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Tribological Performance of Different Concentrations of Al_2O_3 Nanofluids on Minimum Quantity Lubrication Milling

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Abstract

Nanofluid minimum quantity lubrication (NMQL) is a green processing technology. Cottonseed oil is suitable as base oil because of excellent lubrication performance, low freezing temperature, and high yield. Al_2O_3 nanoparticles improve not only the heat transfer capacity but also the lubrication performance. The physical and chemical properties of nanofluid change when Al_2O_3 nanoparticles are added. However, the effects of the concentration of nanofluid on lubrication performance remain unknown. Furthermore, the mechanisms of interaction between Al_2O_3 nanoparticles and cottonseed oil are unclear. In this research, nanofluid is prepared by adding different mass concentrations of Al_2O_3 nanoparticles (0, 0.2%, 0.5%, 1%, 1.5%, and 2% wt) to cottonseed oil during minimum quantity lubrication (MQL) milling 45 steel. The tribological properties of nanofluid with different concentrations at the tool/workpiece interface are studied through macro-evaluation parameters (milling force, specific energy) and micro-evaluation parameters (surface roughness, micro morphology, contact angle). The result show that the specific energy is at the minimum (114 J/mm^3), and the roughness value is the lowest (1.63 μm) when the concentration is 0.5 wt%. The surfaces of the chip and workpiece are the smoothest, and the contact angle is the lowest, indicating that the tribological properties are the best under 0.5 wt%. This research investigates the intercoupling mechanisms of Al_2O_3 nanoparticles and cottonseed base oil, and acquires the optimal Al_2O_3 nanofluid concentration to receive satisfactory tribological properties.

Keywords Milling, Al_2O_3 nanofluid, Minimum quantity lubrication (MQL), Surface micromorphology

1 Introduction

Milling, an important processing method, has been widely used in mold processing, automobile manufacturing, aerospace, and other industries because it leads to a high material removal rate and good surface quality [1]. Grade 45 steel is a common medium-carbon steel in mechanical processing and is applied in many industrial fields due to its excellent performance, high strength, plasticity and toughness, and rich reserves [2]. In milling Grade 45 steel, friction and thermal damages will appear due to high temperature and high pressure in the cutting area, thereby reducing the wear resistance, fatigue, and service life of mechanical parts [3]. Therefore, lubrication and cooling are essential in the milling area [4]. The conventional method is pouring a large amount of cutting fluid into the zone area to remove the generated heat and reduce the wear during machining [5]. However, extensive use of cutting fluid will significantly increase the production cost [6–8]. Moreover, cutting fluid causes serious

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pollution to the environment and endangers human health [9, 10]. Milling must comply with current trends and meet the need for a green process to achieve sustainable development [11, 12].

Minimum-quantity lubrication (MQL) is an effective and green method, also known as near-dry machining [13] or micro-lubrication [14], which has been used to improve the machining performances [15]. It only consumes a small amount of cutting fluid (6–100 mL/h) combined with 4–6 bar compressed gas in the machining area [16]. High-pressure airflow plays a role in cooling and chip removal, and the cutting fluid adheres to the machining surface of the workpiece, forming a protective film to exert lubrication effect [17]. Fluid based on vegetable oils is becoming popular because of its advantages of non-toxicity [18], good biodegradability [19], high flash point [20], renewability, and affordability [21, 22].

Araújo et al. [23] evaluated and compared edible vegetable oils (cottonseed, babassu nut, canola, sunflower, corn, and soybean) in milling AISI 1045 steel with vegetable-based fluid LB2000 (not edible). Cottonseed and canola showed promising results in cooling and lubrication. Bai et al. [24] selected five typical vegetable oils (cottonseed, palm, castor, soybean, and peanut) as base oil to experimentally evaluate the lubrication performance of the tool–workpiece interface compared with synthetic cutting fluid. Palm and cottonseed oils with high contents of saturated fatty acids were more suitable as MQL base oils.

However, very little amount of liquid may not perform completely the cooling task due to the evaporation of this liquid immediately with high temperature [25]. The heat exchange capability of solid is superior to that of liquid. Adding nanoparticles into cutting fluid in the so-called nanofluid MQL process increases the heat exchange capability of the liquid and imparts a cooling effect [26, 27]. Vast studies have been concentrated on the nanofluid assisted machining to significantly improve the machining performance [28–30].

Different nanoparticles have varying composition and influence on the lubrication and cooling performance. The hexagonal molecular structure of Al_2O_3 nanoparticles confers them with excellent hardness, heat resistance, and abrasion resistance. Spherical Al_2O_3 nanoparticles converts sliding friction into rolling friction between friction pairs, thereby improving the bearing capacity of lubricating oil [31]. Mao et al. [32] studied the nanofluid (Al_2O_3/water) MQL grinding of hardened AISI 52100 steel. They concluded that adding Al_2O_3 nanoparticles into deionized water decreased the friction coefficient and grinding force. Setti et al. [33] extended the research by comparing the performance of Al_2O_3/water and CuO/water nanofluids during grinding of Ti–6Al–4V. The results revealed that MQL with Al_2O_3 nanofluid significantly reduced the friction coefficient compared with CuO nanofluid under dry and wet environments. Behera et al. [34] determined the effect Al_2O_3 and silver (Ag) nanofluids in MQCL on converting nickel alloy. The lowest magnitude of cutting force was obtained when using Al_2O_3 nanofluids. Al_2O_3 had good lubrication performance in mechanical processing. Gupta et al. [35] evaluated the performance of three nanofluids (Al_2O_3, MoS_2, and graphite) for MQL in turning Ti alloy by using CBN tool in terms of cutting force, cutting temperature, and surface roughness. The graphite nanofluid showed the best features, that is, it decreased the cutting force and temperature and improved the surface roughness.

