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ORIGINAL ARTICLE

Experimental evaluation of the lubrication performances of different nanofluids for minimum quantity lubrication (MQL) in milling Ti-6Al-4V

Xiufang Bai [1,2] · Changhe Li [3] · Lan Dong [1,2] · Qingan Yin [3]

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Abstract

The objective of this research is to experimentally evaluate the lubrication performances of different nanofluids in milling titanium alloy Ti-6Al-4V. Six types of nanofluids, namely, Al_2O_3, SiO_2, MoS_2, CNTs, SiC, and graphite, were selected. Cottonseed oil was used as the base oil. The lubrication performance was investigated in terms of milling force, surface roughness, and morphology of workpiece surface. Experimental results demonstrated that the Al_2O_3 nanoparticle obtained the minimal milling force ($F_x = 277.5$ N, $F_y = 88.3$ N), followed by the SiO_2 nanoparticle ($F_x = 283.6$ N, $F_y = 86.5$ N). The surface roughness obtained by the Al_2O_3 nanofluid was the minimum ($R_a = 0.594$ μm), whereas it was the maximum by using minimum quantity lubrication ($R_a = 1.772$ μm). The surface roughness of the six nanofluids was described by the following order: $Al_2O_3 < SiO_2 < MoS_2 <$ CNTs < graphite < SiC. The workpiece surface morphology was the best for Al_2O_3 and SiO_2. The viscosity of the nanofluids was also analyzed. Spherical Al_2O_3 and SiO_2 nanoparticles improved the lubrication effect of base oil mostly and were more suitable as environment-friendly additives for the base oil compared with the others.

Keywords Milling · Nanofluid · Minimum quantity lubrication · Surface morphology

Nomenclature

MQL	Minimum quantity lubrication
NMQL	Nanofluid minimum quantity lubrication
SEM	Scanning electron microscope
EDS	Energy-dispersive spectrometer
F_x, F_y, F_z	Cutting force components in x, y, and z directions, respectively (N)
R_a	Arithmetic average height (μm)
RS_m	Mean spacing at mean line (mm) components (N)
F	Resultant cutting force (N)
$\overline{F}_{max}$	Mean of milling force peak
R_a	Arithmetic average height (μm)

Highlights

- Lubrication performance of different nanofluids in milling Ti-6Al-4V was studied.
- The surface integrity of six typical nanoparticles were studied.
- EDS elements of different nanoparticles were analyzed to validate lubrication performance.
- The best lubrication performance was obtained by Al_2O_3 and SiO_2 nanofluid MQL.

✉ Changhe Li
sy_lichanghe@163.com

Xiufang Bai
bxf1979@126.com

Lan Dong
804203464@qq.com

Qingan Yin
15154215806@163.com

1 Engineering and Technology R&D Center of Mechanical and Electrical in Colleges of Shandong, Qingdao Binhai University, Qingdao 266555, China

2 School of Mechanical and Electrical Engineering, Qingdao Binhai University, Qingdao 266555, China

3 School of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao 266520, China

1 Introduction

Titanium alloy is popular in various fields, such as the aerospace, automotive, shipbuilding, and ocean industries, due to its high strength and high resistance to corrosion. However, its low thermal conductivity and high chemical activity cause poor machinability; thus, it is categorized as a difficult-to-machine material [1]. A large amount of cutting fluid is applied in machining titanium alloy to reduce temperature and improve surface quality and tool life. The high pressure in the contact interface among the tool, debris, and workpiece allows only a small proportion of cutting fluid to enter the milling zone and be used in cooling lubrication. The heat created in the milling zone is consequently difficult to effectively dissipate [2]. The usage of a large amount of cutting fluid not only greatly increases production cost but also causes serious pollution to the environment and endangers human health [3, 4].

Minimum quantity lubrication (MQL), also known as near-dry machining, has been popularized over the last decade. MQL is a technique for mixing a minimum quantity of lubricants with high-pressure gases, which can break through the air-barrier layer and arrive at the milling area after atomization. High-pressure gas plays a role in cooling and debris removal [5]. MQL has been widely used in the titanium alloy machining process. Pervaiz et al. [6] researched the machining characteristics of titanium alloy under the vegetable oil-based MQL condition and achieved better lubrication performance in reducing friction compared with those of dry cutting and conventional flood cooling. Rahim and Sasahara [7] examined the machinability of Ti-6Al-4V by employing palm oil-based and synthetic ester-based lubricants using MQL arrangements and revealed that the palm oil-based MQL system performed better than the synthetic ester-based system did. Mark et al. [8] compared MQL and minimum quantity cooling lubrication (MQCL) on milling titanium alloy in terms of cutting temperature, surface roughness, and debris. The results revealed that MQCL showed a considerable improvement compared with MQL, with improved lubricity of the cutting fluid at lower temperatures and easier separation of debris from the rake face.

Nanoparticles are dispersed into cutting fluids as additives to form nanofluids according to the theory of solid-enhancing heat transfer to improve cooling and lubrication. Ding et al. [9, 10] investigated green machining technology and the removal mechanism of brittle particles in mechanical machining. Li et al. [11–13] confirmed the excellent cooling and lubrication effects of nanofluid MQL. Park et al. [14] found that nanofluids can improve MQL milling, especially for chipping at cutting edges. The application of nanofluids in MQL processing not only exhibits all the advantages of MQL machining but also solves the fatal defect of insufficient heat transfer capability. Many studies have been conducted and reported in grinding, turning, and milling to understand the cooling and lubrication characteristics of nanofluids.

