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Tribological evaluations of modified RBD palm olein-based lubricants in machining processes

T. Norfazillah [1,*], S. A. S. Amiril [2,*], E. A. Rahim [1], A. C. G. Saiful [2], S. Syahrullail [3]

[1] Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat Johor, MALAYSIA.
[2] Universiti Malaysia Pahang, 26600 Pekan, Pahang, MALAYSIA.
[3] School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, MALAYSIA.
[*]Corresponding author: fazillah@uthm.edu.my

KEYWORD

Hexagonal boron nitride
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RBD Palm Olein
Sustainable machining

ABSTRACT

Metalworking fluids from palm oils are desirable as the alternative to mineral oil that possesses negative effects on humans and environment. The aim of this study is to evaluate the tribological and machining performances of the modified refined, bleached and deodorized (RBD) palm olein-based lubricants (MRPOs) containing low number of additives during the tapping torque and orthogonal cutting processes. The additives that were mixed in the neat MRPO were 0.05 wt. % of hexagonal boron nitride (hBN) particles and 1 wt. % of phosphonium-based ionic liquid (PIL). The rheological properties of these MRPOs are also analyzed. Results showed that high synergistic effects of the additives being blended in the MRPOs have exhibited excellent rheological properties and machining performances with high tapping torque efficiency and low cutting force and temperature in comparison with the commercial synthetic ester-based cutting fluid. They prove to have a great potential to substitute the mineral oil-based metalworking fluids in regard to the increasing demands of environment and health concerns for a sustainable manufacturing activity.

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1.0 INTRODUCTION

Palm oil is an edible and highly biodegradable vegetable oil that has been primarily used for food and cosmetic industry (Sapawe et al., 2014). Recently, the uses of palm oils as the industrial lubricant have been extensively explored as the alternative to the mineral oil-based lubricant. Mineral oil-based lubricants negatively affect people and the environment due to the toxicity of hydrocarbons and are not readily biodegradable and non-renewable.

Palm oils are desirable as metalworking fluids that can contribute towards the development of 'greener' machining operations (Rahim et al., 2017a; Sapawe et al., 2014). Previous research revealed that the use of palm oil-based lubricant indicated better performance in drilling process by promoting a stable thin boundary lubrication film, subsequently reduced the cutting force, cutting temperature and tool wear rate than the synthetic ester (Rahim and Sasahara, 2011). This phenomenon was due to the high viscosity of palm oil that tends to resist the lubricant flow, thus provided effective lubrication at the tool-chip interfaces, reduced the friction and prevented the cutting tool from rapid wear. Additionally, Wang et al. (2016) and Sapawe et al. (2014) also found that palm oil-based lubricants show excellent lubrication properties due to the high content of saturated fatty acids (palmitic acids) that increases the adsorption film strength on the metal surface. The high viscosity of palm oil provided better anti-friction and anti-wear effects, thus reduced the coefficient of friction and specific energy.

PIL and hBN particles were mixed in the MRPO in order to improve their tribological properties. The suitability of ionic liquids (ILs) to be used as lubricant additives has been reported in previous researches whereby excellent physicochemical and tribological characteristics of many room temperature ionic liquids (RTILs) have been tested in various types of base oils including mineral, synthetic and vegetable lubricants (Amiril et al., 2017a; 2017b; 2017c; 2018; Rahim et al., 2016; 2017a; 2017b; 2018). ILs are organic compounds that consist of cations and anions which provide unique characteristics such as low volatility, high thermal stability and highly miscible in organic compounds. The excellent properties of using 1 wt. % of PIL in a vegetable-based lubricant during the tapping torque experiment was reported for example in the study by Amiril et al. (2018). It was reported that excellent lubrication ability and strongly adsorbed lubrication layer on the sliding surfaces were formed which then helps in reducing friction and wear even at high load and temperature working conditions. Several studies have pointed out that PIL is biocompatible, pose low toxicity and fully miscible in many polar base oils (Amiril et al., 2017a; González et al., 2016; Yu et al., 2012; Zhang et al., 2012).