Mandal et al. [36] investigated the effect of three volume fractions of Al_2O_3 nanoparticles (1%, 3%, and 5% vol) during MQL grinding of hardened AISI 52100 steel. The nanofluid with higher concentration of nanoparticles contributed lower grinding force, grinding temperature, and surface roughness than that with lower concentrations of nanoparticles. Hadi et al. [37] studied the effects of Al_2O_3 nanoparticles with volume fractions of 1% and 2% when milling AISI D3 steel. The results showed that the surface roughness improved by 15% and 25%, respectively, compared with that of pure MQL. These studies reported that the surface finish of the workpieces increased with increasing concentration of nanoparticles. However, Wang et al. [38] obtained a different result after conducting an experimental study on the tribological properties of grinding Ni-based alloy. In the study, a nanofluid, as lubricating fluid, was prepared by adding 0.5 vol% to 4.0 vol% Al_2O_3 nanoparticles to palm oil. The overall tribological performance was the best when the concentration of the nanofluid was 2 vol%. This finding indicated that higher concentrations do not necessarily lead to better tribological performance. Rahman et al. [39] obtained a similar conclusion after a comprehensive study of 18 nanofluids during turning of Ti-6Al-4V ELI. Nanofluids were prepared by adding three different nanoparticles (Al_2O_3, MoS_2, and rutile TiO_2) to vegetable oils (canola and extra virgin olive oils) respectively, at three different concentrations (0.5%, 2%, and 4% vol). They revealed that 0.5 vol% Al_2O_3–canola nanofluid provided a superior surface finish.

Although Al_2O_3 nanofluid has been discussed in previous literature, existing researches have not systematically analyzed the influence of different mass concentrations of nanofluids on face milling. In particular, no research has investigated the lubrication performance of cottonseed-based Al_2O_3 nanofluid with different concentrations. In China, cottonseed oil is suitable as base oil because it has excellent lubrication performance, low freezing temperature, and high yield. Therefore, an analysis is necessary to explore the interation and discover the mechanisms of cottonseed oil and Al_2O_3 nanoparticles with different mass concentrations. An experiment was conducted on nanofluid MQL milling of 45 steel with cottonseed-based oil under different mass concentrations of Al_2O_3 (0, 0.2%, 0.5%, 1%, 1.5%, and 2% wt). The lubrication performance of the tool/workpiece interface was experimentally evaluated using the following parameters: the milling force, surface roughness, and micromorphology of the workpiece and chip surface. Furthermore, the viscosity and contact angle of different concentrations of nanoparticles were analyzed. This research will promote the optimum concentration of Al_2O_3 nanofluid and its tribological characteristics.

2 Materials and Methods

2.1 Experimental Setup

The experiment was performed at the machining center of Dema ML1060B with dimensions of 3200 mm × 2450 mm × 2000 mm (L × W × H). The main technical parameters are as follows: spindle power of 11 kW, a maximum speed of 8000 r/min, worktable driving motor power of 5 kW, cutting range of 1000 mm × 600 mm, and cutting feed rate of 10000 mm/min. MQL device KS-2106 was used to convey the lubricant. Milling force was measured by tridirectional piezoelectric dynamometer JR-YDCL-III I05B. The surface roughness of the workpiece was measured by contact pointer measuring instrument SC6C. DV2TLV was used to measure the surface micromorphology by scanning electron microscopy (SEM). The viscosity of each nanofluid was measured by Viscometer DV2T. The experimental equipment and schematic of the milling experiment are shown in Figure 1.

2.2 Materials

Grade 45 steel with size of 40 mm × 30 mm × 30 mm (L × W × H) was utilized as the workpiece in the experiment. The chemical composition and mechanical properties of the material are shown in Tables 1 and 2, respectively.

2.3 Experimental Scheme

In the experiment, cottonseed oil was used as the base oil and Al_2O_3 nanoparticles of different concentrations were added to the oil to form nanofluids. When the concentration of nanoparticles was 0, the sample consisted of pure cottonseed oil, which was set as the reference group. In each group, only the quantity of Al_2O_3 nanoparticles was changed, while the other experimental conditions remained the same.

Nanofluid is a mixture of base oil and nanoparticles. According to a previous experimental study [24], Al_2O_3 nanoparticles with cottonseed oil and palm oil as base oils obtained the best lubrication performance over those with castor oil, soybean oil, and peanut oil. However, the viscosity of palm oil is higher than that of cottonseed. When the room temperature was low, palm oil easily solidified in the experiment. Therefore, cottonseed oil was used as base oil, and Al_2O_3 nanoparticles were

Table 1 Chemical composition of Grade 45 steel

Element	C	Si	Mn	Cu
Component (%)	0.42–0.50	0.17–0.37	0.50–0.80	≤ 0.25
Element	Ni	Cr	P	S
Component (%)	≤ 0.30	≤ 0.25	0.035	0.035