Regarding grinding, Zhang et al. [15] used MoS_2, CNT, and ZrO_2 nanoparticles as additives to grinding fluid to perform grinding experiments. The results demonstrated that MoS_2 nanoparticles achieved the lowest specific energy and the best workpiece surface quality. Zhang et al. [16] mixed Al_2O_3 and SiC nanoparticles. The influences of different mixing ratios and grain sizes on the lubrication performance were discussed. The best lubrication performance was achieved under 2:1 mixing ratio and 30:70 grain size ratio. Wang et al. [17] investigated the tribological performance of the wheel/workpiece interface in MQL grinding with different concentrations of Al_2O_3 nanofluids and concluded that the optimal nanofluid concentration was 1.5 vol%. Mao et al. [18, 19] observed grinding performances under dry, flood, MQL, and Al_2O_3 NMQL conditions. The experimental results demonstrated that nanofluid MQL achieved low grinding force and cutting temperature and good workpiece surface quality. Shen et al. [20] grinded cast iron with Al_2O_3 and diamond nanofluids. The process was compared with dry, pouring, and MQL grinding. NMQL reduced the grinding force and surface roughness considerably and eliminated workpiece burn. Shen et al. [21] and Kalita et al. [22] obtained excellent performances of MoS_2 nanoparticles in improving grinding force.

Regarding turning, Krishna et al. [23] investigated the performances of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel and found that 0.5% nanoboric acid in coconut oil performed well in terms of cutting temperature, tool wear, and surface roughness. Rao et al. [24] experimentally estimated tool wear and cutting temperatures in MQL using cutting fluids with carbon nanotube (CNT) inclusion and concluded that nodal temperature was decreased up to 2% CNT inclusion; beyond 2%, change was minimal, and high CNT % reduced flank wear. Yan et al. [25] investigated the effect of nanoparticle lubrication in diamond turning of reaction-bonded SiC and found that copper nanoparticle (10%) mixed in grease generated the surface with lowest roughness and yielded minimum tool wear. Khandekar et al. [26] and Prasad et al. [27] obtained reduced cutting force, surface roughness, and tool wear using a cutting nanofluid, thus enhancing metal cutting performance. Su et al. [28] evaluated the performance of nanofluid MQL with vegetable-based oil and ester oil as base fluids in turning and concluded that the nanofluids decreased cutting force and temperature significantly and that graphite-LB2000 nanofluid outperformed graphite-PriEco6000 nanofluid, especially at a high cutting speed.

Regarding milling, Sayuti et al. [29, 30] observed that SiO_2 NMQL can achieve less cutting force and surface roughness than can MQL and traditional cutting fluid in milling a hard aluminum aeronautical material. Ming et al. [31] observed that SiO_2 nanofluid reduced cutting force and improved surface roughness under high-pressure airflow when milling aluminum alloy. Marcon et al. [32] found that graphite-water nanofluid could remarkably reduce cutting force and improve surface quality in comparison with dry milling. Rahmati et al. [33, 34] identified an improvement in workpiece surface quality when MoS_2 nanofluid was used because of the rolling, polishing, and mending effects of the MoS_2 nanoparticle. Uysal et al. [35] obtained minimum tool wear and surface roughness when using MoS_2 NMQL compared with those obtained using traditional MQL and dry machining. Najiha et al. [36] investigated the effects of cutting parameters on the wear mechanism when milling aluminum alloy Al6061 using water-based TiO_2 nanofluids. Hadi et al. [37] studied the effects of Al_2O_3 nanoparticles when milling AISI D3 steel. The experimental results showed that the surface roughness decreased by 0.5 μm compared with that of pure MQL when the volume fraction of nanoparticles in vegetable oil was 2%. Yin et al. [38] studied lubrication performances under four conditions, namely, dry, flood, MQL, and Al_2O_3 NMQL milling 45 steel. The results proved that Al_2O_3 NMQL had the lowest force and friction coefficient in milling 45 steel.

In milling titanium alloy, Kim et al. [39] added nanodiamond particles to vegetable oil to prepare a nanofluid under the micro-end-milling process of titanium alloy (Ti-6Al-4V). They concluded that a low concentration of nanodiamond nanofluid (0.1 wt.%) was conducive to decreasing milling force, friction coefficient, and tool wear, whereas a high concentration (1.0 wt.%) effectively reduced surface roughness. Li et al. [40] dispersed graphene to vegetable oil-based cutting fluids in milling TC4 alloy and concluded that the graphene additive was effective for improving the milling characteristics because the graphene additive could enhance the cooling and lubrication performances of the oil film formed in the milling zone.

From the literature, good lubrication effects have been achieved with NMQL. However, few studies have been reported in milling titanium alloy, and only one nanoparticle has been used as an additive for NMQL. A systematic comparison of the performances of various nanofluids also has not been performed. Nanofluids prepared with different nanoparticles have various lubrication effects due to the physicochemical characteristics and viscosity of nanoparticles. In this study, experiments on milling Ti-6Al-4V were conducted by using six types of nanoparticles and pure cottonseed oil. The lubrication performance was evaluated in terms of milling force, surface roughness, debris, and surface morphology of the workpiece surface under different lubrication conditions.

2 Experiment

2.1 Experimental setup

The experiment was conducted on a Dema ML1060B machine center with overall dimensions of 3200 mm × 2450 mm × 2000 mm ($L \times W \times H$). The main technical parameters are as follows: spindle power, 11 kW; maximum speed, 8000 r/min; motor power driving the workbench, 5 kW; cutting range, 1000 mm × 600 mm × 600 mm; and cutting feed rate, 10,000 mm/min. The nanofluid was conveyed by MQL device KS-2106. The milling force was measured by tridirectional piezoelectric dynamometer JR-YDCL-III05B. Surface roughness was measured by contact pointer measuring instrument SC6C. The surface morphologies of the debris

(a) Milling force measuring device, (b) MQL oil supply system

Fig. 1 Experimental instruments. **a** Milling force measuring device. **b** MQL oil supply system

