Tribological Study of Activated Carbon Nanoparticle in Nonedible Nanofluid for Machining Application

Talib, Norfazillah
Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia

Nor Athira Jamaluddin
Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia

Tan Kai Sheng
Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia

Lee Woon Kiow
Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia

他

https://doi.org/10.5109/4480728

出版情報：Evergreen. 8 (2), pp.454-460, 2021-06. Transdisciplinary Research and Education Center for Green Technologies, Kyushu University
バージョン：

Tribological Study of Activated Carbon Nanoparticle in Nonedible Nanofluid for Machining Application

Norfazillah Talib[1,*], Nor Athira Jamaluddin[1], Tan Kai Sheng[1], Lee Woon Kiow[1], Haslina Abdullah[1], Said Ahmad[1], Aslinda Saleh[2]

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

[2] Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Muar, Johor, Malaysia.

*Author to whom correspondence should be addressed:
E-mail: fazillah@uthm.edu.my

(Received January 7, 2021; Revised April 26, 2021; accepted April 26, 2021).

Abstract: Nonedible vegetable-based oil was recently explored due to the demand for a sustainable element in a machining process. The aim of this study is to critically analyse the tribological performance of nanofluid from nonedible (modified jatropha oil, MJO) nanofluid added with activated carbon nanoparticles. The tribology test was conducted through four-ball test using various concentration ratios of nanoparticles. According to the findings, MJOa2 (0.025wt.% activated carbon in MJO) showed the lowest coefficient of friction and mean wear scar diameter, produced a smoother surface with low surface roughness value, followed by MJOa3 (0.05wt.% activated carbon in MJO), MJOa1 (0.01wt.% activated carbon in MJO) and synthetic ester (SE). Therefore, MJOa2 was considerably suitable for metalworking fluid application which emphasizing the element of sustainability.

Keywords: Activated carbon; Nanofluid; Tribology

1. Introduction

A lubricant has been functionally used in various usages in reducing friction, minimizing wear, releasing heat, eliminating impurity and enhancing the efficiency in between two contact surfaces[1]. Lubricant can act as anti-oxidants, rust and corrosion inhibitors, anti-wear agent and viscosity index improver. Tribological performance in lubrication is the study of controlling and managing the lubricity, friction and wear.

Nowadays, a utilization of petroleum based-oil as the lubricant is very common in the machining industry. However, a choice of environmental-friendly oil has been introduced to gradually phase out the use of petroleum based-oil in the machining process as the latter type of oil has depleted due to the high demand in this era[2),3)]. This phenomenon was due to the increasing demand for the sustainable element in the machining industry. The usage of petroleum based-oil as metalworking fluid (MWF) is harmful and it may lead to polluting the environment, subsequently increase the disposal costs after the usage of the oil[4),5)].

At present, vegetable oils are considered as environmental-friendly lubricants as it is highly biodegradable, harmless, sustainable as well as good lubricity[6),7)]. Nonedible oil such as jatropha oil was reported to have good lubrication properties. Nevertheless, there are several disadvantages including low thermal and oxidative stability[8)]. This condition is due to the presence of triglycerides in the vegetable oil, where the glycerol particles with three long-chain fatty acids connected to the hydroxyl group through ester linkages[9),10)]. The long carbon chain might contain one, two, or three double bonds of fatty acids like oleic, linoleic, and linolenic.

Shashidhara & Jayaram[11)] suggested that some appropriate modifications of the vegetable oil have to be performed to solve the adverse effect of the vegetable oil. Talib et al. [12)] have confirmed that the modified jatropha oil (MJO) played a crucial role in the tribological performance on the metal sliding pairs in the aspects of superior wear and friction reduction. In addition, it is crucial to mix the vegetable oil with nanoparticle which can produce a better lubricant in establishing a protective layer between the contact surfaces[1)]. In this condition, nanoparticles can provide a rolling effect at the mating surfaces that may alter sliding friction into both sliding and rolling friction. Furthermore, the addition of nanoparticles in the nanofluids enhance the thermal stability and lubricating properties[13–15]. Previously, Sayuti et al.[16] reported that nanoparticles in nanofluid formed good protective films, provided a effect of rolling between the contact surfaces and formed tribofilms by depositing the nanoparticles at the contact surfaces. Subsequently, the friction between the two contact surfaces can be productively diminished. Moreover, the existence of nanoparticles in the base fluids might contributed to enhance a flow of mixing and provide higher thermal conductivity [17),18)].