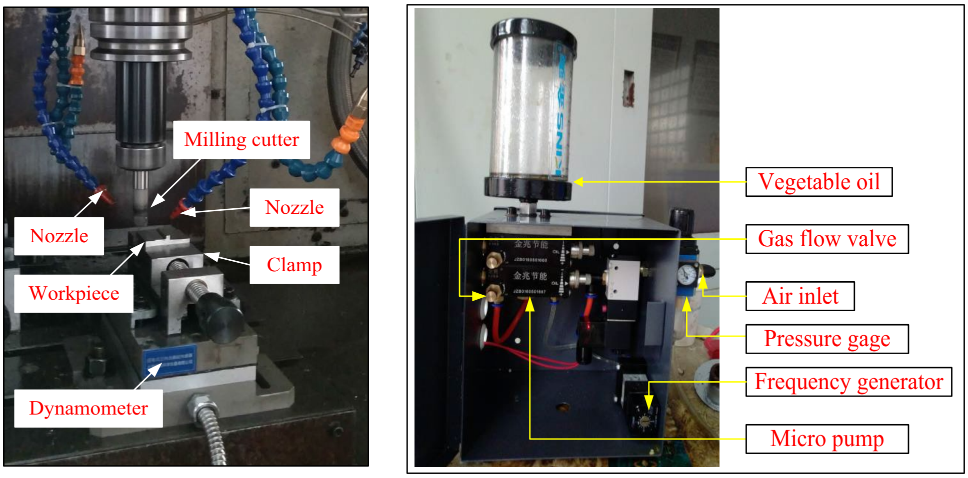


Figure 1 Experimental equipment

Table 2 Mechanical properties of Grade 45 steel

Parameter	Value
Modules of elasticity (GPa)	210
Poisson's ratio	0.31
Tensile strength (MPa)	600
Yield strength (MPa)	355
Hardness (HRC)	48–55
Elongation (%)	16
Density (g/m^3)	7.85

Table 3 Properties of Al_2O_3 nanoparticles

Properties	Value
Particle shape	Sphere
Purity (%)	99.9
Average particle size (nm)	70
Apparent density (g/cm^3)	0.33
Specific surface area (m^2/g)	30.21
Thermal conductivity (W/m·K)	36

Table 4 Experimental design

Expt. No.	Milling fluid	Nanoparticle's concentration (wt %)	Lubricating condition
1	Pure castol oil	0	Pure oil MQL
2	Al_2O_3 nanofluid	0.2	Nanofluid MQL
3	Al_2O_3 nanofluid	0.5	Nanofluid MQL
4	Al_2O_3 nanofluid	1	Nanofluid MQL
5	Al_2O_3 nanofluid	1.5	Nanofluid MQL
6	Al_2O_3 nanofluid	2	Nanofluid MQL

Table 5 Milling parameters

Milling parameter	Parameter setting
Milling way	Plane milling
Tool type	Machine-clamped two-tooth end milling cutter
Tool diameter (mm)	20
Spindle speed (r/min)	1200
Feed speed (mm/min)	500
Axial depth (mm)	0.25
Radial depth (mm)	10
MQL flow rate (mL/h)	85
MQL nozzle distance (mm)	40
MQL nozzle angle (°)	45
MQL gas pressure (MPa)	0.4

selected as additive. The physical properties of Al_2O_3 nanoparticles are listed in Table 3. Ref. [40] investigated that even adding a small number of nanoparticles could significantly improve the lubrication performance. However, the performance of the nanoparticles was nonlinear with their concentration. In the present experiment, the tribological performance at the tool/workpiece interface was studied using different mass concentrations (0%, 0.2%, 0.5%, 1.0%, 1.5%, 2.0%) of the nanoparticles. Al_2O_3 nanoparticles have high surface energy and thus can easily cause the reunion phenomenon when nanoparticles are added to the base oil. Therefore, lauryl sodium sulfate (SDS) with 0.3 wt% was added as surfactant to the nanofluid to improve the stability of the suspension. Six groups of experiments were conducted under six different mass concentrations, and each experiment was repeated three times to reduce the error caused by the experiment operation, and obtain precise experimental data.

The experiment design with different mass concentrations is listed in Table 4. Nanofluids were prepared via a two-step method. The nanoparticles were dispersed into cottonseed oil and stirred for 1 h by using a numerical control ultrasonic oscillator. The milling parameters in the experiment are listed in Table 5.

3 Results and Discussion

3.1 Macro-Parameters of Milling Performance

3.1.1 Milling Force

In machining, milling force is one of the most critical parameters. Higher milling force can produce higher heat and promote interface adhesion phenomenon, seriously affecting the surface quality of the workpiece and the service life of the cutter. Therefore, milling force is of great significance to improve machinability [41]. Milling force is divided into *X* milling force *Fx*, *Y* milling force *Fy*, and axial force *Fz* for analysis. The trend of cutting force under the six different concentrations of nanofluids measured by dynamometer is shown in Figure 2.

Figure 2 depicts that the peaks of the cutting forces at three directions appeared by the order of $F_x > F_y > F_z$. F_z was extremely minimal and did not change and thus could be ignored. The milling force increased periodically from zero and reached stability, then decreased to zero. Only one period was drawn to present the cutting force value of the three directions. The overall cutting force was the lowest when the concentration of the nanofluid was 0.5 wt% (Figure 2c).

