Research of The Effect of Graphene Nanoparticles and Sulfurized Additives to MQL for Machining of Ti-6Al-4V

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Abstract

given its favourable comprehensive properties, titanium alloy has been extensively developed and used in numerous fields. However, its low thermal conductivity and strong chemical activity have led to its reputation as a difficult-to-machine material. Thus, graphene nanoparticles and sulfur-based extreme pressure (EP) additive were added to rapeseed oil to increase the lubrication and cooling properties of the machining region. In this study, three lubricants were used to machine titanium alloy: rapeseed oil+graphene+sulfur-based EP additive, rapeseed oil+sulfur-based EP additive, and rapeseed oil; and the subsequent wear of cutting tools, cutting temperature, surface roughness, and cutting force were compared. The most favourable results were found for the combination of rapeseed oil+graphene+sulfur-based EP additive, effectively decreasing the temperature of the cutting area and wear of cutting tools. In comparison with rapeseed oil, the flank wear value decreased by 56.4%. Similarly, the surface roughness and cutting force with the rapeseed oil+graphene+sulfur-based EP additive were lowest, showing a decrease of 36.1% and 27.0% respectively when compared with rapeseed oil.

1 Introduction

As a research hotspot in the field of machining, the minimal quantity of lubricant (MQL) has been extensively applied in the turning of titanium alloy ^[1]. In the MQL environment, a small amount of cutting fluid (10-100ml/h) is atomized together with compressed air and sprayed to the cutting area as a lubricating and cooling aerosol ^[2]. The consumption of mineral oil as the MQL is lower in comparison to water injection machining, but the mineral oil is not recovered during evaporation. Evaporation of mineral oils can be harmful because they are highly toxic, non-renewable, and costly to dispose of. Therefore, a research priority is to make use of vegetable oil in MQL machining ^[3].

In the machining of titanium alloy, vegetable oil-based MQL upgrades surface quality and reduce wear on cutting tools by virtue of its superior cooling and lubricating properties ^[4]. Rahim and Sasahara studied the life of cutting tools when using palm oil in the course of drilling titanium alloy. The results demonstrate that in the MQL environment, the lifespan of cutting tools was extended by 306% compared with dry cutting ^[5]. Khan et al. studied the impact of vegetable oil-based cutting fluid on cutting properties in the MQL turning of low alloy steel (AISI9310). They concluded that compared with water injection machining, MQL using vegetable oil-based cutting fluid can lower the temperature of the average chip-cutter interface by 10%; and enhance the formation mode of the chip, wear of cutting tools, and surface finish to different degrees ^[6]. Vegetable oil boasts more superior lubrication and cooling properties, chiefly because oleic acid and ricinoleic acid contained in vegetable oil provide high binding energy and a low coefficient of friction ^[7].

Thus, in a bid to further enhance cooling and lubrication properties, a range of nanoparticles have been dispersed into vegetable oil, following the heat transfer enhancement theory of solids ^[8]. Su et al. compared experiments with dry turning and concluded that the addition of graphite nanoparticles under

MQL conditions can reduce the cutting force by 26% and the cutting temperature by 21% ^[9]. Rapeti et al. mixed MoS₂ nanoparticles with different vegetable oils in the MQL environment. The results suggested that MQL fluid with nanoparticles can decrease the wear of cutting tools, cutting force, cutting temperature, and surface roughness in comparison with other selected machining environments ^[10]. For Al₂O₃ nanoparticles, Hadi and Atefi investigated the effect of Al₂O₃NMQL in the milling processes of AISI D3 steel and found that the surface roughness was 25% less than that of pure MQL ^[11]. Sharma et al. compared the simulation and experiment of nano-additive based on alumina/multi-walled carbon nanotubes in the course of turning. The results indicated that the coefficient of friction on the rake face of cutting tools was decreased and the temperature distribution was uniform ^[12].

Apart from that, an extreme pressure (EP) additive provides low viscosity, favorable water solubility, and a high lubricating function. Extreme pressure additive reacts with the surface at high temperature and under high pressure, absorbing the surface and decreasing the shear stress ^[13]. Babur Ozcelik et al. compared the properties of four vegetable oils in a turning test, including EP additive and two kinds of commercial cutting fluid (semi-synthetic and mineral). They found that EP additive brings out the best in surface roughness, feed force, and wear of cutting tools ^[14]. Maruda et al. figured out that in comparison with dry cutting, phosphate-based EP additive decreased friction in the contact zone between the cutting tool and the workpiece, thereby lowering the parameters of selected surface topography by 6–38% and the wear of flank surface by 23%. The reason behind these findings is the high-concentration anti-wear friction film that takes shape on the machined surface ^[15].