Sharma et al.[19] reported the usage of nanoparticles in nanofluid during the turning process improved the tribological properties by reducing the friction coefficient, thus reduced the machining force and tool wear. Whilst, Singh et al.[20] discovered that the addition of nanoparticles enhanced the thermal conductivity and viscosity of the nanofluid. They revealed that the nanofluid significantly improved the performance of turning operation in connection with machining force and surface roughness.

Activated carbon is a processed carbonaceous materials with uniform surface morphology, outstanding biocompatibility, good mechanical strength and stability[21),22)]. Pertaining to the previous study by Kaggwa et al.[23], activated carbon in nanofluid has significantly increased the lubricant viscosity and improved the heat transfer efficiency. Furthermore, Ayuma et al.[24] found that the activated carbon generated a tribofilm between two contact surfaces thus prevented wear and friction during the pin-on-disc test. The carbon-based tribofilm adhered at the contact surfaces which prohibited the adhesion to occur.

Jamaluddin et al.[25] conducted tribological performance of MJO based nanofluids by mixing with hexagonal boron nitride and graphene at three different concentration of 0.01 wt.% to 0.05 wt.%. The result signified that MJO incorporated with 0.025 wt.% of graphene was the best among other MJO samples by providing low coefficient of friction (COF). Meanwhile, MJO with 0.025 wt.% hBN showed the lowest mean wear scar diameter (WSD) although their coefficient friction value was slightly higher than the other MJO samples. The presence of nanoparticles as filler to fill asperity valleys between two sliding surfaces, resulted in a reduction of COF as well as WSD.

Hence, this current study was emphasized on the tribological analysis of nanoparticle from activated carbon added in nonedible metalworking fluid from MJO using different concentration ratios which was evaluated through the four-ball test. This new nanofluid formulation can provide new opportunities for machining operation particularly in minimizing a quantity lubrication-based oil.

2. Research Procedure

2.1 Development of nanofluid

The nanofluid was formulated using modified jatropha oil (MJO) which was synthesized through two-step acid-based catalyst transesterification process involved crude jatropha oil and trimethylolpropane[12]. The activated nanoparticles (size <100 nm) as shown in Fig.1 from bamboo was used as an additive as it offered a very high removal capacity for organic components and considered as cost-effective with good lubrication performance. Table 1 indicates the physical properties of activated carbon. Initially, MJO was blended with activated carbon nanoparticles at different concentration ratios (i.e. 0.01, 0.025, and 0.05 wt. %) in order to develop the nanofluids as shown in Table 2. The blending process was regulated at a fixed stirring rate of 700 rpm using a magnetic stirrer for an hour at 60 °C. The nanofluid oil was stirred well again prior to every new test in order avoid agglomeration and sedimentation of nanoparticles in the base oil. The nanofluids were compared with commercial Unicut Jinen MQL which was a synthetic-based oil (SE).

Fig. 1: Activated carbon nanoparticle from bamboo

Table 1. Physical properties of activated carbon[23].

Properties	Description
Density (g/cm3)	3.3
Size (nm)	50
Melting point (°C)	1772
Solubility in water	Insoluble
Thermal expansion coefficient (K^{-1})	3.6×10^{-6}

Table 2. Samples of nanofluid.

Sample	Description
MJO+ 0.01wt.% activated carbon	MJOa1
MJO+ 0.025wt.% activated carbon	MJOa2
MJO+ 0.05wt.% activated carbon	MJOa3

2.2 Four ball testing

The tribology testing was performed using four-ball tribotester equipment, DUCOM TR-30L based on ASTM D4712. Four steel balls made of AISI 52100 with the hardness of 64 to 66 HRC and the diameter of 12.7 mm were used in each testing. 10 ml of oil sample was poured into the ball port. As shown in Fig. 2, the three stationary balls were clamped in the ball pot assembly. The rotating ball was placed inside the collet. Then, it was squeezed into the spindle. Further, the ball port was fitted in the tribotester machine and slowly, a normal load of 392 ± 2 was applied to avoid any intense stress. The heating temperature of oil was fixed at 75 ± 2 °C. After reaching the required temperature, the rotating ball was operated for 60 minutes at the constant speed of 1200rpm. Subsequently, the steel balls were taken out from the ball port and washed using acetone to remove the oil stain. From the testing, the coefficient of friction (COF) was determined using Winducom software. The stationary steel balls were observed and the mean wear scar diameter (MWSD) was measured using a scanning electron microscope (SEM, Toshiba S-3000N) equipped with energy-dispersive X-ray spectroscopy (EDX). The worn surface roughness (R_a) was measured using surface roughness measuring set (Mahr Perthometer PGK 120).