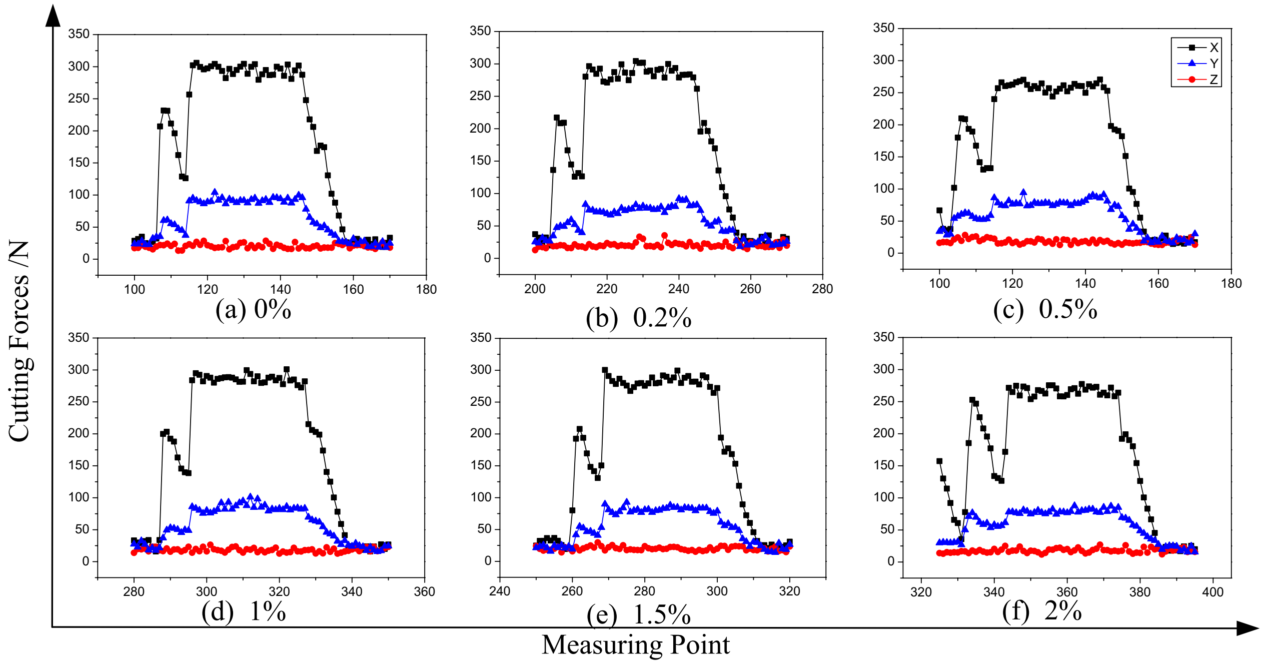


Figure 2 Trend of cutting force under six different concentrations of nanofluids

3.1.2 *Specific Cutting Energy*

Specific cutting energy indicates the energy consumed during machining and includes energy consumed by plastic deformation and friction between the interface of the tool/workpiece and the newly formed processing surface [31]. Lower specific energy leads to higher processing efficiency. Thus, machining is an environment-friendly and energy-saving process. Controlling specific energy is important. The specific energy of milling can be calculated using Eq. (1):

$$U = \frac{P}{Qw} = \frac{F \cdot t}{\alpha p \cdot t \cdot \alpha e} = \frac{F}{\alpha p \cdot \alpha e}, \tag{1}$$

where U is the specific energy (J/mm^3); P is the total energy consumed; Q_w is the volume of material removed by the tool; α_p is the radial depth of cut (mm), α_e is the axial depth of cut (mm), and F is the resultant force (N) calculated using Eq. (2). According to Eq. (1), the unit J/mm^3 is equivalent to N/mm^2.

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2}. \tag{2}$$

The specific energy obtained using different Al_2O_3 concentrations (wt%) is shown in Figure 3. The specific energy gradually decreased with increasing Al_2O_3 concentration. However, after 0.5 wt%, the magnitude of the specific cutting energy increased. The lowest specific energy of 114 J/mm^3 was obtained when the Al_2O_3 concentration was 0.5 wt%. Hence, slight mixing between Al_2O_3 and cottonseed significantly enhanced the tribological properties of cottonseed, but a very high concentration of nanoparticles was not conducive to improving the tribological properties.

Nanoparticles have excellent anti-friction and anti-wear effects [42], and they can increase the compressive capacity of the oil film to reduce milling force. Al_2O_3 nanoparticles also have high thermal conductivity, which can reduce the milling force. When added into lubricants, these nanoparticles will infiltrate into the pores on the surface of the workpiece and form an oil film due to the shearing of nanoparticles with each other. The film helps to decrease the magnitude of cutting forces and the

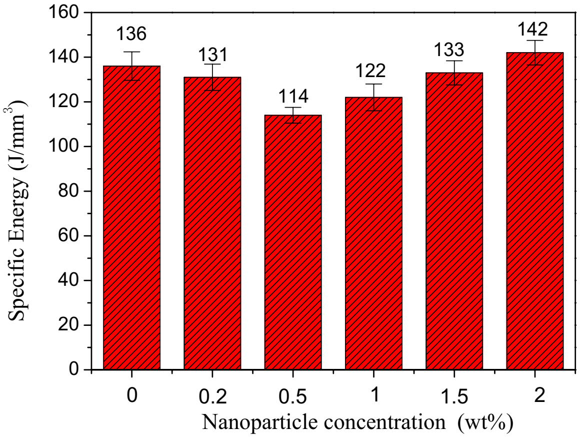


Figure 3 Specific energy obtained using different Al_2O_3 concentrations

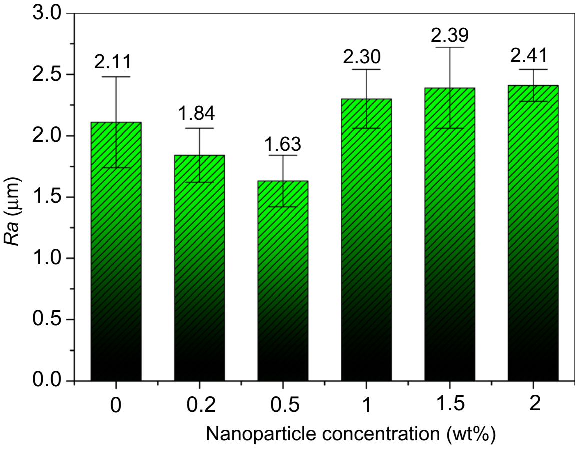


Figure 4 Surface roughness under different nanoparticle concentrations

energy consumption. However, too many nanoparticles will result in their collision and aggregation with the surface of the workpiece, and thus affect the surface quality and produce high milling force in motion.

