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# Heat transfer and lubrication performance of palm oil-$Al_2O_3$ nanofluid compared to traditional cutting fluid

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**ABSTRACT**: The heat transfer and lubrication ability of palm oil-based $Al_2O_3$ nanofluid were investigated experimentally. Palm oil-$Al_2O_3$ nanofluids with different sizes and concentrations of nanoparticles were prepared by a two-step method. Through analysis of its specific experimental performance in the process of milling, it was found that both the heat transfer and lubrication ability of $Al_2O_3$ nanofluid were superior to those of traditional cutting fluid. Moreover, the temperature difference of the workpiece was more than 10 °C when the spindle speed was 1000 rpm, and the average deviations of three-dimension cutting forces were about 8%, 10% and 13%, respectively. Furthermore, the heat transfer and lubrication ability varied with the size and concentration of nanoparticles in the nanofluid. Under the same operation conditions, the milling process with 1.0 vol% $Al_2O_3$ nanofluid bearing 20 nm-nanoparticles showed the best heat transfer and lubrication performance.

**KEYWORDS**: cutting fluid, $Al_2O_3$ nanofluid, lubrication, heat transfer

## INTRODUCTION

As an important part of metal cutting process system, cutting fluid is widely used in high-precision turning and milling processes. However, the traditional cutting fluid consists of mineral oil, which is degreasing and irritating. Hence, it can cause damage to the skin and eyes of operators with long time contact. Moreover, a large amount of heat is released in the cutting process, and the volatilization of cutting fluid can cause respiratory diseases in workers. The traditional cutting fluid also has the drawbacks of difficult degradation and high recovery cost [1–3]. It has been pointed out that the cost of treating the waste liquid of cutting fluid and discharging is quite high, and accounts for 54% of the cost of cutting fluid [4]. Bork [5] compared the lubrication property of vegetable oil and mineral oil through experiments and found that vegetable oil is better than mineral oil in turning aluminum alloy. Cetin et al [6] evaluated the performance of four different vegetable oils and two types of commercial semi-synthetic and mineral oils in terms of reducing surface roughness. The results showed that sunflower and canola oils perform better than others as minimum quantity lubrication (MQL) base oil. It was also reported that when used vegetable and mineral oil-based cutting fluids in turning AISI 4340 steel, both palm oil- and cottonseed oil-based cutting fluids have better heat conductivity and environment-friendly properties [7]. When the lubrication properties of the wheel/workpiece interface in MQL grinding using different types of vegetable oils were investigated, it was found that castor oil and palm oil have the best lubrication properties [8]. It has been reported that nanofluids have excellent heat transfer and lubrication performance [9]. If they are used in the milling process of Numerical Control (NC) machine tools, they can play a major role in heat dissipation. Moreover, nanoparticles can improve the lubrication ability of the cutting area due to their wear resistance. Therefore, nanofluids are a promising choice to replace the traditional cutting fluid.

A new method to prepare a polymer-based multi-walled carbon nanotube (MWNT) composite was proposed, the composites were found to exhibit excellent light absorption properties and heat transfer coefficient [10]. Kurniawan et al [11] prepared three pentanal-derived acetal esters following the principles of green chemistry using a sonochemical method and found that octanoate was the most suitable novel biolubricant to replace the current commercial lubricants. Vaibhav et al [12] studied the influence of hybrid nanocutting fluid in turning of Titanium alloy grade 5, they found that it significantly reduced the cutting force and surface roughness compared to pure coconut oil by 21.19% and 18.9%, respectively. The addition of different nanoparticles into cutting fluid in different weight percentages to form nanofluids was studied [13]. John [14] evaluated the performance of several nanoparticles in oil and water based cutting fluids in machining processes and discussed the enhancement of the colling effect. The addition of nano materials along with the cutting fluid or the coolant led to the increase in the same amount of heat removed and thus increased tool life [15]. When nanoparticle-enriched cutting fluid was used in a turning process, the inclusion of silver nanoparticles greatly reduced the cutting force, temperature of the tool, and surface workpiece roughness [16]. Uma et al [17] developed an eco-friendly cutting fluid to promote cleaner and more efficient MQL machining and found that the thermal conductivity and viscosity increased with the mass fraction of nanoparticles. Alumina nanofluid was evaluated as a thermo-fluid with different volume fractions to observe the heat transfer enhancement under several conditions [18–20]. In the study of the influence of MQL with $Al_2O_3$ nanoparticles on the milling processes of AISID3 steel, it was found that surface roughness decreased by approximately 0.5 mm and improved by nearly 25% [21]. The maximum enhancement in heat transfer coefficient was 42.1% when the volumetric concentration of $Al_2O_3$ nanofluid was 0.5% [22]. Mao et al [23] compared the lubrication performance of four kinds of grinding methods in the surface grinding of AISI52100 steel. The results showed that $Al_2O_3$ nanofluid provided the lowest grinding force and temperature but the best workpiece surface quality.