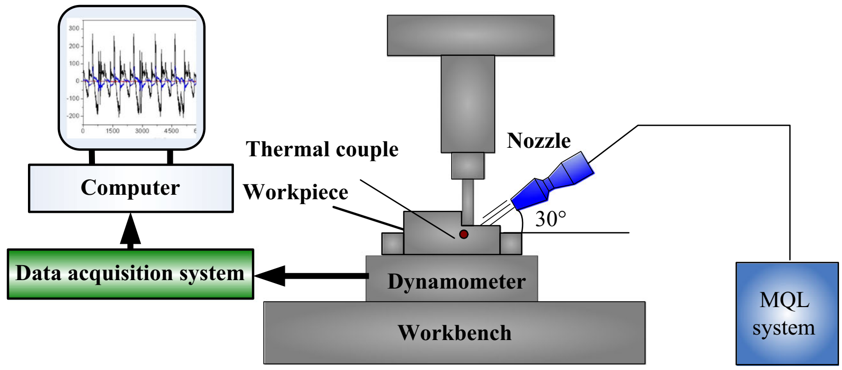


Fig. 2 Diagram of experimental data measurement

and workpiece were measured by electronic scanning electron microscope (SEM) DV2TLV. The viscosity of nanofluids was measured using a Brookfield DV2T viscometer. The experimental instruments and the milling force measurement diagram are shown in Figs. 1 and 2, respectively.

2.2 Experimental materials

In the experiment, titanium alloy Ti-6Al-4V with dimensions of 40 mm × 30 mm × 30 mm was used as the workpiece material; it is a typical α + β titanium alloy with a domestic brand of TC4 and contains 6% of the α stable element Al, which increases the stable temperature. This alloy accounts for 75–85% of all Chinese alloys due to its advantages, such as good heat resistance, strength, plasticity, toughness, formability, weldability, corrosion resistance, and biocompatibility. The chemical composition is detailed in Table 1.

2.3 Experimental scheme

Two types of milling fluids, namely, pure cottonseed oil and cottonseed oil-based nanofluid milling fluid, were used in the experiment. Nanofluids are mainly composed of cottonseed-based oils and nanoparticles. The main fatty acid types of cottonseed oil are linoleic acid (approximately 44.9–55%) and oleic acid (approximately 18–30.7%). Oleic acid is an unsaturated fatty acid with low viscosity. However, this fatty acid can easily form a layer of physical adsorption film because of its high-pressure resistance and load-carrying capacity.

Six types of nanoparticles, namely, Al_2O_3, MoS_2, SiO_2, CNTs, SiC, and graphite, were used. Table 2 lists the physical properties of the nanoparticles. The diameters of all nanoparticles are 70 nm. Nanofluids were prepared with 1.5 wt.% mass fraction [17]. Nanoparticles were unstable in the base oil and prone to agglomeration; therefore, a surfactant was added to the nanofluids to improve their stability and accounted for 0.3 wt.% of the total mass [41].

In the experiment, pure cottonseed oil MQL and six types of nanofluid MQL were compared according to cutting force, surface roughness, debris, and surface morphology, and other milling parameters were uniform. The milling parameters and experimental design are listed in Tables 3 and 4, respectively.

3 Results and discussion

3.1 Milling force

Milling force plays an important role in the milling process; it is not only an important basis for the reasonable selection of cutting parameters but also exerts an important influence on cutting heat. It affects the tool wear, machining accuracy, and surface quality of the processed workpiece and reflects the lubrication performances of various cutting fluids. A reduction in cutting force leads to improvement in lubrication performance and thereby enhanced cutting performance [42, 43].

Milling force was divided into x direction milling force (F_x), y direction milling force (F_y), and axial force (F_z) during problem analysis. The milling forces were measured three times by the dynamometer under each condition. The discontinuity of tool-workpiece contact caused dramatic changes in milling force because milling is intermittent cutting by nature. An example of measured cutting force in the x, y, and z axes is shown in Fig. 3.

Figure 3 depicts that the milling force changed periodically, and the trend of cutting force in the three directions changed alternately from zero to positive, and negative peaks reached stability after the cutting process. The peaks of the three-

Table 1 Chemical composition of Ti-6Al-4V workpiece material

Element	Ti	Al	V	Fe	C	N	H	O
Component (%)	Remaining	5.5–6.8	3.5–4.5	0.3	0.08	0.05	0.015	0.01

Table 2 Physical properties of different nanoparticles

Particle type	Al_2O_3	MoS_2	SiO_2	CNTs	SiC	Graphite
Particle size (nm)	70	70	70	70	70	70
Nanoparticle shape	Spherical	Layered	Spherical	Tubular	Hexahedral crystal	Layered
Mohr's hardness	9	1–1.5	7	10	9.5	1–2

direction cutting forces appeared by the order of $F_x > F_y > F_z$. The axial force F_z was extremely small, and the amplitude changed inconsiderably and could be ignored. For the high-speed milling process, milling force was usually determined by the average of milling force peaks F_{max}, and the average milling force peak value $\overline{F}_{max}$ was used as the basis for discussing the influences of different working conditions on milling force.

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2}, \tag{1}$$

$$\overline{F}_{max} = \frac{F_{max}}{N} = \frac{\sum_{i=1}^{N} F_{pi}}{N}, \tag{2}$$

where F_{pi} is the peak of the ith milling force peak. According to Eq. (1), the milling force F at each data point under different lubrication conditions was calculated. F_x, F_y, and F_z, as measured by the dynamometer, and the resultant milling force F were integrated into Eq. (2) for obtaining the corresponding milling force peaks (Figs. 4 and 5).