Solid additives like hBN particles are "green" solid powder with high biodegradability, which possess a lamellar crystalline structure with strong covalent bonds among the molecules within each layer, but with weak van der Waals forces between each layer (Reeves et al., 2013; Talib et al. 2017a; Wang et al., 2017). An excellent anti-friction ability of a modified Jatropha oil containing 0.05 wt. % of hBN particles was reported in Talib et al. (2017b). The small quantity of hBN particles contained in the vegetable oil has successfully reduced the friction coefficient of the materials in contacts because of the ability of hBN particles to roll on the sliding metal surfaces, thus reduced the real contact area on the worn surface by filling up the asperity valleys which resulted in low friction and wear in comparison to the surface lubricated with the synthetic ester. In addition, the particles may slide over one another and therefore reduces contact loads which also contributes to the reduction of the friction and wear.

In this study, the tribological performances of vegetable-based lubricants (MRPOs) being blended with hBN and PIL were compared with a commercial synthetic ester (SE, Unicut Jinen MQL) as the reference oil. The additives were mixed into the pure MRPO at a very small quantity, in accordance to the previous successful tribology studies (Amiril et al., 2018; Talib et al., 2017a). Experimental evaluations were conducted on the rheological properties (kinematic viscosity and viscosity index), tapping torque tests (tapping torque efficiency) and orthogonal cutting performances (cutting force and cutting temperature), in order to experimentally evaluate the effectiveness of these types of additives when blended in the modified palm olein-based lubricant.

2.0 EXPERIMENTAL PROCEDURE

2.1 Preparation of lubricant samples

Initially, MRPOs were modified through transesterification process between fatty acid methyl ester and trimethylolpropane (TMP). MRPO was chemically modified via base transesterification processes in two stages. Methanol was used in the first stage with the objective of removing the glycerol content of the vegetable oil. Next, TMP was used in the second stage to produce a biolubricant of TMP-ester (Zulkifli et al., 2014). Lastly, MRPOs were mixed with 0.05 wt. % of hBN particles and 1 wt. % of PIL. The rheological properties were determined through kinematic viscosity and viscosity index. The kinematic viscosity (ASTM D445) was measured using a viscometer at 40 and 100 °C (Ahmed et al., 2014). The correlation between viscosity and temperature was further associated with viscosity index (ASTM D2270). The testing was repeated for three times and the average value was recorded.

2.2 Machining experiments

The tapping test setup was installed and conducted on a CNC machine (Vertical Center Nexus 410-A II) with a dynamometer attached underneath the workpiece sample of a low carbon steel AISI 1215 according to ASTM D5619. The dynamometer was connected to a multichannel amplifier (Kistler 5070) and the tapping torque values were recorded by using a computer (Dynoware software). The complete setup of the tapping torque tests is shown in Figure 1. The workpiece is a cylindrical steel rod of 12 mm height and 37 mm diameter. Each test was conducted by using a new uncoated high speed steel tapping tool of M6 x 1.0 on a fully flooded workpiece of about 20 ml lubricant. The tool rotation speed was set at 400 rpm and feed rate at 1 mm/rev. The torque efficiency of the lubricant samples is determined according to equation (1):

$$\text{Tapping Torque Efficiency} = \frac{\text{Reference Fluid Torque}}{\text{Test Fluid Torque}} x\ 100\% \quad (1)$$

Next, the orthogonal cutting processes were carried out on an NC lathe machine (Alpha Harrison 400). The workpiece material used in this study was a disc of AISI 1045 steel with a diameter and thickness of 150 mm and 2 mm, respectively. The uncoated carbide inserts (SPGN120308) with a positive rake angle of 5° was mounted on a tool holder (CSDPN2525M12) as shown in Figure 2. Both insert and tool holder were fixed on a dynamometer (Kistler 9257BA), which was connected to a multichannel amplifier prior to the cutting force measurements.

The cutting temperature during the machining operation was captured via FLIR T640 thermal infrared camera by placing the camera in the axial direction towards the cutting zone (cf. Figure 2). The maximum side face temperature radiated from the cutting zone at the tool/workpiece interfaces was recorded during the cutting process and the peak temperature was measured as the maximum cutting temperature. The lubricant was supplied through a minimum quantity lubrication (MQL) system with an input air pressure of 0.4MPa. The oil flow rate coming out from the nozzle with an orifice diameter of 2.5 mm was fixed at 0.16 l/h. The nozzle was fixed at an angle of 45° and located at approximately 8 mm from the cutting edge (cf. Figure 2). The experiment was conducted at constant machining parameters (cutting speed, v_c = 350 m/min, feed rate, f_r = 0.12 mm/rev and width of cut, w = 2mm). The nozzle angle and cutting parameters were selected as suggested from the previous studies conducted by Rahim et al., (2017a) and Talib et al., (2017b).

