Tribology International 118 (2018) 89–104

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Performance of modified jatropha oil in combination with hexagonal boron nitride particles as a bio-based lubricant for green machining

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ARTICLE INFO

Keywords:
Jatropha oil
Hexagonal boron nitride
Turning
Bio-based metalworking fluid

ABSTRACT

This study evaluates the machining performance of newly developed modified jatropha oils (MJO1, MJO3 and MJO5), both with and without hexagonal boron nitride (hBN) particles (ranging between 0.05 and 0.5 wt%) during turning of AISI 1045 using minimum quantity lubrication (MQL). The experimental results indicated that, viscosity improved with the increase in MJOs molar ratio and hBN concentration. Excellent tribological behaviours is found to correlated with a better machining performance were achieved by MJO5a with 0.05 wt%. The MJO5a sample showed the lowest values of cutting force, cutting temperature and surface roughness, with a prolonged tool life and less tool wear, qualifying itself to be a potential alternative to the synthetic ester, with regard to the environmental concern.

1. Introduction

Metalworking fluids (MWFs) are used as a lubricant in machining processes to increase tool life, enhance machining efficiency and provide excellent surface quality and accuracy by means of both cooling and lubricating at the tool-workpiece interfaces. The combination of petroleum and synthetic-based MWF with various additives negatively affects the environment and human health. Petroleum-based oil is undesirable due to its toxicity and non-biodegradability, incurring a high waste management cost [1]. The complex formulation of MWF generates fungi and bacteria, causing irritation or allergy upon skin contacts [2]. The worst effects due to the long-term usage of mineral and synthetic-based oil are severe dermatitis, acne, asthma, and a variety of cancers. Reeves and Menezes [3] estimated that, 5% of the industrial lubricants are composed of metalworking fluids. However, 85% of the global lubricant consumption is petroleum-based [4]. Lukoil [5] 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. Thus, in order to reduce the usage of petroleum-based oil and to minimize its hazardous impacts on the environment and human, suitable alternatives for this lubricant type have been thoroughly explored by the research community.

Tribological characteristics which include friction, lubrication and wear mechanism between workpiece-tool-chip interfaces play an important role to selecting a proper MWF. Sayuti et al. [6] stated that, external friction occurs between two metal-to-metal contact surfaces which generate one third of the heat. On the other hand, internal friction occurs due to the deformation process in the shear zone, which generates two thirds of the heat. Therefore, MWF is applied at the cutting zone to reduce both external and internal frictions, and heat generated, thus increasing the machining efficiency. The use of MWF during a machining process could improve the surface quality and part accuracy as well as extending the tool life. Vegetable-based oil, solid lubricant, minimum quantity lubrication (MQL), dry machining and cryogenic cooling all have a higher potential to substitute the conventional MWF. Vegetable oil, comprising fatty acids in triglyceride structure, is deemed a suitable substitute for petroleum-based oil, as it offers higher lubricity, lower volatility, higher viscosity index and flash point, and rapid biodegradation [7]. In addition, it possesses a strong adsorption capability which contributes to good lubricating effects, thus resulting in a lower coefficient of friction and a better workpiece surface quality [8]. Ruggiero et al. [9] indicated that, the fatty acids contained in the vegetable oils would stick on the sliding surfaces, thus providing a low coefficient of friction. Furthermore, Lawal et al. [10] compared the turning performance of MWF from palm kernel oil, cotton seed oil and mineral oil on surface roughness and cutting force. The results thus obtained showed that, the palm kernel oil and the cotton seed oil provided higher strength lubrication films that interacted strongly on tool-workpiece interfaces,

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https://doi.org/10.1016/j.triboint.2017.09.016
Received 20 March 2017; Received in revised form 16 August 2017; Accepted 14 September 2017
Available online 18 September 2017
0301-679X/

compared with the mineral oil. A study found that, ester molecules in vegetable oil formed an adsorption layer that reduced wear and friction [11]. Bork et al. [12] studied the performance of jatropha oil, canola oil and semisynthetic oil (mineral oil) as the MWF through a milling process. It was revealed from the study that, jatropha oil showed the best performance, in terms of surface roughness and tool life. They observed that, jatropha oil had the best lubrication properties and cooling rate, thus providing a superior lubricant stability. In addition, Wang et al. [13] reported that, vegetable oil provided better lubrication performances, compared with mineral oil. This was attributed to the presence of various vegetable components having strong molecular structures due to long carbon chains in fatty acid and a higher viscosity index which all contributed to a more stable lubricity. They also described that, peanut, sunflower, and soybean oils with more saturated fatty acids, castor oil with more ricinoleic acids, and palm oil with numerous palmitic acids, all had a great potential to be used as MWF for the machining process.

Despite the advantages mentioned previously, vegetable oil has its weakness in terms of poor thermal and oxidative stability, reflected by poor lubrication performance [11]. To overcome this, Shashidhara and Jayaram [14] initiated various methods to improve vegetable oil, based on reformulation of additives, chemical modification on vegetable-based oil and genetic modification of the oil seed crop. They continued further experiments on comparing modified and unmodified pongam and jatropha oil through a turning process [15]. They found that, the modified jatropha oil exhibited excellent performance of MWF with a reduced cutting force and a better material removal rate, compared to mineral oil and raw jatropha oil. The oil modification process eliminated the C=C bonds in the oil structure, thus improving the thermal and oxidative stability and increasing the lubricant stability from molecular breakdown or molecular rearrangement at elevated temperatures. Talib and Rahim [16] attempted to experimentally study the performance of MJO by an orthogonal cutting process, in comparison with crude jatropha and synthetic oil. It was discovered in their study that, MJO had a superior tribological behaviour, due to long and branched molecular chains in the oil molecule, corresponding to lower friction, thus resulting in low cutting force and low cutting temperature. In their previous study, it was shown that, the lubricant viscosity significantly affected the tribological behaviours [17]. In the same study, the tribological behaviour of the MJO was evaluated by using four ball and tapping torque test. The results thus obtained indicated that, the lubrication film formed from MJO was able to resist friction and wear between two contact surfaces, resulting in smoother surface roughness, a low wear rate and an improved tapping torque efficiency, as compared with synthetic ester and crude jatropha oil.