Figures 4 and 5 demonstrate that the milling force was the greatest when pure cottonseed oil was used as lubricant. With the addition of nanoparticles, the capability of base oil in friction and wear reduction was improved significantly. In particular, the addition of Al_2O_3 nanoparticle showed the most significant effect in improving the tribological properties of the base oil and obtained the lowest milling force, which implied that the Al_2O_3 nanoparticle exerted a more significant friction and wear reduction effect than did the other nanoparticles. The milling forces obtained by using MoS_2, SiC, and graphite nanofluids appeared relatively similar, and their differences were extremely small, which showed that they were similar in terms of friction performance to a certain extent. All nanoparticles improved the lubrication performance of the base oil because of the formation of friction film on the contact surface and due to the influence of nanofluid viscosity. After the addition of nanoparticles, the viscosity of the base oil increased significantly. The Al_2O_3 and SiO_2 nanoparticles had higher viscosity than did the others; accordingly, the adhesive strength, Brownian motion, and viscous force among the nanofluid molecules increased. This characteristic is conducive to the formation of oil films on friction surfaces and the enhancement of the thickness and strength of adsorption films; hence, the lubrication performance should be improved [44]. Lubricants with low viscosity do not easily form oil films with sufficient thickness on friction surface with high temperature, and the films have a small bearing capacity. Therefore, such films can be easily damaged and disappear under loading, which results in insufficient lubrication.

Table 3 Milling parameters

Milling parameters	Parameter setting
Milling way	Plane milling
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)	30
MQL nozzle angle (°)	30
MQL gas pressure (MPa)	0.4

3.2 Surface roughness

Surface roughness is an important parameter in evaluating the surface quality of a workpiece, which determines the surface smoothness. A small surface roughness corresponds to high surface quality. This parameter has an important influence on fatigue strength, contact stiffness, corrosion resistance, and coordination among parts. Surface roughness also affects the service life and reliability of mechanical products. Poor surface quality will lead to poor performance and failure of workpiece before the end of its life expectancy. Therefore, research

Table 4 Experimental design

No.	Milling fluid	Lubrication condition
1	Al_2O_3–cotton oil	Nanofluid MQL
2	MoS_2–cotton oil	Nanofluid MQL
3	SiO_2–cotton oil	Nanofluid MQL
4	CNT_S–cotton oil	Nanofluid MQL
5	SiC–cotton oil	Nanofluid MQL
6	Graphite–cotton oil	Nanofluid MQL
7	Pure cottonseed oil	MQL

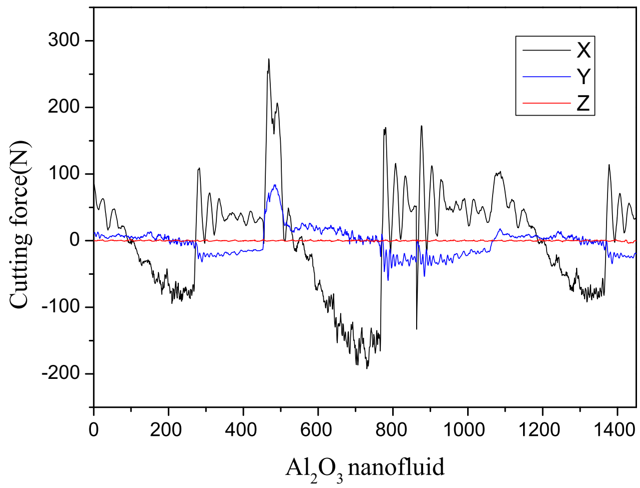


Fig. 3 Example of measured cutting force in *x*, *y*, and *z* axes

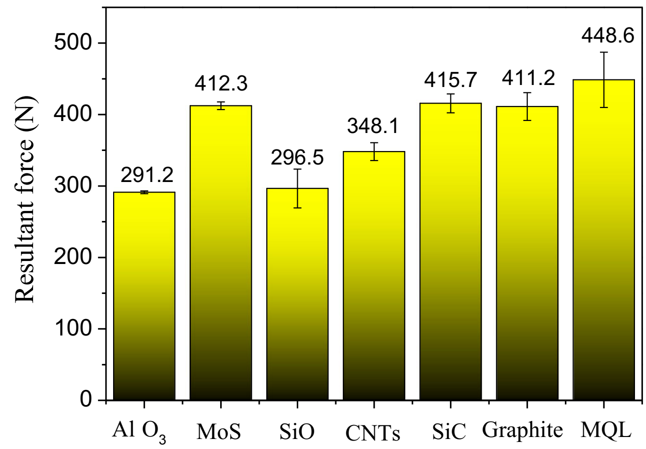


Fig. 5 Resultant force of different nanofluids

on surface roughness has not only theoretical significance but also practical value for mechanical machining production.

The spacing characteristic parameter RS_m and height characteristic parameter R_a were used as evaluation parameters in characterizing surface roughness. RS_m is the mean of profile irregularity distance in the sampling length L. Profile irregularity distance refers to the length of profile peak and the adjacent valley on the median. R_a is the arithmetic mean of the absolute deflection distance from profile points to the base line in the sample length L. A large R_a leads to a high absolute deflection value, and R_a is obtained as

$$R_a = \frac{1}{L}\int_0^L y(x)dx, \tag{3}$$

where $y(x)$ is the vertical coordinate of the profile curve. The profile curves of the workpiece surface under different nanofluids MQL and pure cottonseed oil MQL are shown in Fig. 6.

The surface roughness was measured under NMQL and MQL conditions by selecting five points on the workpiece surface; therefore, seven groups of roughness values were obtained. R_a and RS_m with standard deviation measured by a roughness-measuring instrument are shown in Figs. 7 and 8, respectively.