As discussed above, various studies have been conducted to solve the environmental problems caused by traditional cutting fluid, and there has been considerable research on nanofluid-based cutting fluid and vegetable oil-based cutting fluid. However, there has been no report yet on the experimental evaluation of both heat transfer and lubrication property of palm oil-$Al_2O_3$ nanofluid as cutting fluid. A previous study reported that [8], among various vegetable oils, palm oil shows the best lubrication property and is relatively cheaper than castor oil in China. $Al_2O_3$ nanofluid also has the advantages of low price and high heat transfer coefficient. This work aims to study the lubrication property and heat transfer performance of palm oil-$Al_2O_3$ nanofluid used as cutting fluid in an actual milling process. Experimental evaluations were conducted on the milling force, surface morphology and temperature under different operating conditions.

## MATERIALS AND METHODS

$Al_2O_3$ nanoparticles are among the most commonly used nanoparticles in nanofluids because they are relatively inexpensive. They are also known to provide good heat transfer performance when used in heating devices. In this study, $Al_2O_3$ nanofluid was prepared by a two-step method for application as the cutting fluid in milling process. A precise mass of nanoparticles for a given concentration of nanofluid was mixed with palm oil. A dispersion stabilizer (gum arabic) was then added to the mixture. The resulting mixture was stirred for 3 h using a magnetic stirring apparatus and oscillated for 8 h using an ultrasonic oscillation apparatus.

In the preparation of nanofluids, the volume of nanoparticles is usually difficult to determine accurately. Hence, the volume fraction of particles in nanofluids can be calculated by the mass percentage of particles, according to the following equation (1).

$$\phi = \frac{\rho_f \phi_m}{\rho_f \phi_m + \rho_d (1-\phi_m)} \tag{1}$$

where $\rho_f$ and $\rho_d$ are densities of nanoparticles and base fluid, respectively, $\phi$ and $\phi_m$ are the volume fraction (vol%) and mass fraction (wt%) of total nanoparticles in nanofluids, respectively.

## EXPERIMENT DESIGN

In this paper, the lubrication ability and heat transfer performance of $Al_2O_3$ nanofluid were experimentally studied, taking milling force and surface temperature of the tool and workpiece as evaluation parameters. The effects of the size and concentration of different kinds of nanoparticles on the experimental results were also studied.

The complete experimental system is shown in Fig. 1. Main devices include computer numerical control (CNC) machine, piezoelectric dynamometer, roughness meter, scanning electron microscope (SEM), lubrication device and infrared thermometer. In the process of the experiment, piezoelectric dynamometer was used to measure and record the three-dimensional milling forces. The sampling frequency of milling force measurement was 15 000 Hz. Considering the accidental factors of the experiment, two sets of experimental data of milling force image and milling force were measured to ensure the reliability of the data. The roughness meter was used to measure and record the surface roughness of the machined workpiece. To ensure reliability, the data were measured at four places and recorded under each working condition. SEM was used to observe the micro morphology of chip surface to judge whether there are cracks, shear slippage or wrinkles, and to comprehensively analyze the lubrication ability. Furthermore, an infrared thermometer was used to measure the temperature of the workpiece surface and the tool to analyze the comprehensive heat transfer ability of the nanofluid/cutting fluid.