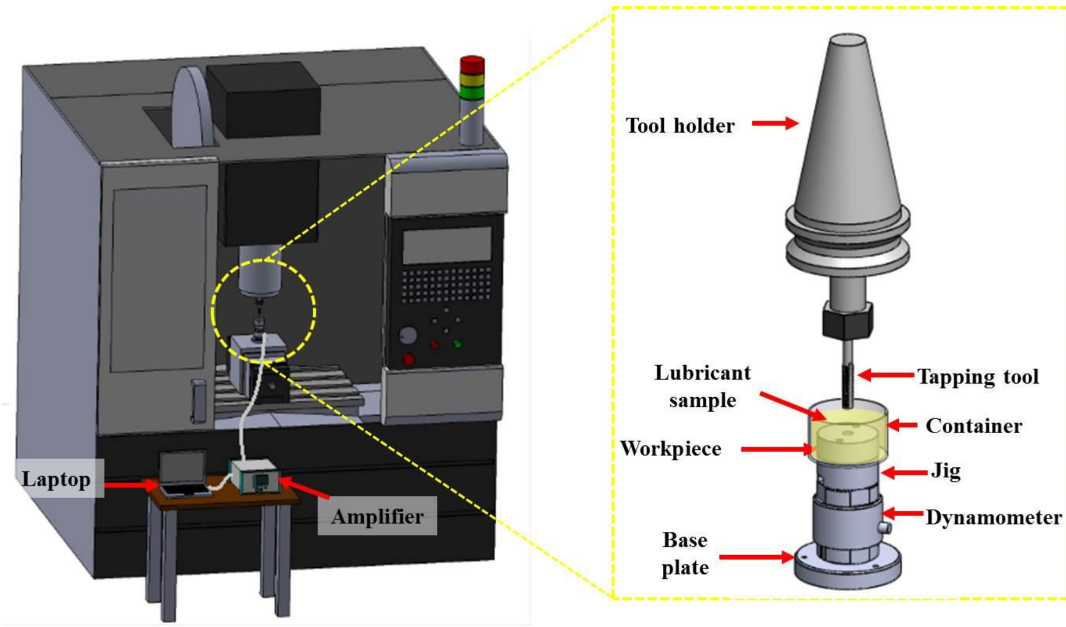

Figure 1: Configuration of the tapping torque setup on the CNC Vertical Center machine.

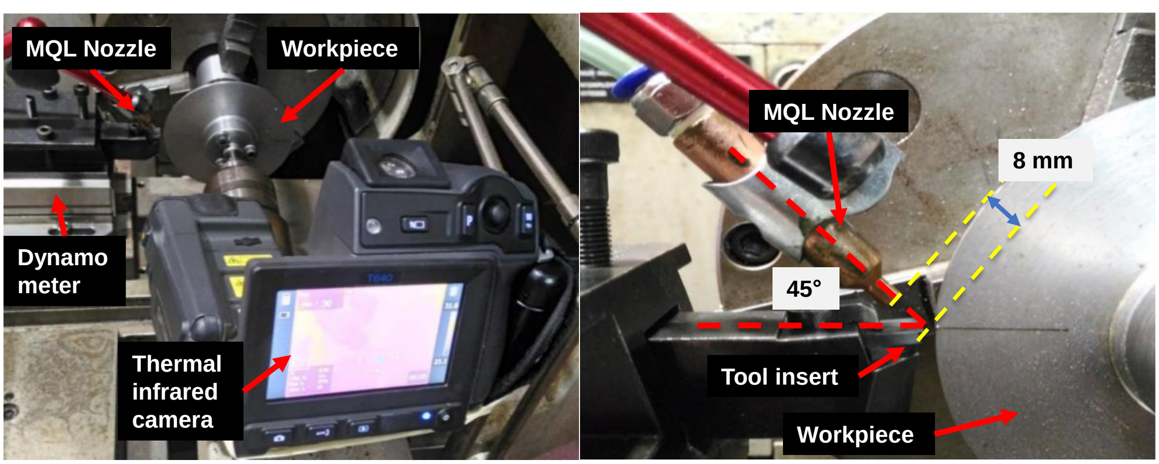

Figure 2: Configuration of the orthogonal cutting setup. Left: Location of thermal camera; Right: Position of MQL nozzle.