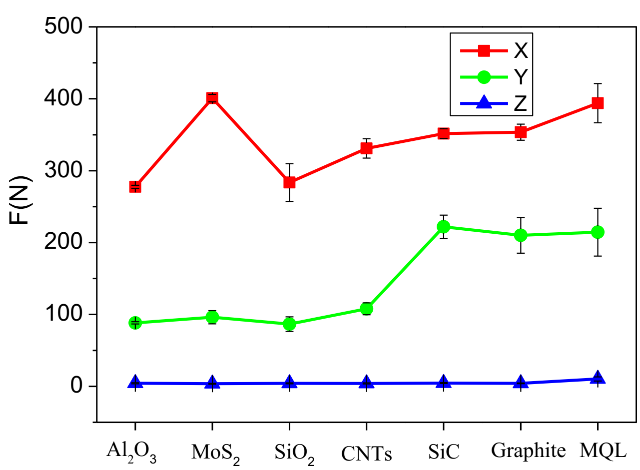


Fig. 4 Component force of different nanofluids

Figure 7 shows that pure cottonseed oil MQL obtained the highest value (R_a = 1.772 μm), whereas R_a obtained with the addition of Al_2O_3 nanoparticles was the lowest (R_a = 0.594 μm). R_a values measured under six types of nanofluids were in the following order: $Al_2O_3 < SiO_2 < MoS_2 <$ CNTs < graphite < SiC. Figure 8 presents that the minimum RS_m was achieved by the Al_2O_3 nanofluid (0.093 mm), whereas the maximum RS_m was obtained by the CNT nanofluid (0.409 mm). According to Guo [45], R_a contains most profile irregularities only; it can represent profile surface characteristics but cannot fully characterize spacing features. Therefore, the weight of R_a reached 76%, and that of RS_m was 24%. The comprehensive values were calculated and found to be in the following order: $Al_2O_3 < SiO_2 < MoS_2 <$ CNTs < graphite < SiC, which was consistent with the order of R_a. Therefore, Al_2O_3 NMQL milling obtained the best surface quality.

3.3 Debris and workpiece surface morphology

The lubrication performances of different milling fluids were demonstrated by using the debris and the workpiece surface morphology. Morphology is an important index in evaluating workpiece surface integrity; it can reflect the interaction between tool and workpiece and the removal mode of metal material [46]. Observation of surface morphology is one of the most direct methods of evaluating surface quality. The morphologies of the debris and workpiece surface in MQL and NMQL are shown in Figs. 9 and 10, respectively.

The figures depict that the debris surface obtained using pure cottonseed oil was rough and had many raised stripes on the surface (Fig. 9g), and considerable plastic deformation occurred on the workpiece surface (Fig. 10g). Compared with the raised stripes under pure cottonseed oil, those on the debris

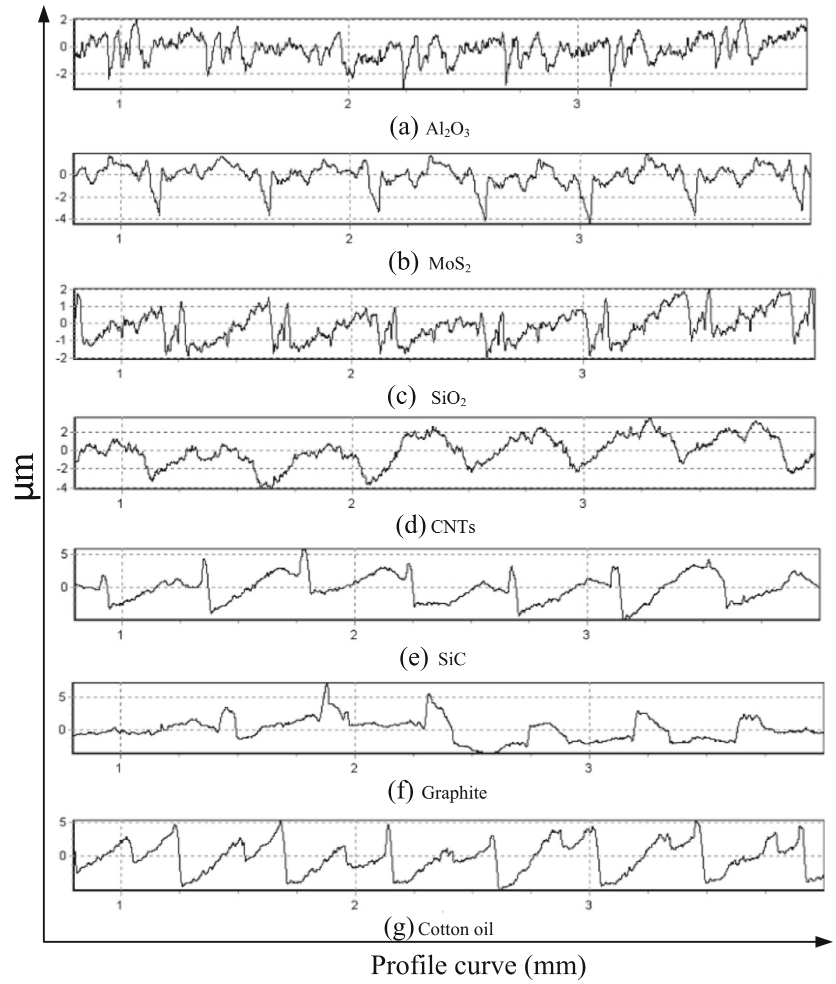


Fig. 6 Typical surface roughness measurement signal image

surface under nanofluids were small; particularly, Al_2O_3 and SiO_2 nanofluids exhibited the smallest stripes (Fig. 9a, c). The corresponding workpiece surface morphology was also the best, with only small furrows and a clear texture even at ×250 magnification (Fig. 10a, c). The furrows obtained by the other nanofluids were larger.