## RESULTS AND DISCUSSION

In this study, nanoparticles of three different diameters (20, 50, and 100 nm) were adopted for preparation of nanofluids. Fig. 2 shows SEM images of the three particle sizes of $Al_2O_3$. The particles were spherical or near spherical and most of them had uniform size, as shown in Fig. 2. The nanoparticles were also effectively dispersed in the nanofluid. In addition, three different concentrations of the nanofluid were mixed (0.5 vol%, 1.0 vol%, and 1.5 vol%) in order to investigate the effects of nanofluid concentration on the

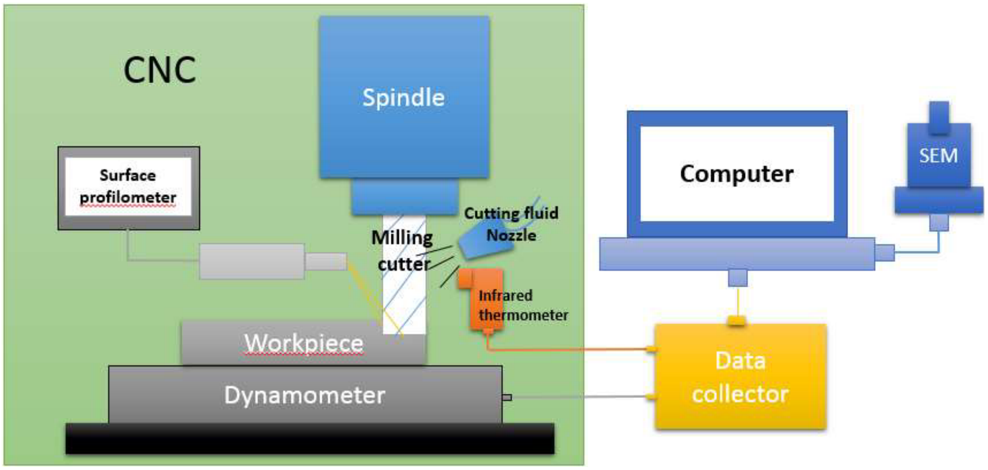


**Fig. 1** Schematic of experiment system.

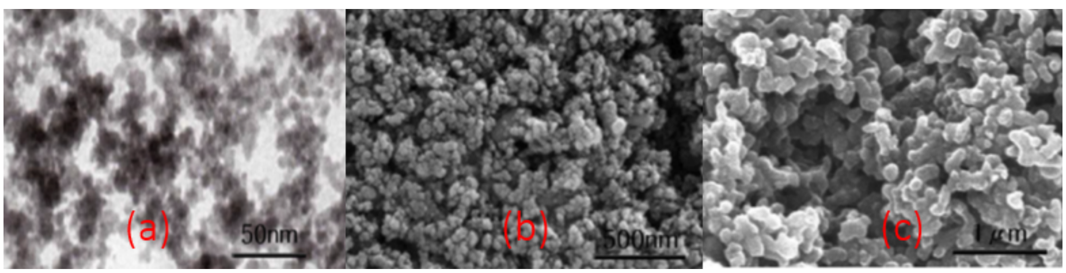


**Fig. 2** SEM micrographs of $Al_2O_3$ nanoparticles with diameter of (a) 20 nm, (b) 50 nm, (c) 100 nm.

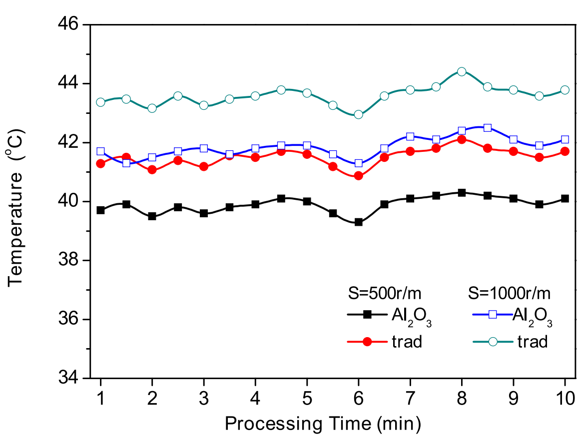


**Fig. 3** Temperature of the workpiece surface using two kinds of cutting fluids.

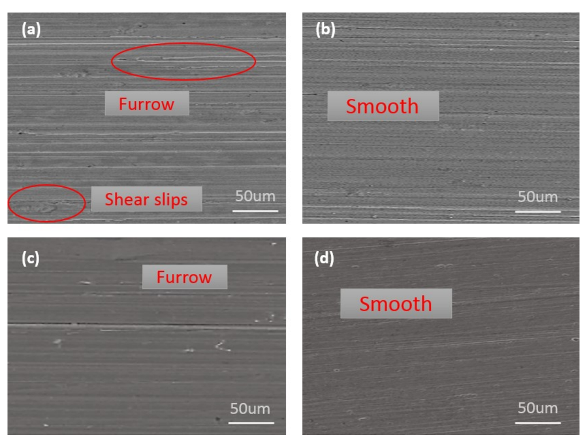


**Fig. 4** SEM images under different working conditions (a) S=500 rpm, Traditional cutting fluid (b) S=500 rpm, $Al_2O_3$ nanofluid (c) S=1000 rpm, Traditional cutting fluid (d) S=1000 rpm, $Al_2O_3$ nanofluid.

lubrication and heat transfer performance. Nanofluid samples with three different concentrations and three nanoparticle sizes were prepared and used as cutting fluids for the experiments.

In order to investigate and compare the heat transfer performance of the nanofluid and traditional cutting fluid, an infrared thermometer was used to monitor the temperature of the tool and the surface of the workpiece. Under the same operation conditions, two groups of experiments were performed. In the first group, the speed of the spindle was 500 rpm, while it was 1000 rpm in the second group. As shown in Fig. 3, the $Al_2O_3$ nanofluid at a concentration of 1.0 vol% and nanoparticle size of 20 nm showed much better heat transfer