Previous studies have shown favorable results by adding a range of additives to vegetable oil, but most of the studies are restricted to one additive, which may make the cutting fluid play an incomplete role in the machining region. Sulphur is extensively applied as an additive in cutting fluid because of its special structure and properties. It also plays a role in reducing friction, compression resistance, and dispersion in the machining region. Similarly, graphene can be used as an additive in cutting fluid to decrease the generation of heat and enhance the heat absorption at the contact interface of the tool-chip and the tool-workpiece ^[16]. Thus, it may be possible to further enhance the friction performance and heat absorption of the cutting area by taking graphene nanoparticles and sulfur-based EP additive as additives to the cutting fluid. This paper evaluated the influence of graphene nanoparticles and sulfur-based EP additive on turning titanium alloy from four points: wear of cutting tools, cutting temperature, surface roughness, and cutting force.

2 Experimental Design

2.1 Workpiece Materials and Tools

The material used in this study was titanium alloy Ti6Al4V, with a diameter of 30 mm and a length of 200 mm. A carbide blade was used, with the model being DCMT11T304-SMIC907. The machining method

was cylindrical turning. The chemical composition of the workpiece is displayed in Table 1, and its chief mechanical properties are listed in Table 2. The parameters of the cutter are detailed in Fig. 1.

Table 1
Ti6Al4V chemical composition

Element	Al	V	O	Fe	C	H	N	Ti
Weight(%)	5.72	4.1	0.1	0.004	0.02	0.005	0.022	Balance

Table 2
Ti6Al4V mechanical properties

Young Modulus	Shear Modulus	Ultimate Tensile Strength	Hardness	Poisson Ratio
110GPa	40GPa	1020MPa	348HV	0.34

2.2 Test Plan

Three machining conditions were compared as below: 1) rapeseed oil + graphene + sulfur-based EP additive, 2) rapeseed oil + sulfur-based EP additive, and 3) rapeseed oil. The cutting speed was set to 60 m/min and 100 m/min. The feed speed was $f = 0.1$ mm/rev and the cutting depth was 0.5 mm. Under a range of machining conditions, the turning length was 80 mm. A new blade was applied after turning under each condition.

2.3 Measuring Equipment and MQL System

The computer numerical control lathe used in the test was the CAK4085nj, and the temperature of the machining region was measured using a FLIRT630sc infrared thermal imager. The wear of cutting tools was measured by VMX-2000C ultra-large depth-of-field optical three-dimensional microscope. The microscopic surface morphology of the workpiece was observed using a ZEISS thermal field emission scanning electron microscope and the force during machining was measured with a Kistler9257b three-dimensional dynamometer. The cutting tool was installed on the dynamometer by a specially designed fixture, and the cutting force in the machining process was measured with a DAQ card and Dynoware software. The test device is displayed in Fig. 2.

The roughness of the machined surface was measured using a TR240, with a sampling length of 0.8 mm. Measurements were made by dividing the workpiece into four sections on average, randomly selecting six points in each section along the circumferential direction, and then measuring the 24 selected points and calculating an average value. This was done to sample the workpiece area comprehensively and decrease errors, as displayed in Fig. 3.

The outlet temperature of the SUNAIR of MQL equipment was -10°C , the air pressure of the air compressor was 10 bar, and the liquid flow rate of the nozzle was 70 mL/h. The sprayed liquid formed a

complete cone, which was around 15 degrees. The nano nozzle exerted the best effect in the spraying range with a length of 190 mm, as presented in Fig. 4. Therefore, the tool was used within this effective parameter range during the test.

2.4 Preparation of the Cutting Fluid

Both the one-step and two-step approaches are commonly used to disperse nanoparticles into solution^[17]. In this study, the two-step approach was chosen. The content of graphene nanoparticles was 0.5%, and the content of sulfur-based EP additive was 12%. The chosen vegetable oil was rapeseed oil with a single layer of graphene applied.

The rapeseed oil, graphene nanoparticles, and sulfur-based EP additive were weighed using a high-precision electronic balance (precision = 0.001 g). The solution was thoroughly stirred with a magnetic stirrer and then dispersed with an ultrasonic disperser. The mixing process is displayed in Fig. 5. The dispersion state of graphene when observed under an optical microscope is presented in Fig. 6.

After the machining was finished, the surface of the workpiece was cleaned to prevent the cutting fluid from remaining on the surface of the workpiece and interfering with EDS element testing.