The Al_2O_3 and SiO_2 nanoparticles exhibited good lubrication performances, which are inseparable from their structures. Spherical or approximately spherical nanoparticles act as ball bearings on friction surfaces with good smoothness; therefore, the sliding friction becomes a rolling one. The friction

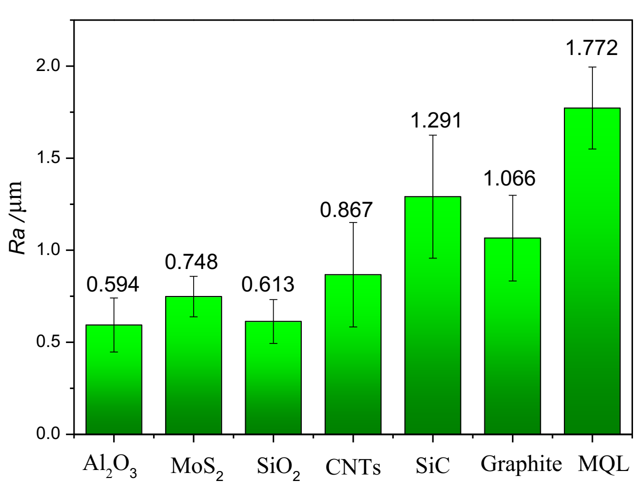


Fig. 7 R_a under different lubrication conditions

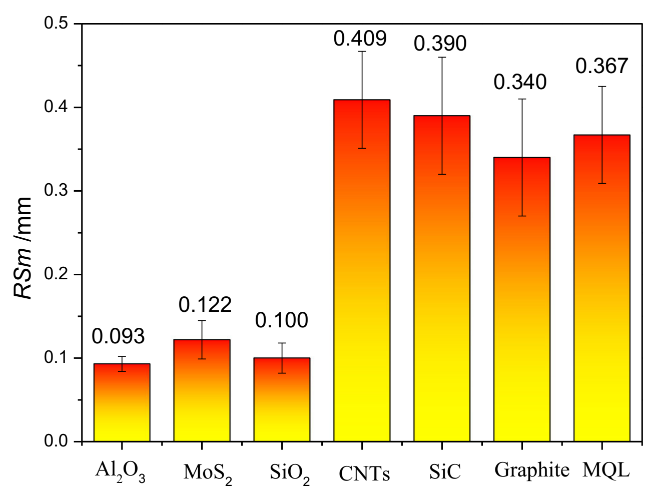


Fig. 8 RS_m under different lubrication conditions

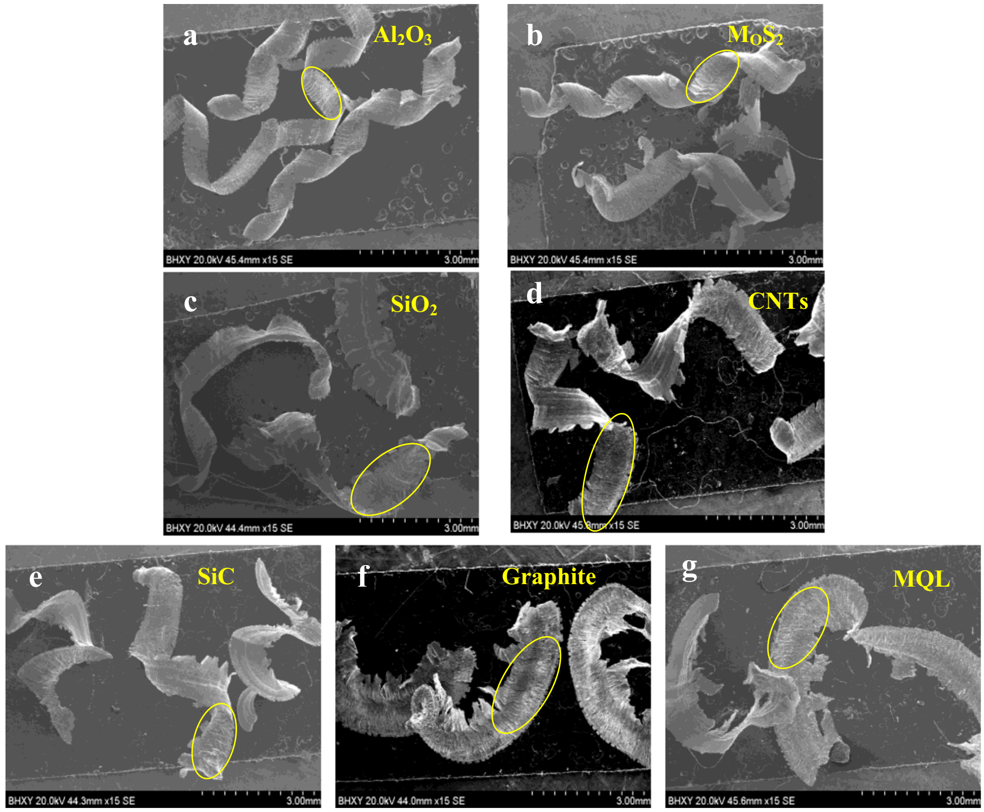


Fig. 9 Morphology of milling debris under different conditions

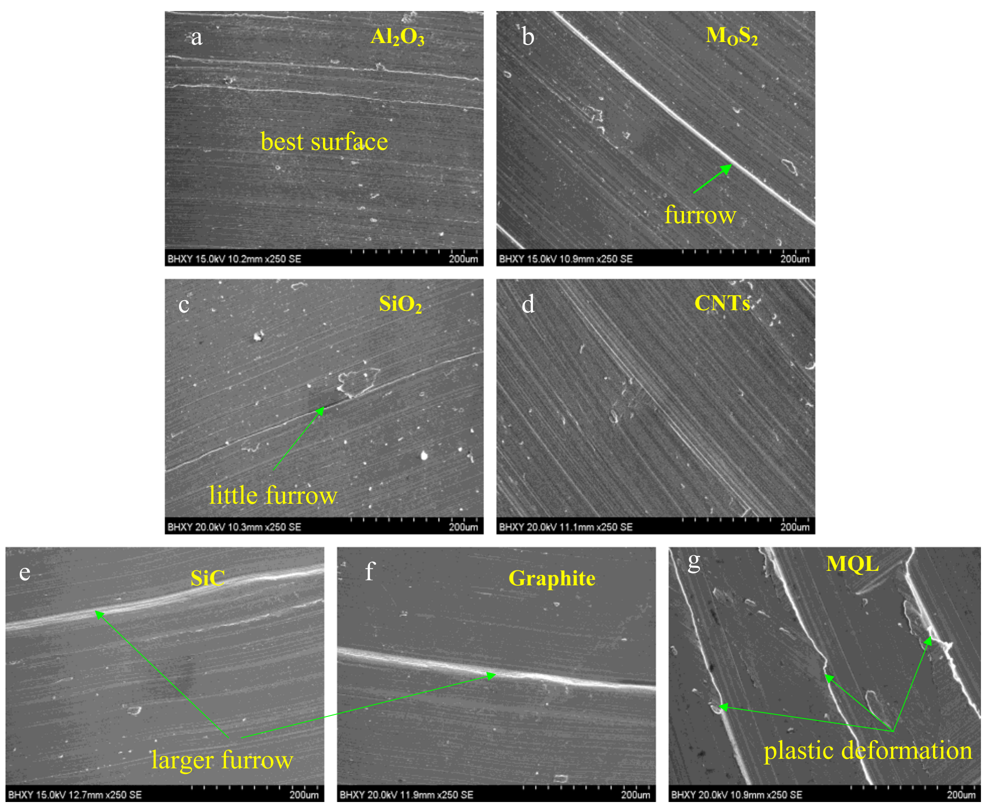


Fig. 10 SEM of workpiece surface under different conditions

coefficient is accordingly reduced, and excellent friction reduction performance is obtained. Al_2O_3 and SiO_2 nanoparticles are spherical and could thus be well adsorbed or embedded into the texture of the debris surface and the furrow on the workpiece surface, thereby becoming "bearing-like" and acting as lubrication media for the formation of the oil film. In addition, nanoparticles can fill the missing parts on a workpiece surface, thus playing a mending role and improving the lubrication effect. The lubrication mechanism of nanoparticles is shown in Fig. 11.

3.4 Viscosity analysis

Viscosity is the exchange of variables caused by the irregular movement of molecules and adhesion between adjacent molecules. In a milling area, the relative motion between tool and workpiece produces shear force; consequently, internal friction force is generated between fluid layers. The property that affects the internal friction force is called viscosity. In this work, the addition of nanoparticles to the base oil would increase the viscosity of the pure cotton oil. In the milling process, the viscosity is the main factor that affects the lubrication performance of nanofluids.