3.2 Microstructure Characterization and Morphology Analysis

3.2.1 Surface Roughness and Micromorphology

Surface roughness can quantitatively determine the machining surface quality, and surface micromorphology can qualitatively evaluate the surface quality. Six groups of roughness values were obtained by selecting five points to measure the surface roughness of the six workpieces machined by nanofluid MQL milling. The surface roughness and surface micromorphology under different nanoparticle concentrations are shown in Figures 4 and 5, respectively.

As shown in Figure 4, the roughness values differed under different nanoparticle concentrations. The surface roughness of the workpiece under 0.5 wt% was the smallest (R_a = 1.63 μm), which is 22.7% lower than that of pure cottonseed oil. As such, the best surface quality was obtained under 0.5 wt% nanoparticle concentration. As the concentration increased from 1 wt% to 2 wt%, the surface roughness increased, and the surface quality worsened. Similar result was obtained on surface morphology under different nanoparticle concentrations.

Figure 5 shows many extensive spalling and deep scratches on the workpiece surface under pure cottonseed oil. Hard spots obviously appeared on the surface of the tool scratch of the workpiece, and the lubrication effect of pure cottonseed oil was poor. When the concentration of the nanoparticles was increased to 0.2 wt%, the scratches became lighter, and the spalling became minor, indicating that the lubrication performance was superior to that of pure cottonseed oil. When the concentration of the nanoparticles was 0.5 wt%, the surface quality of the workpiece was the best despite the very minimal peeling and slight furrow. The nanoparticles deposited onto the workpiece surface formed a lubrication film, which decreased the friction between the tool and the workpiece. However, when the concentration was further increased, the surface quality decreased. In 2 wt% sample as an example, intense scratches, big cracks, and large-area peeling were observed. The reason is that when the

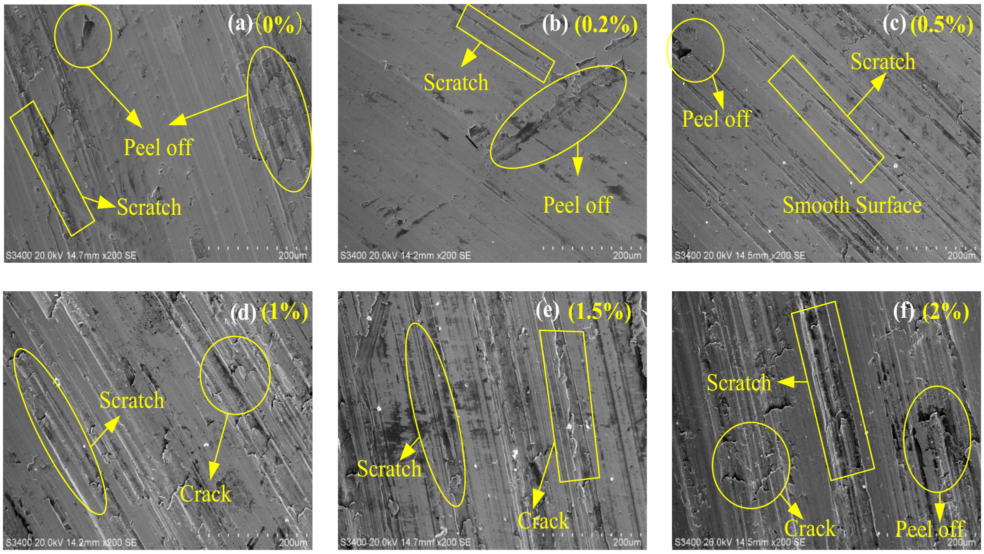


Figure 5 Surface morphology under different nanoparticle concentrations

concentration of the nanoparticles is high, they will penetrate the surface cavity of the workpiece. The particles will then be sheared off by the incoming ones and appear in the oil film, thereby enhancing wear and dramatically reducing the surface quality of the workpiece.

3.2.2 Morphology of Chip Surface

The chip formation process is essential to change physical and chemical phenomena, such as force and temperature during cutting. The chip morphology can reflect the frictional properties of the tool/workpiece and tool/chip interface; as such, the mechanism of high-speed cutting should be studied to increase the machining efficiency.

As shown in Figure 6, strip-shaped chips were obtained under the six lubrication conditions. The front side of the chip was in contact with the rake face of the tool, so the surface was relatively smooth. When the chips flowed along the rake face of the tool, they were sheared and extruded on the front surface, resulting in higher contact stress and shear stress. As a result, linear scratches were formed along the direction of chip outflow. In the absence of contact with the cutter, the back of the chip had a large number of dense stripes caused by shear plastic deformation.