performance than traditional cutting fluid. The temperatures of the tool and workpiece are shown in Fig. 4. The results show that the temperature of the workpiece surface for both $Al_2O_3$ nanofluid and traditional cutting fluid varied with time, which was because the milling program was not constant and the tool path was always changing. It can also be seen from Fig. 3 that the temperature was proportional to the spindle speed under the same milling condition. Compared to the traditional cutting fluid, the curve of $Al_2O_3$ nanofluid showed better stability during the milling time. The differences between the two kinds of fluids varied from 1.6 °C to 2.2 °C in the first group and from 1.8 °C to 2.6 °C in the second group. This would be beneficial to the protection of the work piece and tool. The above results proved that the $Al_2O_3$ nanofluid can fully meet the cooling capacity requirements in machining.

This study evaluated two groups with different spindle speeds, as shown in Fig. 4a. When the speed of the spindle was 500 rpm, several shear slips and furrows were observed, which were caused by the adiabatic shear instability in the chip. These defects will rub with the rake face of the tool intermittently and cause the cutting system to produce high frequency vibration, thus affecting the surface quality of the workpiece. At the same time, the surface was rough, and the phenomenon of ploughing was obvious. In contrast, with $Al_2O_3$ nanofluid under the same conditions (Fig. 4b), the furrow on the surface was shallow, which indicated that the nanofluid had a good protective effect on the surface quality. The two kinds of fluid showed the same behavior under the spindle speed of 1000 rpm, as shown in Fig. 4c. There were several deep furrows in the workpiece surface, but it was better than that under the condition of 500 rpm, and the surface in Fig. 4d was smooth.