3 Results And Discussion

3.1 Wear of Cutting Tools

The wear value V_b of the flank surface of cutting tools directly embodies the service life of the tools. Figure 7 shows the wear length of the flank surface under three machining conditions at 60 m/min and 100 m/min. It can be seen that the order of wear length of the flank surface from small to large was rapeseed oil + graphene + sulfur-based EP additive < rapeseed oil + sulfur-based EP additive < rapeseed oil. The wear on the cutting tools was the most severe with rapeseed oil, and the wear length of the flank surface was 0.262 mm (60 m/min) and 0.436 mm (100 m/min). However, after adding sulfur-based EP additive into rapeseed oil, the wear of the flank surface of cutting tools was significantly reduced, at 0.206 mm (60 m/min) and 0.247 mm (100 m/min). Most importantly, the cutting tools with rapeseed oil + graphene + sulfur-based EP additive experienced the smallest wear, at 0.132 mm (60 m/min) and 0.190 mm (100 m/min). In comparison with rapeseed oil at cutting speeds of 60 m/min and 100 m/min, the wear length of the flank surface of rapeseed oil + graphene + sulfur-based EP additive was decreased by 49.6% and 56.4%, respectively.

The temperature of the machining region plays a vital role in the wear of cutting tools, as displayed in Fig. 8, which demonstrates the temperature comparison of two cutting speeds under three machining conditions. The temperature was highest with rapeseed oil at 158.3°C (60 m/min) and 177.6°C (100 m/min). Rapeseed oil and sulfur-based EP additive were 132.8°C (60 m/min) and 147.2°C (100 m/min). Rapeseed oil + graphene + sulfur-based EP additive was the lowest temperature at 108.3°C (60 m/min) and 124.5°C (100 m/min). Under the action of vegetable oil, the molecules of sulfur-based EP additive

readily react with the surface of cutting tools. The instantaneous high temperature and high pressure on the friction surface resulted in the S-S bond and C-S bond in the molecules of EP additive to break and generate organic iron mercaptide and inorganic films of iron sulfide^[18]. Such inorganic films hinder the contact between the cutting tool and the workpiece, reducing the wear and extreme pressure. This, in turn, reduces the temperature of the cutting area and the wear of the cutting tools. Likewise, after adding graphene nanoparticles into rapeseed oil, the temperature decreased even further. Graphene as an additive also reduces the temperature of the cutting area and the wear of the cutting tools.

3.2 Surface Roughness

Surface roughness exerts an enormous influence on parts. The smaller the surface roughness, the more complete the contact between mating surfaces and the smaller the wear. It also influences the fatigue strength of the workpiece. A workpiece with large surface roughness is uneven and the stress is concentrated on the raised sections. Figure 9 lists the average surface roughness of each machining environment at two different cutting speeds. It shows that the order of surface roughness from small to large was rapeseed oil + graphene + sulfur-based EP additive < rapeseed oil + sulfur-based EP additive < rapeseed oil. Compared with rapeseed oil alone, oil + graphene + sulfur-based EP additive decreased the surface roughness by 30.6% at 60 m/min and 36.1% at 100 m/min. The lowest surface roughness was found for rapeseed oil + graphene + sulphur-based EP additive.

Chips stuck on the workpiece surface, along with scratches on the workpiece surface caused by chips stuck on the cutting tool, can decrease the surface roughness of a workpiece. The results from this study show that larger and a higher number of chips adhered to rapeseed oil, and the adhesion was more severe, as displayed in Fig. 10(a) (red region). However, chip adhesion was lower in rapeseed oil with sulfur-based EP additive, as shown in Fig. 10(b) (red region), although irregular scratches were discovered on the surface of the workpiece, as indicated in Fig. 10(b) (yellow region). Under the machining conditions of rapeseed oil + graphene + sulfur-based EP additive, the volume of adhered chips became smaller, as displayed in Fig. 10(c) (red region).

The reason behind these findings is that as there is no additive in the rapeseed oil, the blade is tightly attached to the workpiece, which results in increased friction force and an inability to disperse heat. This results in the chips clumping together and adhering to the surface of the workpiece, as presented in Fig. 11(a). The direct contact between the cutting tool and the workpiece can be alleviated by adding sulfur-based EP additive to rapeseed oil^[19]. Sulfur-based EP additive decreases friction and pressure on the surface of the cutting tool-workpiece and then lowers the cutting temperature. Low temperature is not favorable for the aggregation of chips and may inhibit their adhesion. In addition, low temperatures can inhibit the peeling of chips on the cutting tool more easily, which leads to increased hardness of the cutting tool and helps the tool to form scratches on the surface of the workpiece, as shown in Fig. 11 (b). However, the heat absorption and lubrication of the cutting fluid can be increased considerably by adding graphene nanoparticles into rapeseed oil^[20]. The heat in the cutting area was dispersed to a greater extent, which effectively inhibits the agglomeration of chips, decreases the adhesion of chips to the

surface of the workpiece, and causes the surface roughness to decrease further, as demonstrated in Fig. 11(c).