3.0 RESULTS AND DISCUSSION

3.1 Rheological properties

Table 1 exhibits the results of kinematic viscosity and viscosity index of all lubricant samples. It was noticed that the kinematic viscosity of the reference oil (SE) at 40 and 100 °C are 21.5 mm^2/s and 5.6 mm^2/s, respectively. The kinematic viscosity value of MRPO+hBN0.05% obtained the highest kinematic viscosity of 23.5 mm^2/s at 40 °C and 6.35 mm^2/s at 100 °C. This scenario was due to the lower thermal expansion ($1x10^{-6}$/°C) of hBN particles, thus improved the viscosity value (Amiril et al., 2017c; Talib et al. 2017a). Meanwhile, MRPO+PIL1% recorded the kinematic viscosity values of 22.21 mm^2/s at 40 °C and 6.25 mm^2/s at 100 °C, an increment of about 3 and 11 %, respectively compared to the SE. Both MRPO-based lubricants demonstrated higher kinematic viscosity than SE, which was influenced by the presence of trimethylolpropane triester in the MRPO that provides good low-temperature properties (Ahmed et al., 2014; Amiril et al., 2017c). In addition, MRPO+PIL1% exhibited the highest viscosity index of 259 amongst all the tested lubricants and this was followed by MRPO+hBN0.05% at 245. The high viscosity index is desirable as it indicates little changes in viscosity across a wide range of operating temperature.

Table 1: The rheological properties

Lubricant	**Kinematic viscosity, ν in mm^2/s**		**Viscosity index, VI**
	40 °C	**100 °C**	
Synthetic Ester (SE)	21.5	5.6	221
MRPO+PIL1%	22.21	6.25	259
MRPO+hBN0.05%	23.50	6.35	245

3.2 Analysis of tapping torque tests

Figure 3 shows the results of tapping torque and tapping efficiency of all lubricant samples after the tapping experiments. Based on ASTM D5619, a higher efficiency number depicts a lower tapping torque against the reference oil, SE. The reduction of wear rate of the tapping tool and a good lubricity performance at the contact surfaces during the tapping process which subsequently minimizes the friction force as well as improves the anti-wear ability of the lubricants are the direct implication of high torque efficiency value, which is posed by tapping system lubricated with the MRPO-based lubricants.

It is clearly shown that SE posed the highest tapping torque of 129 Nm as the reference oil compared to the tested lubricant samples of MRPOs. SE generated poor lubrication effect compared to the MRPO-based lubricants with high friction and wear generated during the tapping tests. From the results, MRPO+PIL1% showed the lowest tapping torque of 121 Nm with a tapping torque efficiency of 7 % higher than SE. MRPO+hBN0.05% presented the second-best result with 6 % increment of torque efficiency than SE with a tapping torque value of 122 Nm. The action of additives lubrication being present in the MRPOs on the tool-workpiece surfaces supported the formation of thick boundary layer that reduces the direct contact between the metal asperities and consequently resulted in low friction force, which subsequently reduces torque and increases lubrication efficiency (Amiril et al., 2017a).

The quick adsorption mechanisms of the additives on the metal surfaces in a relatively short contact time during the material removal process are the most notable characteristics of the selected additives for the application in the metalworking fluids. Additionally, the number of carbon chains in MRPO that contains fatty acids and alkyl groups of additives have successfully increased the viscosity and the load carrying capacity of the lubricant, which is very important for a lubricant to function especially in the boundary lubrication regime compared to the neat SE (Aiman & Syahrullail, 2017).