Figure 6 shows that the chip surface was relatively flat when the cutting fluid was pure cottonseed oil. However, the surface of the chip was flaked and deeply scratched, indicating poor lubrication effect at the tool/chip interface. When the concentration of the nanoparticles was 0.2 wt%, peeling off still occurred, but the scratch was reduced obviously. When the concentration of the nanoparticles was increased to 0.5 wt%, light scratches, smooth surface, and the flattest surface appeared. This finding reveals that this concentration of the nanofluid enabled the chips to bear high friction and shear forces at the workpiece/tool interface and dramatically reduce the contact area, which are essential to reduce the friction. When the concentration of the nanoparticles was increased to 1 wt%, the surface of the chip was scratched obviously, but no peeling or debris deposition occurred. When the concentration was further increased, peeling and debris deposition increased obviously. This finding may explain the high concentration of the nanoparticles deposited on the surface of the workpiece. These nanoparticles were strongly sheared by the newly injected nanoparticles, so high concentrations of the nanoparticles are not conducive to forming a suitable surface.

3.3 Contact Angle Analysis

Nanofluid is sprayed from the nozzle to the cutting area in the form of droplets to reach the milling tool/workpiece interface and plays a cooling and lubricating role. Therefore, the state of droplets on the workpiece determines the lubrication effect. Contact angle should be studied because it is a critical parameter to measure wettability, which describes the spread, penetration, and ability of fluid covering the tool and workpiece.

After the Al_2O_3 nanofluid was sprayed into the machining zone, a droplet was formed (Figure 7). When the droplet reached the equilibrium on the solid surface, the angle between the gas–liquid interface and the liquid–solid interface is called the contact angle, which is expressed by Eq. (3):

$$\cos\theta = \frac{\gamma_s - \gamma_{sl}}{\gamma_l}, \tag{3}$$

where θ is the contact angle, γ_s, γ_l, γ_{sl} refer to the surface tension of vapor, liquid, and solid, respectively.

According to Eq. (3), when γ_l decreases, the θ decreases and the wettability increases. A larger infiltration area means that the milling fluid can effectively cover more regions, resulting in better lubrication. Accordingly, the surface roughness of the workpiece decreases.

Figure 8 shows the contact angle of different concentrations of nanofluids sprayed on the workpiece surface. With the addition of the nanoparticles, the contact angle decreased significantly. When the concentration of the nanoparticles was 0.5 wt%, the contact angle decreased to the minimum value, and the lubrication effect was the best. Since then, the contact angle increased with increasing concentration of the nanoparticles. The possible reason is that the particle size of spherical Al_2O_3 nanoparticles is 70 nm, which is many times larger than that of cottonseed oil. These nanoparticles are larger in size and density than the oil molecules, leading to additional downward pressure on the oil molecules to the contact surface as well as reduced contact angle of the droplets and increased wettability. When an appropriate amount of the nanoparticles was added to the base oil, more particles participated in this action, further reducing the contact angle [43]. Accordingly, the strength of the lubricating oil film was enhanced by adding the nanoparticles. However, when the concentration was higher than 0.5 wt%, the contact angle increased. This finding may explain why too many nanoparticles cannot disperse wholly into the base oil, resulting in aggregation, dynamic stability loss, and precipitation. Therefore, the wettability of the fluid was reduced, and the surface quality of the workpiece correspondingly decreased, consistent with the outcome of surface roughness in Figure 5.

3.4 Viscosity Analysis

Viscosity reflects the adhesion among molecules due to irregular motions and is an essential factor that influences lubrication properties. The distances between