3.3 Cutting Force

Figure 12 shows that the order of cutting force from small to large was rapeseed oil + graphene + sulfur-based EP additive < rapeseed oil + sulfur-based EP additive < rapeseed oil at two cutting speeds of 60 m/min and 100 m/min. The figure reveals that the cutting force does not decrease distinctly after adding sulfur-based EP additive to vegetable oil, particularly at the cutting speed of 100 m/min, from 98.21N to 94.97N. This may be because sulphur-based EP additive is not effective enough in reducing cutting forces. However, after graphene was added, the cutting force distinctly decreased, and the cutting force achieved a minimum value of 73.17N at a cutting speed of 100 m/min. In comparison with rapeseed oil, the cutting force of rapeseed oil + graphene + sulfur-based EP additive decreased by 27.7% and 27.0% at the two cutting speeds of 60 m/min and 100 m/min, respectively.

As an additive, graphene decreases the cutting force more efficiently than sulfur-based EP additive. As revealed in Fig. 13, important elements of C and O were found in the EDS element of the chips adhered to the surface of the workpiece, but there was no element of S. This suggests that graphene can penetrate into the machining region and burn at high temperature instantaneously, thereby adhering to the chips. This may be because the single-layer graphene is characterized by ultra-thin layered structure and large specific surface area and thus it can readily penetrate into the contact area of the cutting tool-workpiece. Similarly, because of its netlike structure, graphene will only cover the tip of the cutter, which will be more beneficial to inhibiting direct contact between the tip of the cutter and the workpiece, increasing lubrication action and reducing cutting force.

4 Summary

In the turning process of Ti-6Al-4V, three machining conditions, respectively rapeseed oil + graphene + sulfur-based EP additive, rapeseed oil + sulfur-based EP additive, and rapeseed oil, were chosen for comparison. The machining effect was assessed from four perspectives: wear of cutting tools, cutting temperature, surface roughness, and cutting force. The conclusions were specifically outlined below:

1. the least wear of cutting tool occurred with the rapeseed oil + graphene + sulfur-based EP additive. When compared with rapeseed oil, the wear of the flank surface was lowered by 49.6% and 56.4% at cutting speeds of 60 m/min and 100 m/min, respectively. Graphene and sulfur-based EP additive were beneficial for lowering the temperature of the cutting zone and reducing the wear of cutting tools.
2. graphene and sulfur-based EP additive inhibited the agglomeration of chips, reducing the volume of adhered chips and upgrading the quality on the surface of workpieces. When compared with rapeseed oil, the surface roughness decreased by 30.6% and 36.1% at cutting speeds of 60 m/min and 100 m/min, respectively.

3. the cutting force was the smallest with the rapeseed oil + graphene + sulfur-based EP additive. When compared with rapeseed oil, the cutting force decreased by 27.7% and 27.0% at cutting speeds of 60 m/min and 100 m/min, respectively. The testing on elements revealed that graphene nanoparticles can play a lubricating and cooling role by penetrating into the machining region.

Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

Not applicable (Secret information)

Authors' Contributions

Ben Wang: Conceptualization, Methodology, Writing - Review & Editing.

Quanwei Yang: Formal analysis, Writing - Original Draft.

Jiawei Deng: Investigation.

Ning Hou: Data curation.

Xuezhi Wang: Supervision.

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Figures

Figure 1

Parameters of the cutting tools

Figure 2

Detailed schematic diagram of the test device

Figure 3

Measurement of surface roughness

Figure 4

Best spray range of nozzle.

Figure 5

Preparation of the cutting fluid

Figure 6

Dispersion state of graphene

Figure 7

Wear length of the flank surface of rapeseed oil+graphene+sulfur-based EP additive, rapeseed oil+sulfur-based EP additive, and rapeseed oil at two cutting speeds of 60 m/min and 100 m/min

Figure 8

Comparison of cutting temperatures of rapeseed oil+graphene+sulfur-based EP additive, rapeseed oil+sulfur-based EP additive, and rapeseed oil at two cutting speeds of 60 m/min and 100 m/min

Figure 9

Comparison of the surface roughness with rapeseed oil+graphene+sulfur-based EP additive, rapeseed oil+sulfur-based EP additive, and rapeseed oil at two cutting speeds of 60 m/min and 100 m/min

Figure 10

Surface micrographs of rapeseed oil (a), rapeseed oil+sulfur-based EP additive (b), and rapeseed oil+graphene+sulfur-based EP additive (c) at the cutting speed of 100 m/min

Figure 11

Mechanism diagram of action of additives

Figure 12

Comparison of the cutting forces with rapeseed oil+graphene+sulfur-based EP additive, rapeseed oil+sulfur-based EP additive, and rapeseed oil at two cutting speeds of 60 m/min and 100 m/min

Figure 13

Testing of EDS elements adhering to chips