Fig. 5 shows the comparison results of three-dimensional milling force between traditional cutting fluid and $Al_2O_3$ nanofluid at a concentration of 1.0 vol% and nanoparticle size of 20 nm. This study also separated the experiments into two groups by different spindle speeds, and the other operation conditions were the same. The results exhibited a similar trend as that of previous studies [24, 25], which indicated that nanoparticles significantly improved the lubrication performance of the cutting area and reduced milling forces due to their antifriction effect. When the speed of the spindle was 500 rpm and $Al_2O_3$ nanofluid was used, it is found from Fig. 5a that the milling force reduced significantly, especially in Z-axis. The maximum deviation occurred at 7 s. The milling force of $Al_2O_3$ nanofluid was 116 N while that of traditional cutting fluid was 135 N, and the average deviations of X, Y and Z dimensions were about 8%, 10% and

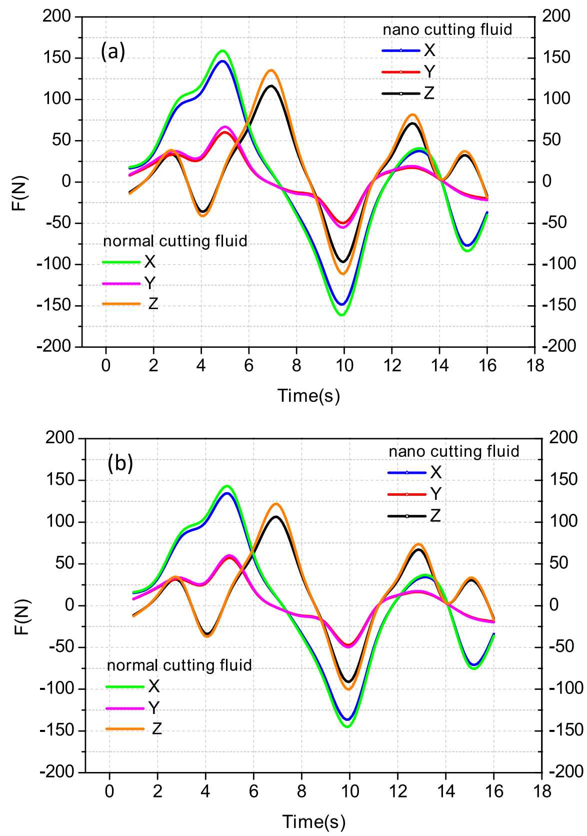


**Fig. 5** Comparison of the results of lubrication performance of $Al_2O_3$ nanofluid and traditional cutting fluid (a) S=500 rpm, (b) S=1000 rpm.

13%, respectively. When the speed of the spindle was 1000 rpm, similar results were obtained, as seen from Fig. 5b. The maximum deviation occurred in the Z-axis at 7 s. The milling force of $Al_2O_3$ nanofluid was 106 N while that of traditional cutting fluid was 121 N, and the average deviations of X, Y and Z dimensions were about 6%, 5% and 9%, respectively. These results indicate that the $Al_2O_3$ nanofluid (1.0 vol%, 20 nm) had better lubrication ability than traditional cutting fluid and can meet the requirement of milling process.

To investigate the heat transfer performance and lubrication ability in the milling process as a function of the volume concentration and nanoparticle size of nanofluid, the temperature difference and milling force between traditional cutting fluid and $Al_2O_3$ nanofluid were evaluated as a function of the volume concentration. Fig. 6 shows the comparison results for various volume concentrations of the $Al_2O_3$ nanofluid bearing 20 nm-nanoparticles. It can be seen that the heat transfer and lubrication ability did not increase monotonously with the increase in concentration. The average temperatures of the workpiece surface for 0.5 vol%, 1.0 vol% and 1.5 vol% nanofluids under the stan-