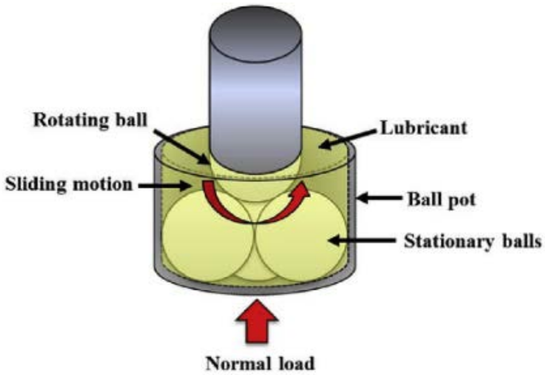

Fig. 2: Illustration of the clamped balls [12]

3. Result and discussion

3.1 Coefficient of friction and mean wear scar diameter

Fig. 3 displays the reading of COF and MWSD for each oil sample. MJOa1, MJOa2 and MJOa3 were improved by 50.6%, 44.9%, 59.6%, respectively in term of COF as compared to commercially used SE. Whilst, the MWSD reading of MJOa1, MJOa2 and MJOa3 were reduced from a range of 45 to 51% compared to SE. The fatty acids in MJO provided effective lubrication performance[26]. MJOs contained fatty acids that can form a thin lubrication layer that sticks on the contact surfaces. The polar carboxyl group in the fatty acids remained closely packed thus provided adequate lubrication film that might reduce the friction[27]. As illustrated in Fig. 4, the inclusion of nanoparticles (activated carbon) significantly provided a rolling mechanism that changed the sliding effect into the rolling effect, thus reduced the friction at the contact area[28]. Moreover, among three concentration ratios, 0.025 wt.% of activated carbon nanoparticle in MJO (MJOa2) offered a significant improvement of COF (0.036) and smallest MWSD (457.63µm). This phenomenon was attributed to a sufficient concentration of nanoparticles that offered a rolling effect between the friction area, thus reducing the COF value[12]. However, the addition of 0.01 wt.% and 0.05 wt.% of activated carbon nanoparticles in MJO produced poor tribological performances. The smallest concentration of nanoparticles (0.01 wt.%) provided an insufficient protected layer between the friction surfaces and increased the exposed area thus resulted in increment in the COF and produced larger MWSD. Concurrently, the presence of 0.05 wt.% nanoparticles caused particles agglomeration that substantial effect the quality of the lubricant. Due to the relatively high concentration of added nanoparticles, the lubrication film became thick thus increased the COF and MWSD[29].

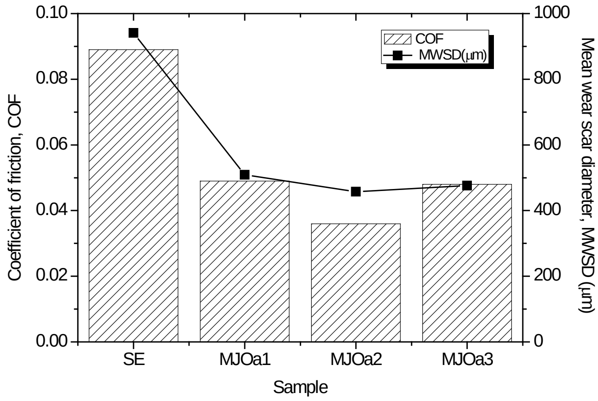

Fig. 3: COF and MWSD for all samples

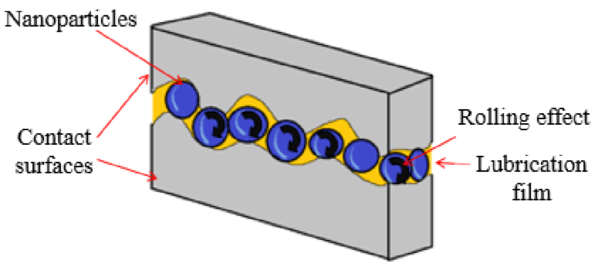

Fig. 4: Schematic diagram of lubrication film[30]

