp. 1136–1146, 2011

[6] N. A. Jamaluddin, N. Talib, A. Sahab, and A. Sani, “Tribological Assessment of Modified Jatropha Oil with hBN and Graphene Nanoparticles as a New Preference for the Metalworking fluid,” *Int. J. Eng. Adv. Technol.*, vol. 9, no. 3, pp. 3144–3149, 2020

[7] M. C. de Souza, J. F. de S. Gonçalves, S. Y. S. Lutif, and J. de O. Gomes, “Tribological evaluation of the Jatropha and Tung-based oils as bio-lubricants on Al-7050-T7451 alloy,” *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 41, no. 6, pp. 1–11, 2019

[8] S. Syahrullail, S. Kamitani, and A. Shakirin, “Performance of vegetable oil as lubricant in extreme pressure condition,” *Procedia Eng.*, vol. 68, pp. 172–177, 2013

[9] H. M. Mobarak, “Non-Edible Oil as a Source of Bio-Lubricant for Industrial Applications : A Review,” *Int. J. Eng. Sci. Innov. Technol.*, vol. 2, no. 1, pp. 299–305, 2013

[10] S. A. Lawal, “A review of application of vegetable oil-based cutting fluids in machining non-ferrous metals,” *Indian J. Sci. Technol.*, vol. 6, no. 1, pp. 3951–3956, 2013

[11] M. S. Nathe, V. . Kadlag, and V. P. Chaudhari, “Effect of Castor Oil as Bio Lubricant on Tribological Characteristics of EN31 Steel,” *Int. J. Mod. Trends Eng. Res. Eff. Addit. Ordinary Portl. Cem. Geopolymer*, no. 2349, pp. 960–965, 2016

[12] N. Talib, A. S. A. Sani, and N. A. Hamzah, “Modified jatropha nano-lubricant as metalworking fluid for machining process,” *J. Tribol.*, vol. 23, no. September, pp. 90–96, 2019

[13] K. D. Vázquez, D. S. Cantú, A. F. Segura, F. Araiz, L. Peña-Parás, and D. Maldonado, “Application of Nanofluids to improve tool life in machining processes,” *Lubr. Maint. Tribotechnology LUBMAT 2014, Manchester, UK*, no. Paper number: L146058, pp. 1–8, 2014

[14] S. K. Das, S. U. S. Choi, W. Yu, and T. Pradeep, *Nanofluids Science and Technology*. 2008

[15] M. Mosleh, N. D. Atnafu, J. H. Belk, and O. M. Nobles, “Modification of sheet metal forming fluids with dispersed nanoparticles for improved lubrication,” *Wear*, vol. 267, no. 5–8, pp. 1220–1225, 2009

[16] N. Talib, H. Sasahara, and E. A. Rahim, “Evaluation of modified jatropha-based oil with hexagonal boron nitride particle as a biolubricant in orthogonal cutting process,” *Int. J. Adv. Manuf. Technol.*, vol. 92, no. 1–4, pp. 371–391, 2017

[17] N. Talib and E. A. Rahim, “Performance of modified jatropha oil in combination with hexagonal boron nitride particles as a bio-based lubricant for green machining,” *Tribol. Int.*, vol. 118, no. March 2017, pp. 89–104, 2018

[18] Y. M. Shashidhara and S. R. Jayaram, “Vegetable oils as a potential cutting fluid-An evolution,” *Tribol. Int.*, vol. 43, no. 5–6, pp. 1073–1081, 2010

[19] N. Talib, R. M. Nasir, and E. A. Rahim, “Investigation on the tribological behaviour of modified jatropha oil with hexagonal boron nitride particles as a metalworking fluid for machining process,” *Int. J. Integr. Eng.*, vol. 10, no. 3, pp. 57–62, 2018

[20] C. H. Chan, S. W. Tang, N. K. Mohd, W. H. Lim, S. K. Yeong, and Z. Idris, “Tribological behavior of biolubricant base stocks and additives,” *Renew. Sustain. Energy Rev.*, vol. 93, no. March 2017, pp. 145–157, 2018

[21] A. E. Atabani *et al.*, “Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production,” *Renew. Sustain. Energy Rev.*, vol. 18, pp. 211–245, 2013

[22] C. J. Reeves and P. L. Menezes, “Evaluation of boron nitride particles on the tribological performance of avocado and canola oil for energy conservation and sustainability,” *Int. J. Adv. Manuf. Technol.*, vol. 89, no. 9–12, pp. 3475–3486, 2017

[23] Ç. V. Yıldırım, M. Sarıkaya, T. Kıvak, and Ş. Şirin, “The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625,” *Tribol. Int.*, vol. 134, no. February, pp. 443–456, 2019

[24] V. H. Rajubhai, Y. Singh, K. Suthar, and A. R. Surana, “Friction and wear behavior of Al-7% Si alloy pin under pongamia oil with copper nanoparticles as additives,” *Mater. Today Proc.*, vol. 25, no. xxxx, pp. 695–698, 2019

[25] C. J. Reeves, P. L. Menezes, M. R. Lovell, and T. C. Jen, “The size effect of boron nitride particles on the tribological performance of biolubricants for energy conservation and sustainability,” *Tribol. Lett.*, vol. 51, no. 3, pp. 437–452, 2013

[26] B. V. Manoj Kumar, J. R. Kumar, and B. Basu, “Crater wear mechanisms of TiCN-Ni-WC cermets during dry machining,” *Int. J. Refract. Met. Hard Mater.*, vol. 25, no. 5–6, pp. 392–399, 2007

[27] A. C. A. De Melo, J. C. G. Milan, M. B. Da Silva, and Á. R. Machado, “Some observations on wear and damages in cemented carbide tools,” *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 28, no. 3, pp. 269–277, 2006

[28] K. Kadirgama, K. A. Abou-El-Hossein, M. M. Noor, K. V. Sharma, and B. Mohammad, “Tool life and wear mechanism when machining Hastelloy C-22HS,” *Wear*, vol. 270, no. 3–4, pp. 258–268, 2011