Recently, it was revealed that, nanoparticles dispersed in MWF effectively reduced friction between two contact surfaces. There are four mechanisms of friction and wear reduction involved in the addition of nanoparticles in the base oil; (1) smaller-size nanoparticles form better protective films when interacting with friction pairs, (2) small spherical nanoparticles cause rolling effect at the contact surfaces that change sliding friction into the combination of sliding and rolling friction, (3) nanoparticles are deposited on the contact surface to form physical tribofilms that compensate for the loss of mass, known as mending effect, (4) nanoparticles can withstand compressive stress concentration due to high contact pressure [18]. Various types of nanoparticles from solid lubricant were added into the oil base, such as, boric acid, hexagonal boron nitride (hBN), molybdenum disulphide (MoS_2) and aluminium oxide (Al_2O_3) to enhance the lubrication efficiency. Zhang et al. [8] indicated that the addition of solid lubricant in oil base increased the viscosity, produced the best lubricating properties and increased heat transfer rate. They found that the addition of MoS_2 in soy bean oil increased the nanoparticle concentrations, thus improving the strength of the adsorption film. Padmini et al. [19] investigated the performance of MoS_2 nanoparticle added into coconut oil, sesame oil and canola oil as MWF for the turning process. The results obtained showed that, the combination of 0.5 wt% of MoS_2 with coconut oil performed better by reducing cutting force, cutting temperature and tool wear. They highlighted that, an excessive amount of nanoparticles in oil base would result in particle agglomeration, resulting in poor lubricant stability. Vasu and Reddy [20] conducted an experiment on a turning process via MQL method, with the addition of Al_2O_3 nanoparticles. The presence of Al_2O_3 in MQL oil contributed to the reduction in cutting force, cutting temperature and tool wear as well as improving workpiece surface due to excellent thermophysical properties of nanofluids. Notably, previous studies reported that hBN offered good anti-wear and anti-friction ability that resulted in low coefficient of friction, reduced wear and improved surface roughness [21,22]. Nguyen et al. [23] performed a linear ball-on-disc type of testing and used the mixture of hBN particle with vegetable based oil (Unist-Coolube2210) as the minimum quantity lubrication (MQL) oil. The results showed reduced wear at the flank and central part of the tool, thus showing great ability to resist friction at the contact surfaces. In a study by Talib et al. [24], an orthogonal cutting test was conducted on modified jatropha oil with hBN particles as MWF. It was shown that, the combination of modified jatropha oil with hBN particles formed a lubrication film that reduced the friction and heat generated at the tool workpiece interfaces, resulting in low cutting force, cutting temperature and chip thickness.

Hence, the present study was inspired by the superior lubrication performances of modified vegetable oil with the addition of solid lubricant particles as the MWF for MQL method. In this study, experiments were carried out at various formulations of modified jatropha oils (MJOs) and various concentrations of hexagonal boron nitride (hBN) particles as the lubricant for the turning process. The samples produced were compared with synthetic ester (SE) and crude jatropha oil (CJO), in terms of cutting force, cutting temperature, surface roughness, tool life and wear mechanism.

2. Experimental details

2.1. Preparation of modified jatropha oils

Previous work by Talib et al. [17] has synthesized MJO-based metalworking fluids containing hexagonal boron nitride (hBN) particles as an additive at various weight concentrations as shown in Table 1. The additive hBN particles were mixed into the MJOs by using a magnetic stirrer at 700 rpm and 60 °C for 30 min. The rheological properties of the lubricant samples were characterized in terms of kinematic viscosity and viscosity index (VI).

2.2. Machinability test

The machinability test was carried out using NC lathe machine under the following machining conditions, as shown in Table 2. The schematic diagram of the experimental set-up is shown in Fig. 1. AISI 1045, where a diameter of 100 mm and length 200 mm was chosen as the workpiece while the chemical compositions used are listed in Table 3. The lubricant

Table 1
Descriptions of lubricant samples [17].

Samples Name	Modified jatropha oil	Additive particles (wt.% of hBN)
MJO1	JME:TMP; 3.1:1	Non-additive
MJO1a	JME:TMP; 3.1:1	0.05
MJO1b	JME:TMP; 3.1:1	0.1
MJO1c	JME:TMP; 3.1:1	0.5
MJO3	JME:TMP; 3.3:1	Non-additive
MJO3a	JME:TMP; 3.3:1	0.05
MJO3b	JME:TMP; 3.3:1	0.1
MJO3c	JME:TMP; 3.3:1	0.5
MJO5	JME:TMP; 3.5:1	Non-additive
MJO5a	JME:TMP; 3.5:1	0.05
MJO5b	JME:TMP; 3.5:1	0.1
MJO5c	JME:TMP; 3.5:1	0.5