3.2 Worn surface analysis

Fig. 5 depicts the SEM image of MJOa1, MJOa2 and MJOa3 at 100x magnification. As can be observed, MJOa1 surface showed a large complete round shape of wear scar with a deep groove on the worn surface with a material transfer, whereas, MJOa3 surface showed a mixture of shallow and deep grooves at the worn surface. Furthermore, MJOa2 surface showed a small complete round shape and a shallow groove. This phenomenon showed that the presence of the carbon (C) element from the activated nanoparticles in the nanofluid was capable to provide better thin lubrication film between the contacts surfaces thus improved the value of COF and MWSD. In addition of providing a rolling element at the contact surfaces, the addition of the nanoparticles in the nanofluid led to a formation of an absorption layer that protected the surfaces. According to Fig. 7, the worn surface of the steel ball which was lubricated using the optimum concentration of nanoparticle of MJOa2 showed the highest absorption of 8.22 wt.% of C elements in contrast to the pure MJO without additive which had low C content compared to

MJOa2 with only 5.15 wt.% (Fig. 6). This finding showed the deposition of activated carbon nanoparticles occurred at the friction surface area thus offered the reduction on friction and wear. Meanwhile the depositions of C element at the contact areas of the worn surface on the steel ball which was lubricated by MJOa1 and MJO3 were 4.79 wt.% (Fig. 8) and 5.49 wt.% (Fig. 9) respectively.

According to the current work, it can be seen that both oil and nanoparticles consisted of polarity led to their competing adsorption on the contact surfaces. However, the lower concentration of nanoparticles was unable to absorb much onto the steel ball surface. In this scenario, the formation of film through tribochemical reaction was considerably unstable which influenced the formation film by the base oil alone that contributed rougher worn surface due to an inhibition of the adsorption of lubricants. Meanwhile, the optimum concentration of nanoparticles might provide higher capability of the nanoparticles to be adsorbed in a greater amount and form more stable films via tribochemical reaction with the steel ball surface, thus contributed smoother worn surface[31)]. A physical film was created over the nanoparticles as the nanoparticles of the lubricant filled the grooves of the contact surfaces. The absorption only occurred when the physical film was constructed under sufficiently high temperature and real contact pressure to initiate a reaction between the materials of lubricant, surface and nanoparticles[32),33)]. Therefore, MJOa2 achieved well-deposition of nanoparticles which associated with decreased friction and provided flatter, flatter and smoother surface.

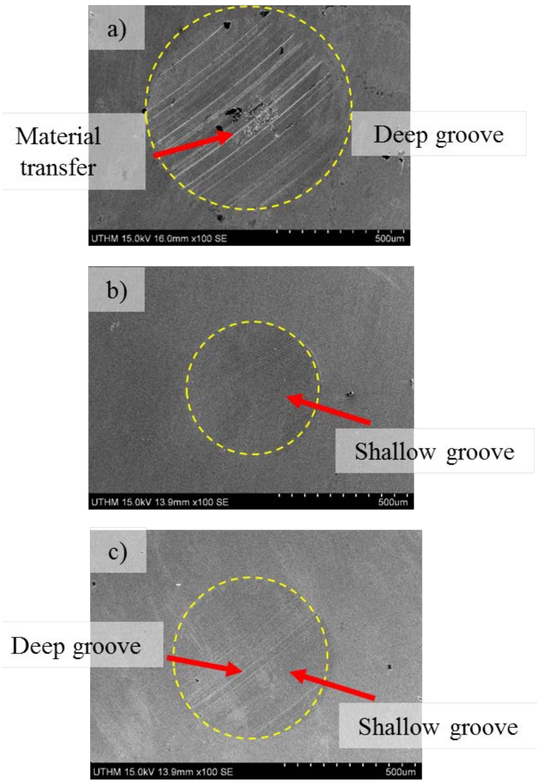

Fig. 5: SEM image of worn surface at the magnification of 100x: a) MJOa1, b) MJOa2 and c) MJOa3