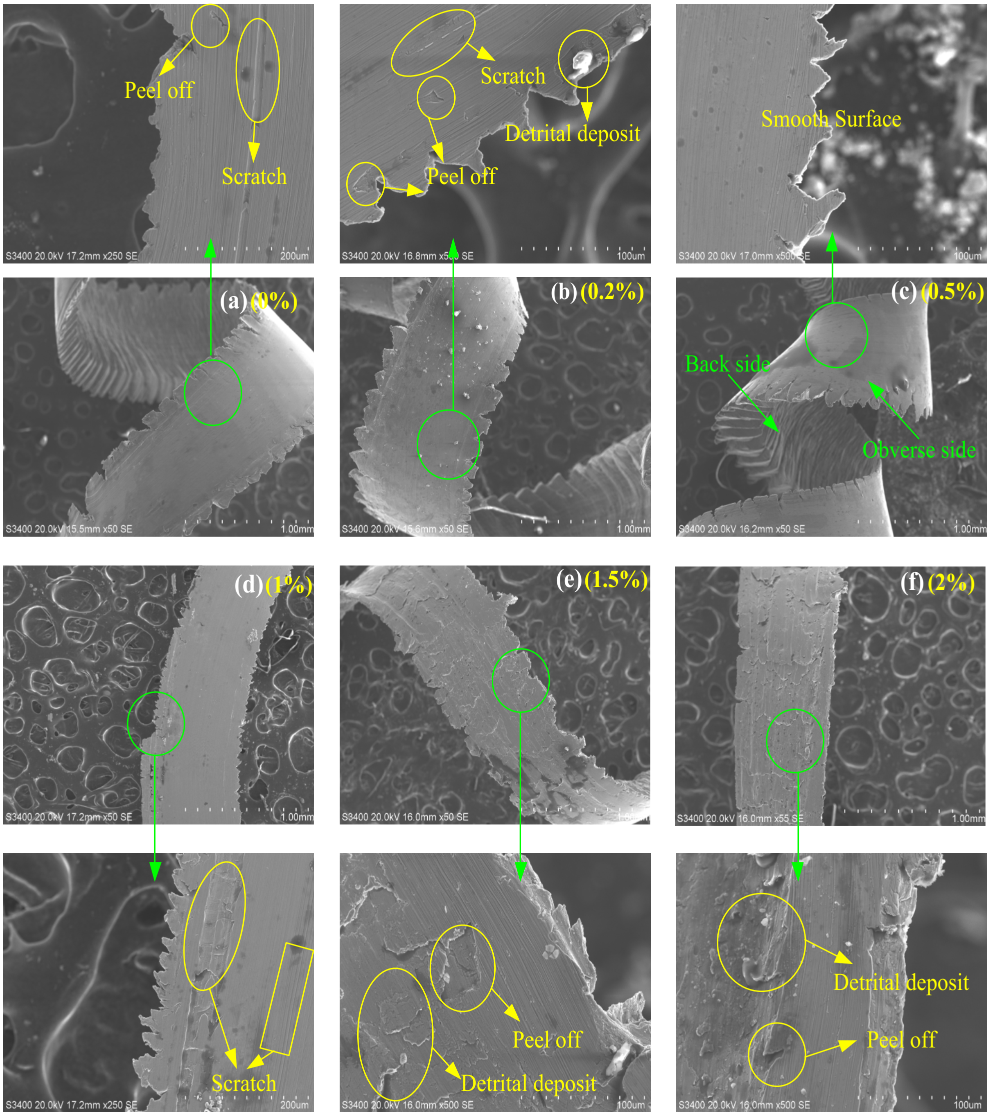


Figure 6 Chip morphology under different nanoparticle concentrations

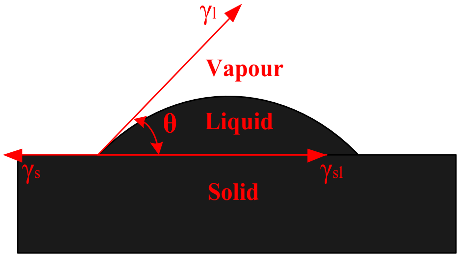


Figure 7 Schematic diagram of contact angle

nanoparticles are large when the mass concentration is low. Brownian random forces and viscous forces are too weak to cause an attraction between them. Therefore, low-viscosity liquid cannot form an oil film with sufficient strength and thickness. The distance becomes shorter with increasing concentration of Al_2O_3 nanoparticles, thereby increasing the probability of nanoparticle collision and enhancing the Brownian random force and viscous force. The viscosity of the cutting fluid will augment gradually with increasing concentration of nanoparticles. The high-viscosity nanofluid can improve the strength and thickness of the adsorption oil film to improve the lubrication performance [44].

As shown in Figure 9, the viscosity of the nanofluid increased from 49.4 mPa·s to 53.6 mPa·s as the nanofluid concentration was increased from 0 to 0.5%. When the nanoparticle concentration was above 0.5 wt%,

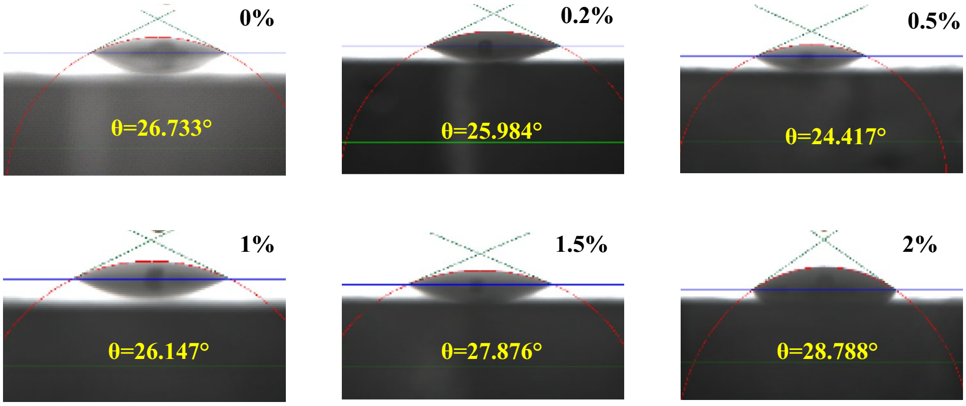


Figure 8 Contact angle under different nanoparticle concentrations

the viscosity fluctuated within a small range possibly because of the aggregation of the high concentrations of the nanoparticles. In the process of random movement, nanoparticles in the suspension collided and aggregated to form nanoparticle clusters (Figure 10). Some nanoparticles lose dynamic stability and deposited, helping to reduce the viscosity and film-forming ability of the nanofluids. Therefore, the viscosity of the nanofluid increased slightly after reaching saturation [45].

3.5 Anti-wear and Anti-friction Mechanism of Al_2O_3 Nanoparticles

Al_2O_3 nanoparticles have excellent hardness, heat resistance, and wear resistance. As additives, these nanoparticles can improve the ability of the cottonseed oil to resist wear. The Al_2O_3 molecular structure can absorb additional cutting fluid due to its strong adsorption capacity, which causes a large quantity of cutting fluid to enter at the workpiece/tool interface. Al_2O_3 nanoparticles are primarily spherical. When their diameters are small ($\leq$ 70 nm), they can quickly enter into the cutting region and form a thin protective film (Figure 11a). The nanoparticles can fill the workpiece surface cavities and repair the dents of the friction surface, playing a mending role (Figure 11b), thereby reducing friction and wear [46].