Figure 12 shows the relationship between the viscosity of the nanofluids and temperature. The viscosity of each nanofluid decreased with increasing temperature. From Fig. 12, the SiO_2 nanofluid had the highest viscosity. On the one hand, high viscosity can prevent the flow of nanofluid; nanofluid can stay in the milling zone for a long time, thus improving the lubrication performance between tool and workpiece, reducing friction, and preventing rapid tool wear. On the other hand, as viscosity increases, the adhesive strength, Brownian motion, and viscous force among molecules increase accordingly and become conducive to the formation of friction surface oil film and the enhancement of the thickness and strength of the adsorption film. The lubrication performance will accordingly be improved.

The viscosities of the graphite and SiC nanofluids were next to that of SiO_2. However, the workpiece surface quality under them was unsatisfactory, which indicates that lubrication performance is concerned not only with viscosity but also the shape of nanoparticles.

The viscosities of the graphite and SiC nanofluids were next to that of SiO_2. However, the workpiece surface quality under them was unsatisfactory. The viscosity temperature

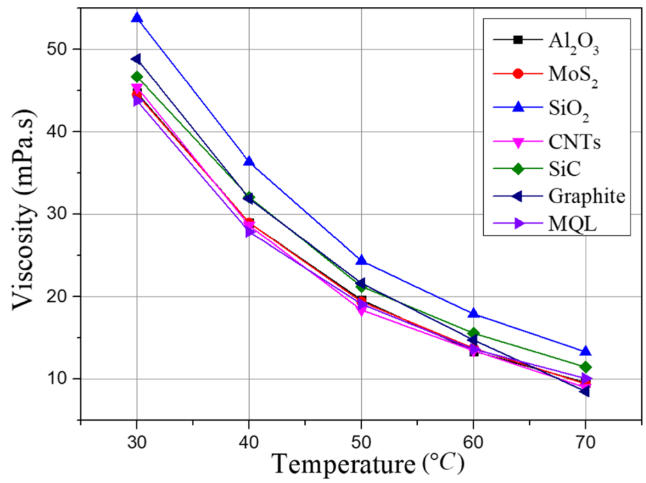


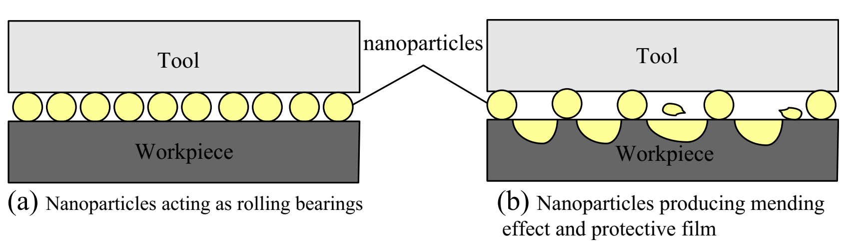
Fig. 12 Viscosity-temperature curves of different nanofluids

curve of Al_2O_3 overlapped with those of MoS_2, CNTs, and MQL, and their viscosity was small, which resulted in thin oil films. An excessively thin oil film will break during processing and form dry friction, thus exacerbating wear. Therefore, the lubrication performances under MoS_2, CNTs, and MQL were poor. The results showed that the better the lubrication performance was, the closer it was to the sphere with the same viscosity. SiO_2 and Al_2O_3 nanoparticles are spheres with different viscosities, but they produced the best workpiece surface quality. This finding suggested that nanoparticles with spherical structures can achieve good lubrication performance despite having different viscosity.