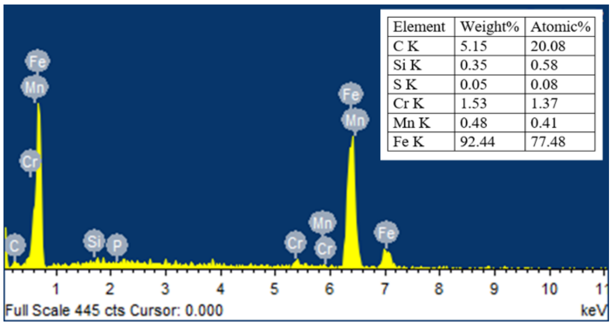

Fig. 6: EDX spectrum at the worn surface for MJO

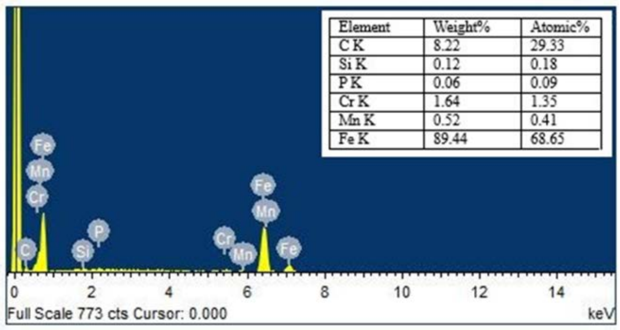

Fig. 7: EDX spectrum at the worn surface for MJOa2

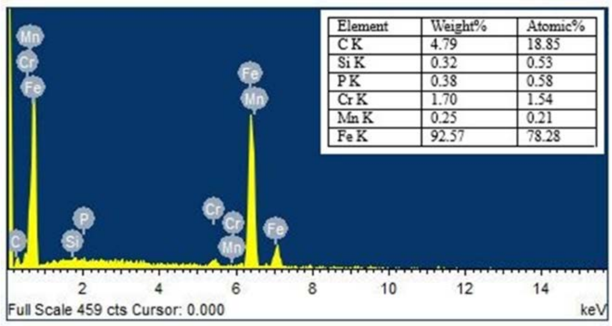

Fig. 8: EDX spectrum at the worn surface for MJOa1

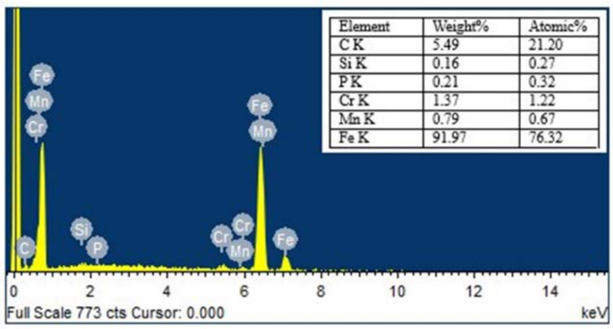

Fig. 9: EDX spectrum at the worn surface for MJOa3

3.3 Surface roughness

Fig. 10 showed the surface roughness (R_a) of oil samples. As can be observed, MJOa2 recorded the smallest R_a value of 0.239 μm among the other oil samples which contributed smoother worn surface. This phenomenon was due to the shallow grooves that were produced at the steel ball surface which led to the lowest surface roughness among the other oil samples clearly demonstrated in Fig

5(b). The activated carbon nanoparticles were welded on the sliding surfaces, thus reacted with the steel ball to create a protective film on the contact surfaces. The nanoparticles functioned similarly as the small bearings on the rubbing surfaces thus reducing the friction and wear [34].

Whereas, MJOa1 contains the low concentration of activated carbon nanoparticles (0.01 wt.%) provided insufficient lubrication film thus increased the unprotected area [25]. Fig. 5(a) shows the exposed area resulted in adhesion wear occurrence which indicated the material transfer at the worn surface. Moreover, the high Ra value of MJOa1 (0.3055µm) was attained due to the insufficient lubrication oil film thus producing a deep groove at the worn surface.

Apparently, Moreover, it can be seen that the agglomerated in 0.05 wt.% activated carbon nanoparticles in the MJOa3 resulted in rougher worn surface thus increased in Ra value of 0.278µm. This phenomenon was explained by the existing of the deep groove as shown in Fig. 5(c). The agglomerated nanoparticles produced poor lubrication oil film thus affected the lubricity performance[35].