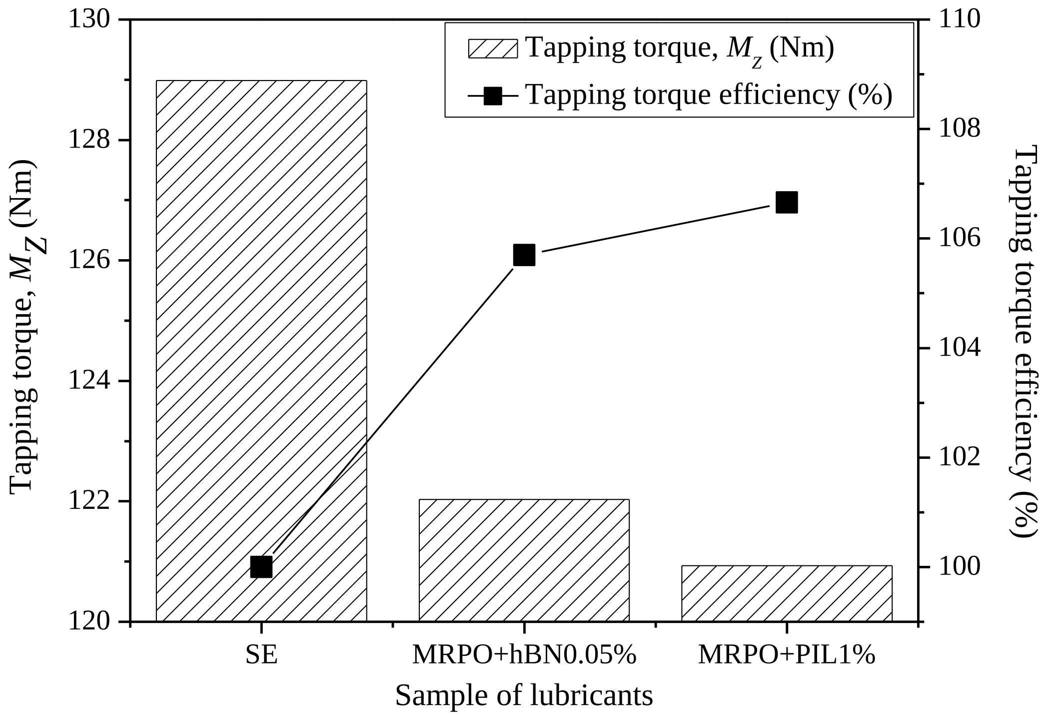

Figure 3: Tapping torque results and tapping efficiency.

3.3 Orthogonal cutting performance

Figure 4 graphically illustrates the cutting force, F_c and the maximum cutting temperature for all lubricant samples after the orthogonal cutting experiments. Principally, cutting forces were highly influenced by the depth of cut, feed rate, cutting speed, and the types of lubricant being applied. In this experiment, the depth of cut, feed and cutting speed were fixed throughout the experimental trials in order to effectively evaluate the significant influence posed by the additive packages being blended into the MRPO in comparison with the benchmark oil (SE).

It can be observed that SE recorded the highest cutting force of 612 N and cutting temperature of 308 °C, respectively. SE generated poor performance compared to the MRPO-based lubricants. From the results, MRPO+PIL1% showed the lowest cutting force of 607 N and cutting temperature of 286 °C, respectively. The lubrication film produced on the tool-chip-workpiece interfaces supported the reduction of the tool-chip contact length which then resulted in low friction. MQL system produces very fine droplets of lubricant with a high contact area on the cutting zones and thus enhances the possibility of the lubricant to reach the whole part of the tool-chip-workpiece interfaces, hence enhances the cooling capacity and increases the heat transfer.

Meanwhile, the cutting force and cutting temperature recorded by MRPO+hBN0.05% was at 610 N and 298 °C. MRPO-based lubricants provided better lubrication film, subsequently reduced the friction at the cutting zone (Amiril et al. 2017c). The addition of 1 wt. % of PIL in MRPO-based lubricant attributed to a high polarity of ester molecule, thus resulted in the increased adsorption rate of the additive molecules on the metal surfaces (Amiril et al. 2018). Furthermore, the presence of hBN particles in the MRPO provided a thin lubrication film that allows the particles to change from sliding friction to the rolling friction, thus reduces the force and heat generation (Kannan & Rameshbabu, 2018).