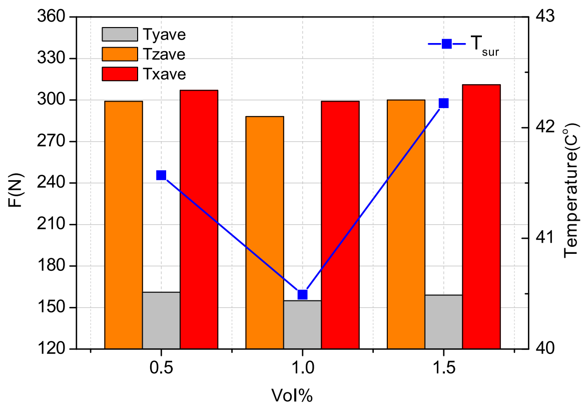


**Fig. 6** Comparison of different concentrations of $Al_2O_3$ nanofluid.

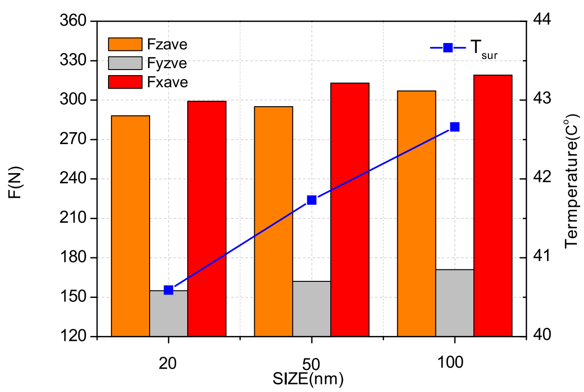


**Fig. 7** Comparison of different nanoparticle sizes of $Al_2O_3$ nanofluid.

dard conditions (S=500 rpm, F=100 mm/min) were 41.57 °C, 40.59 °C and 42.21 °C, respectively. This result was similar to that of $Al_2O_3$ nanofluid applied in other engineering fields [26, 27]. The average milling forces of these samples are also shown in Fig. 6. The X-axis average milling force of 1.0 vol% $Al_2O_3$ nanofluid was 299 N, while the corresponding values for 0.5 vol% and 1.5% nanofluids were 307 N and 311 N, respectively. The same situation was observed for Y-axis and Z-axis. The nanofluid with 1.0 vol% concentration showed the smallest milling force, which had a positive effect on the protection of the tool and spindle.

In order to investigate the influence of the size of nanoparticles, three kinds of nanofluids (20 nm, 50 nm, 100 nm) were prepared in this work, having the same volume concentration (1.0 vol%). It can be seen from Fig. 7 that both lubrication ability and heat transfer performance varied significantly with the size of nanoparticles. Under the same operation conditions (S=500 rpm, F=100 mm/min), the average temperatures of the workpiece surface were 40.59 °C, 41.73 °C and 42.66 °C for nanofluids bearing 20 nm, 50 nm and 100 nm nanoparticles, respectively. Furthermore, the nanofluid with 20 nm nanoparticles showed the smallest X-axis average milling force of 299 N, which was 4.7% and 4% smaller than that of 50 nm and 100 nm nanoparticles, respectively. This was similar to the results of Y-axis and Z-axis; their average milling forces were 155 N and 288 N, 7.7% and 10.2% smaller than those of 50 nm and about 4.5% and 4.3% smaller than those of 100 nm.

## CONCLUSION

In this study, palm oil-$Al_2O_3$ nanofluid was applied as cutting fluid in a CNC machine, and its heat transfer and lubrication characteristics were investigated experimentally. In addition, the size and concentration of nanoparticles were also considered as important factors, which had significant influences on the results.

Overall, according to the experimental results, palm oil-$Al_2O_3$ nanofluid showed better thermal and lubrication performance than traditional cutting fluid. In particular, $Al_2O_3$ nanofluid with 1.0 vol% and 20 nm-nanoparticles showed the best heat transfer and lubrication performance. As the diameters of nanoparticles in this study were all larger than 10 nm, they could be easily recovered by means of ultracentrifugation. Therefore, compared to the traditional cutting fluid which contains chemical additives and mineral oil, the proposed palm oil-$Al_2O_3$ nanofluid is more environment-friendly and safe for humans.

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