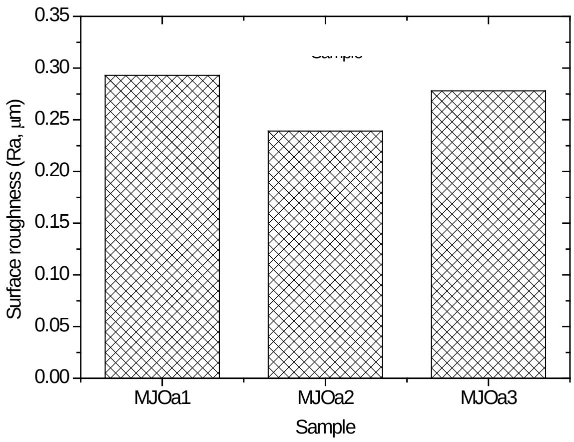

Fig. 10: Surface roughness for all samples

4. Conclusions

According to this present work, it was explained that the nature of the lubricant and concentration of nanoparticles which acted as an additive mainly influenced the tribological characteristics of the nanofluid. MJOa2 (0.025wt.% of activated carbon nanoparticles in MJO based oil) provided the highest improvement of the lubrication performance in terms of COF (0.036), MWSD (457.63 µm), worn surface analysis and surface roughness value (0.2390 µm). This finding was attributed to the adequate concentration of nanoparticles that provided excellent lubrication film layer at the contact surfaces. At this optimum lubricating performance, MJOa2 can be applied in substituting the existing petroleum based-oils as MWF thus emphasizing the element of sustainability in the machining application.

Acknowledgements

This works have initially been accepted and presented at the MERD'20. The authors are grateful for the financial supports from the Ministry of Higher Education Malaysia (MoHE) and University Tun Hussein Onn Malaysia (UTHM) through the Fundamental Research Grant Scheme Vot No. FRGS/1/2018/TK03/UTHM/03/10 (K077) and TIER 1 Research Grant (H176).

References

1) F. Begum, N. Ravi Kumar, and V. Ramachandra Raju, "Experimental Investigations on the Tribological Properties of Jatropha Oil by the Addition of Graphite Nanoparticles," in: S.P.S. Subramonian (Ed.), Recent Adv. Mater. Sci. . Lect. Notes Multidiscip. Ind. Eng., Springer, Singapore, 2019: pp. 645–657. doi:10.1007/978-981-13-7643-6_53.
2) D. Supramono, and J. Edgar, "Characteristics of non-polar bio-oil produced by co-pyrolysis of corn cobs and polypropylene using co2 as carrier gas characteristics of non-polar bio-oil produced by co-pyrolysis of corn cobs and polypropylene using co 2 as carrier gas," *Evergreen*, **6** (*1*) 78–84 (2019).
3) N.K. Maurya, V. Rastogi, and P. Singh, "Experimental and computational investigation on mechanical properties of reinforced additive manufactured component," *Evergreen*, **6** (*3*) 207–214 (2019). doi:10.5109/2349296.
4) I. Jawahir, F. Badurdeen, and K. Rouch, "Innovation in sustainable manufacturing education," *Procedia CIRP*, 9–16 (2013).
5) I. Alhamid, E. Kusrini, D. Supramono, M.I. Alhamid, S. Pranata, D. Wilson, and A. Usman, "Effect of polypropylene plastic waste as co- feeding for production of pyrolysis oil from palm empty fruit bunches effect of polypropylene plastic waste as co-feeding for production of pyrolysis oil from palm empty fruit bunches," *Evergreen*, **6** (*1*) 92–97 (2019).
6) C. Chan, S.W. Tang, N.K. Mohd, W.H. Lim, and S.K. Yeong, "Tribological behavior of biolubricant base stocks and additives," *Renew. Sustain. Energy Rev.*, **93** (*May*) 145–157 (2018). doi:10.1016/j.rser.2018.05.024.
7) Z.F. Zahara, "Economic assessment of the sugarcane-based bio- refinery in indonesia economic assessment of the sugarcane-based bio-refinery in indonesia," *Evergreen*, **5** (*2*) 67–77 (2018).
8) N.H. Arbain, and J. Salimon, "Synthesis and characterization of ester trimethylolpropane based jatropha curcas oil as biolubricant base stocks," *J. Sci. Technol.*, 47–58 (2011).
9) A. Imran, H.H. Masjuki, M.A. Kalam, M. Varman, M. Hasmelidin, K.A.H. Al Mahmud, S.A. Shahir, and M. Habibullah, "Study of friction and wear characteristic of jatropha oil blended lube oil," *Procedia Eng.*, **68**