During the machining process, the power consumed for plastic deformation is largely converted into heat near the tool cutting edge through friction between tool and workpiece. It is anticipated that the heat flux in the shearing zone developed gradually faster due to the tool-chip friction with the high cutting speed which resulted in increased cutting temperature. The heat produced at the cutting zone was distributed at the three major deformation zones during the chip formation processes. The generation of heat was also reported to be reduced by the prevention of direct contact of the metal asperities through the formation of tenacious lubrication layer attributed to the oil viscosity. Therefore, it is expected that a high VI of the MRPO+PIL1% would result in reduced loss of oil volume from emission and vaporization (Amiril et al., 2017a). Significantly, this lubricant sample has a tendency to provide sufficient lubrication characteristic at the cutting zones.

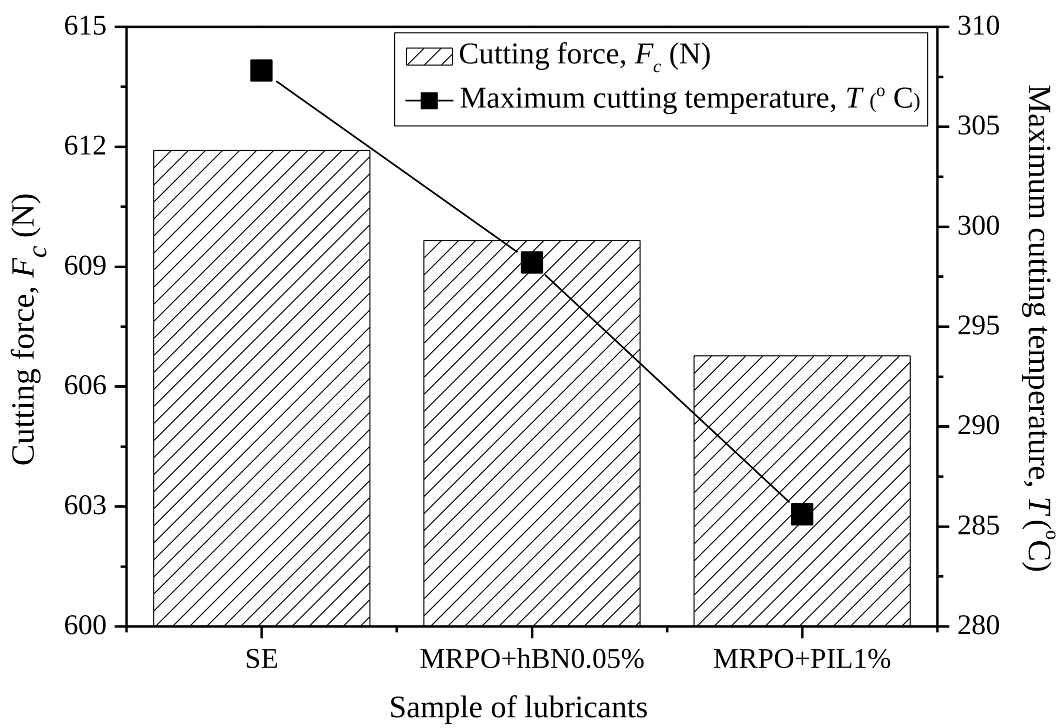

Figure 4: The cutting force and the maximum cutting temperature for all lubricant samples.

4.0 CONCLUSIONS

The presence of polyol ester, fatty acids, and additives in the MRPO plays a significant role at the cutting zone during the tapping torque and orthogonal machining experiments in terms of friction and wear reduction compared to the neat synthetic ester.

The effectiveness of using the MRPO-based lubricants during the machining processes is proven to be higher by the addition of the small volume of additives (1 wt. % of PIL and 0.05 wt. % of hBN). A good synergistic effect of the additives being mixed into the base oil, MRPO was presented by the improved machining performances. The addition of sufficient amount of additives in the MRPO presented greater physical and superior lubrication properties with reduced cutting force, cutting temperature and friction coefficient in comparison with the SE.

From these observations, it can be concluded that the MRPO-based lubricants provided excellent lubrication film which reflected on the tribological performance of the contact surfaces. Thus, both MRPO+hBN0.05% and MRPO+PIL1% have high potential to substitute the mineral oils as the metalworking fluid for machining process regarding environment and health quality.

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