3.5 Energy-dispersive spectrometry analysis

Energy-dispersive spectrometer (EDS) elements were analyzed under different lubrication conditions to evaluate the formation of oil film on the workpiece surface. As shown in Fig. 13, the Al_2O_3 nanofluid was taken as an example. The figure shows a small amount of Al and O elements on the machined workpiece surface under MQL. However, high levels of Al and O elements that formed the oil film on the friction surface could be detected on the workpiece surface with Al_2O_3 NMQL. During the milling process, nanoparticles deposited and spread on the friction surface to form a layer of a physical oil film. Pure cottonseed oil does not contain any additives; hence, it depends only on its own lubrication

Fig. 11 Lubrication mechanism of nanoparticles. **a** Nanoparticles acting as rolling bearings. **b** Nanoparticles producing mending effect and protective film



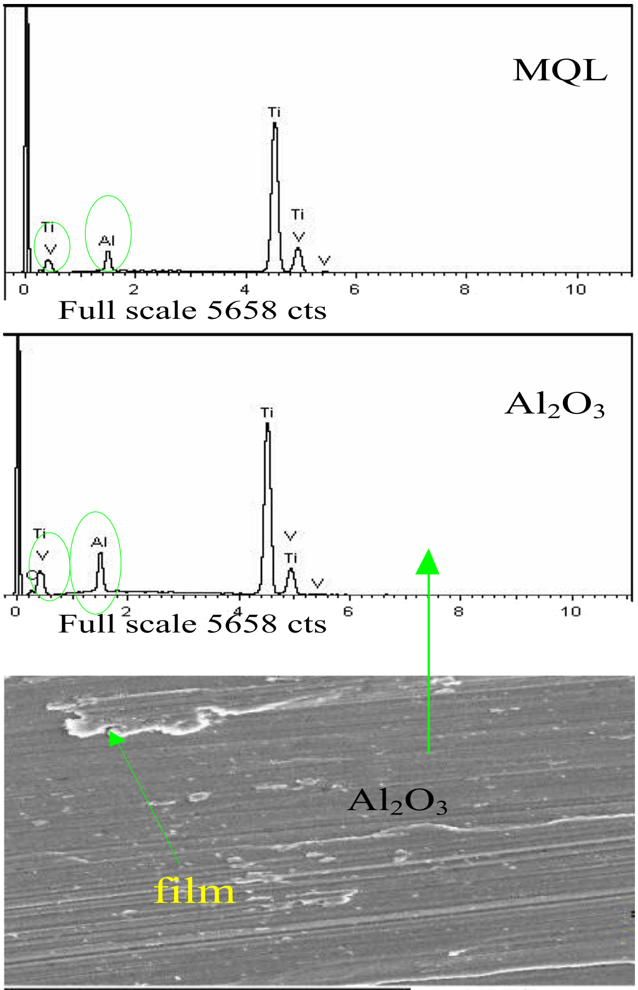


Fig. 13 EDS under Al_2O_3 nanofluid and MQL

performance to reduce friction and can produce a minimal effect only. For NMQL, nanoparticles help in the formation of the lubrication film during processing [47], which considerably improved the tribological properties and friction and wear reduction performances of the nanofluids. Although the film is only a thin oil film, it is significant for improving the tribological performance of the workpiece surface.

4 Conclusion

In this work, the application of different nanofluids in MQL milling Ti-6Al-4V was studied. The effects of different types of nanofluids on milling force, surface roughness, debris, and workpiece surface morphology were discussed. From the experimental results, the following conclusions were drawn.

(1) The milling force is the largest ($F_x = 393.9$ N, $F_y = 214.5$ N) when pure cottonseed oil is used as lubricant. With the addition of nanoparticles, the capability of the base oil in friction and wear reduction is improved significantly. In particular, the Al_2O_3 nanoparticle yields the least milling force ($F_x = 277.5$ N, $F_y = 88.3$ N), followed by the SiO_2 nanoparticle ($F_x = 283.6$ N, $F_y = 86.5$ N), showing the most significant effect compared with other nanoparticles in improving the tribological properties of the base oil.

(2) With pure cottonseed oil as lubricant, the surface roughness is the maximum ($R_a = 1.772$ μm), whereas the value obtained by Al_2O_3 nanofluid is the minimum ($R_a = 0.594$ μm). The relationship of workpiece surface roughness obtained by the six nanofluids is as follows: $Al_2O_3 < SiO_2 < MoS_2 <$ CNTs < graphite < SiC.

(3) The surface of the debris obtained using pure cottonseed oil is rough and has many raised stripes, and considerable plastic deformation occurs on the surface of the workpiece. Compared with pure cottonseed oil, the nanofluids yield only small raised stripes on the debris surface, especially the Al_2O_3 and SiO_2 nanofluids, which produce the smallest stripes. The corresponding workpiece surface morphology is also the best. Nanoparticles with a spherical or approximately spherical molecular structure and nanofluids with high viscosity, such as Al_2O_3 and SiO_2, have good lubrication performances. The good friction and wear reduction performance of the nanofluids is due to the protective oil film that the nanoparticles deposit on the friction surface to form. Although the film is only a thin oil film, it is significant for improving the tribological performance of the surface.

(4) The analysis of nanofluid viscosity shows that high viscosity leads to a good lubricating property and that the spherical Al_2O_3 and SiO_2 nanoparticles can mostly improve the lubrication performance of the base oil.

(5) According to the experimental evaluation parameters (milling force and surface roughness) and the surface morphology of the debris and workpiece surface, the Al_2O_3 and SiO_2 nanoparticles are more suitable as environment-friendly additives for the base oil compared with others.

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