178–185 (2013). doi:10.1016/j.proeng.2013.12.165.
10) S. Nabilla, S.F. Anisa, K. Zara, and S. Bismo, "Fatty acid methyl ester synthesis in the cold plasma reactor using co2 and steam mixture," *Evergreen*, **7** (*2*) 275–279 (2020). doi:10.5109/4055232.
11) Y.M. Shashidhara, and S.R. Jayaram, "Vegetable oils as a potential cutting fluid—an evolution," *Tribol. Int.*, **43** (*5–6*) 1073–1081 (2010). doi:10.1016/j.triboint.2009.12.065.
12) N. Talib, R.M. Nasir, and E.A. Rahim, "Tribological behaviour of modified jatropha oil by mixing hexagonal boron nitride nanoparticles as a bio-based lubricant for machining processes," *J. Clean. Prod.*, **147** 360–378 (2017). doi:10.1016/j.jclepro.2017.01.086.
13) R. Ruliandini, Nasruddin, and T. Tokumasu, "Assessing hbn nanoparticles stability in trimethylolpropane triester based biolubricants using molecular dynamic simulation," *Evergreen*, **7** (*2*) 234–239 (2020). doi:10.5109/4055225.
14) A.K. Sharma, A.K. Tiwari, and A.R. Dixit, "Characterization of tio2, al2o3 and sio2 nanoparticle based cutting fluids," *Mater. Today Proc.*, **3** (*6*) 1890–1898 (2016). doi:10.1016/j.matpr.2016.04.089.
15) D.W. Kim, H.S. Kil, K. Nakabayashi, S.H. Yoon, and J. Miyawaki, "Improvement of electric conductivity of non-graphitizable carbon material via breaking-down and merging of the microdomains," *Evergreen*, **4** (*1*) 16–20 (2017). doi:10.5109/1808307.
16) M. Sayuti, O. Ming, A.A.D. Sarhan, and M. Hamdi, "Investigation on the morphology of the machined surface in end milling of aerospace al6061-t6 for novel uses of sio2 nanolubrication system," *J. Clean. Prod.*, **66** 655–663 (2014). doi:10.1016/j.jclepro.2013.11.058.
17) N.A.C. Sidik, S. Samion, J. Ghaderian, and M.N.A.W.M. Yazid, "Recent progress on the application of nanofluids in minimum quantity lubrication machining: a review," *Int. J. Heat Mass Transf.*, **108** 79–89 (2017). doi:10.1016/j.ijheatmasstransfer.2016.11.105.
18) S. Hirata, and M. Ohtaki, "Simultaneous enhancement in the electrical conductivity and reduction in the lattice thermal conductivity leading to enhanced thermoelectric zt realized by incorporation of metallic nanoparticles into oxide matrix," *Evergreen*, **7** (*1*) 1–6 (2020). doi:10.5109/2740934.
19) A.K. Sharma, A.K. Tiwari, A.R. Dixit, R.K. Singh, and M. Singh, "Novel uses of alumina/graphene hybrid nanoparticle additives for improved tribological properties of lubricant in turning operation," *Tribol. Int.*, **119** 99–111 (2018). doi:10.1016/j.triboint.2017.10.036.
20) R.K. Singh, A.K. Sharma, A.R. Dixit, A.K. Tiwari, A. Pramanik, and A. Mandal, "Performance evaluation of alumina-graphene hybrid nano-cutting fluid in hard turning," *J. Clean. Prod.*, **162** 830–845 (2017). doi:10.1016/j.jclepro.2017.06.104.
21) S.D. Lakshmi, P.K. Avti, and G. Hegde, "Activated carbon nanoparticles from biowaste as new generation antimicrobial agents: a review," *Nano-Structures and Nano-Objects*, **16** 306–321 (2018). doi:10.1016/j.nanoso.2018.08.001.
22) A.F. Ridassepri, F. Rahmawati, K.R. Heliani, Chairunnisa, J. Miyawaki, and A.T. Wijayanta, "Activated carbon from bagasse and its application for water vapor adsorption," *Evergreen*, **7** (*3*) 409–416 (2020). doi:10.5109/4068621.
23) A. Kaggwa, J.K. Carson, M. Atkins, and M. Walmsley, "The effect of surfactants on viscosity and stability of activated carbon, alumina and copper oxide nanofluids," *Mater. Today Proc.*, **18** 510–519 (2019). doi:10.1016/j.matpr.2019.06.240.
24) N.A.M. Tahir, M.F. Bin Abdollah, R. Hasan, and H. Amiruddin, "The effect of temperature on the tribological properties of palm kernel activated carbon-epoxy composite," *Tribol. Online*, **10** (*6*) 428–433 (2015). doi:10.2474/trol.10.428.
25) N.A. Jamaluddin, N. Talib, and A.S. Abdul Sani, "Tribological analyses of modified jatropha oil with hbn and graphene nanoparticles as an alternative lubricant for machining process," *J. Adv. Res. Fluid Mech. Therm. Sci.*, **76** (*2*) 1–10 (2020). doi:10.37934/arfmts.76.2.110.
26) E.A. Rahim, N. Talib, A.S. Abdul Sani, S. Syahrullail, and Z. Mohid, "Tribological evaluation on various formulation of modified rbd palm olein as sustainable metalworking fluids for machining process," *Mater. Sci. Forum*, **882** 13–17 (2017). doi:10.4028/www.scientific.net/MSF.882.13.
27) A. Kashyap, and A.P. Harsha, "Tribological studies on chemically modified rapeseed oil with cuo and ceo2 nanoparticles," *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.*, **230** (*12*) 1562–1571 (2016). doi:10.1177/1350650116641328.
28) R. Kreivaitis, J. Padgurskas, R. Rukuiza, and I. Prosyc, "Tribology international tribological properties of lubricant additives of fe , cu and co nanoparticles," *Tribol. Int.*, **60** 224–232 (2013). doi:10.1016/j.triboint.2012.10.024.
29) R. Padmini, P. Vamsi Krishna, and G. Krishna Mohana Rao, "Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning aisi 1040 steel," *Tribol. Int.*, **94** 490–501 (2015). doi:10.1016/j.triboint.2015.10.006.
30) N. Talib, N.A. Hamzah, L.W. Kiow, H. Abdullah, A. Saleh, and A. Sahab, "Experiment evaluation hBN nanoparticles in modified Jatropha-based oil as metalworking fluid for machining process," in: 3rd Mytribos Symp., Perlis, 2019: pp. 9–11.
31) X. Ji, Y. Chen, X. Wang, and W. Liu, "Tribological behaviors of novel tri(hydroxymethyl) propane esters containing boron and nitrogen as lubricant additives