The surface atoms of the nanoparticles lack adjacent ones and have many unsaturated bonds. Polar atoms in cottonseed oil can easily bind to the surface atoms of the nanoparticles, resulting in higher surface energy in the nanofluid to ensure that it is forcibly adsorbed to the surface of the milling cutter and workpiece and improve the lubrication effect. Nanoparticles can agglomerate quickly and spontaneously due to small size and considerable surface energy. When the concentration of the nanoparticles is high, they deposit in the uneven part of the workpiece surface. The particles are sheared by the newly injected nanoparticles, thereby cutting the nanoparticles remaining in the oil film and reducing the workpiece surface quality. Therefore, appropriate concentrations of nanoparticles should be studied to improve the surface quality of the NMQL milling workpiece.

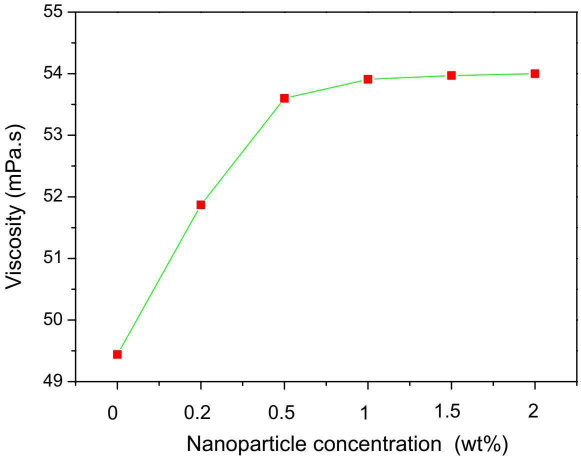
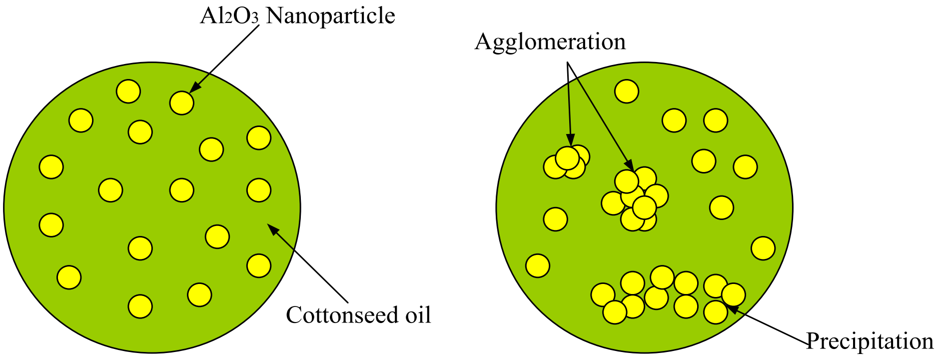


Figure 9 Viscosity under different nanoparticle concentrations

4 Conclusions

In this study, cottonseed-based Al_2O_3 nanofluids with different concentrations were prepared and tested for milling performance. Milling force, specific energy, surface quality and morphology of chip and workpiece were investigated. Viscosity and contact angle were analyzed. Based on the experimental findings, the following conclusions were drawn.

1. The lowest specific energy of 114 J/mm^3 is obtained when the Al_2O_3 concentration is 0.5 wt%. The magnitude of specific energy increases with the increasing of Al_2O_3 concentration. This result indicates that small amounts of Al_2O_3 nanofluid can significantly



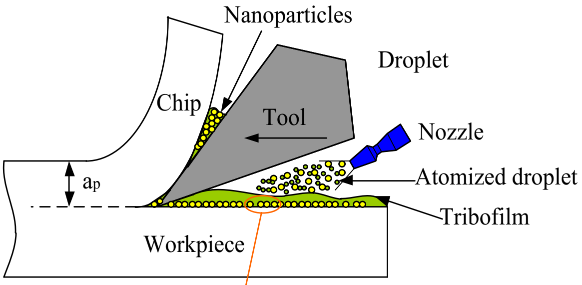
(a) Lower concentration of nanoparticles

(b) Higher concentraion of nanoparticles

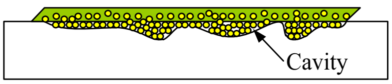
Figure 10 Dispersion of Al_2O_3 nanoparticles

enhance the tribological properties of the nanofluid. However, high concentrations of nanoparticles are not conducive to improving the tribological properties.

2. The surface roughness R_a is the lowest equal to 1.63 μm, and the surface of chips and workpiece is the most smooth with few scratches and peeling when the concentration of Al_2O_3 nanoparticles is 0.5 wt%, When the concentration continues to increase, the surface quality of the workpiece and chips begins to worsen.
3. The viscosity of nanofluids dramatically increases from 49.4 mPa·s to 53.6 mPa·s as the concentration changes from 0 to 0.5 wt%. However, it fluctuates within a small range when the concentration is above 0.5 wt%. Furthermore, the contact angle of the droplet with the concentration of 0.5 wt% has a minimum value, representing the maximum wettability area and optimal lubrication performance.



(a) Al_2O_3 nanoparticles as a protective film



(b) Al_2O_3 nanoparticles as a mending role

Figure 11 Schematic of lubrication at the milling interface

4. The nanofluid has better tribological properties than pure cottonseed oil and significantly improves the milling performance. When the concentration of the nanoparticles is 0.5 wt%, the nanofluid has the best tribological properties.

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Author Contributions
CL was in charge of the whole trial. XB wrote the manuscript. JJ and LD assisted with data collection and laboratory analyse. HMA and SS provided ideas on manuscript writing. All authors read and approved the final manuscript.

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Competing Interests

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