in rapeseed oil," *Ind. Lubr. Tribol.*, **64** (*6*) 315–320 (2012). doi:10.1108/00368791211262453.
32) S.M. Alves, B.S. Barros, M.F. Trajano, K.S.B. Ribeiro, and E. Moura, "Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions," *Tribol. Int.*, **65** 28–36 (2013). doi:10.1016/j.triboint.2013.03.027.
33) I.H. Dwirekso, M. Ibadurrohman, and Slamet, "Synthesis of tio2-sio2-cuo nanocomposite material and its activities for self-cleaning," *Evergreen*, **7** (*2*) 285–291 (2020).
34) Q. Zeng, F. Yu, and G. Dong, "Superlubricity behaviors of si3n4/dlc films under pao oil with nano boron nitride additive lubrication," *Surf. Interface Anal.*, **45** (*8*) 1283–1290 (2013). doi:10.1002/sia.5269.
35) B. Li, C. Li, Y. Zhang, Y. Wang, M. Yang, D. Jia, N. Zhang, and Q. Wu, "Effect of the physical properties of different vegetable oil-based nanofluids on mqlc grinding temperature of ni-based alloy," *Int. J. Adv. Manuf. Technol.*, **89** (*9*) 3459–3474 (2016). doi:10.1007/s00170-016-9324-7.