Experimental Investigation the Cutting Temperature of PCD Tools Turning of Ti-6Al-4V with Graphene Oxide Nanofluids

Shuang Yi, John Mo, and Songlin Ding

Abstract—**In this paper there is comparative study of the cutting temperature mechanism of turning of Ti-6Al-4V with graphene oxide (GO) nanofluids and conventional fluids (CC). The influence of machining parameters, such as cutting speed, feed rate, cutting depth, coolant pressure and coolant concentrations were investigated when turning with polycrystalline diamond (PCD20) insert. The Transmission electron microscopies (TEM) of graphene oxide nanoparticles have been investigated and the thermocouple applied in measurement with cutting temperature in too-chip interface. The cutting temperature was reduced up to 15.13 ℃ when lower velocity, lower feed and higher coolant pressure applied. In the meantime, the cutting temperature decreased by 48.66 ℃ when GO nanofluids applied.**

Index Terms—**Ti-6Al-4V, graphene oxide, nanofluids, PCD, turning.**

I. Introduction

There has been growing concern among manufacturing industry regarding environmental issues, hence industries and academicians have started playing more significant role in the green manufacturing [1]-[3]. In traditional turning, the cutting parameters like cutting speed, feed rate, depth of cutting, coolant pressure and concentration, play an essential role [4], [5]. When conventional coolant is used, the cutting velocity is restricted up to a certain value, due to high heat generated at the cutting area [6]. This heat affects hardness and sharpness of the cutting tools and workpiece, which resulted in premature breakage. Therefore, a suitable coolant is required not only to reduce the cutting temperature and improve lubrication property, but also to be environment-friendly. The primary function of cutting fluids is to cool and lubricate the cutting tool-workpiece interface. Secondly, coolant should wash away the chips from machining zone to reduce friction force. The conventional way of cooling, however, serves the purpose up to a certain extent only by reducing cutting temperature and increasing lubrication. The excessive use of the conventional cutting fluids results in polluting the environment and is hazardous for earth and human beings [7]. Thus, lots of researches have used other coolants rather than the conventional coolant to reduce pollution to the environment. In the cutting fluids application, lots of fluids have been used in the manufacturing like the animal and vegetable oils, liquid nitrogen and additive particles with base fluid [8]. For example, Liu *et al.* [9] investigated that rare earth nanoparticles in lubricating oil could reduce the tribological performance and promote the surface quality. Ahmed and Kumar [10] pointed out that liquid nitrogen cryogenic cooling could reduce 28% of cutting temperature and 14% of cutting force. Su *et al.* [11] based research on the graphite as additive particles in vegetable oil could make the morphology of wear scars smoother and form a thin film on the friction surface to protect the workpiece. However, these methods were hardly used in industry, due to not being environmental-friendly and limitation of improvement. Graphene as a 2D material had different preparation methods including chemical vapour deposition (CVD), ultrasonic or mechanical exfoliation, and reduction of graphene oxide with different chemical procedures [12]. Graphene oxide as an oxidized graphene sheets contains basal planes and decorated with epoxide and hydroxyl groups, in addition to carbonyl and carboxyl groups located presumably at the edges (Lerf–Klinowski model). These oxygen functionalities ensure that the GO layers of GO hydrophilic and water molecules can readily intercalate into the interlayer galleries. It has excellent mechanical, electrical, thermal and optical properties and used in solar, touch screen and biosensors etc. GO nanoparticles' distinct thermal conductivity is up to 5800 w/mk [13] and makes GO nanoparticles a great heat transferring intermediary, which can be applied as metalworking fluids in difficult-to-cut materials such as titanium and its alloy. To reduce the cost of disposal and human problems, GO nanoparticles suspended in the conventional coolant is good alternate solution as it has good biodegradability, lubrication properties and low production cost. Metalworking fluids are essential on metal processing, which directly affect the cutting tool and workpiece causing reduced plastic deformation of the materials, complex mechanical and thermal stress. Kalita *et al.* [14] found that synthetic/mineral oils have good lubrication property, but their low thermal properties limited their use as metalworking fluids in machining. Micro-sized particles may lead to serious issues of clogging and caused drop off the pressure in the pipelines as those have poor stability due to the suspensions. To solve this problem, Pan

Ref. [15] reported that there was a significant improvement

Manuscript received June 19, 2018; revised May 25, 2019. This work was supported in part by the China Scholarship Council.

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doi: 10.18178/ijmmm.2019.7.3.443

in thermal conductivity of conventional coolant by addition of different nanoparticles. Different type of the size, shape, and material of particles could result in diverse of thermal property. For example, higher thermal conductivity can be found metallic nanoparticles with fluids than conventional fluids and the smaller the particle size led to the higher the thermal conductivities of fluids [16]. In the meantime, Murshed *et al.* [16] also presented that thermal conductivity would improve by increasing nanoparticles volumetric concentration in baseline cutting fluids. Yu *et al.* [17] reviewed a lot of research on the nanofluids and found that nanoparticles mixed in the conventional coolant could improve its thermal conductivity, which reduces the tool wear, surface roughness, cutting force in the machining. Based on the previous research, there are combination of nanoparticles which had been applied in the base fluids, such as ZnO-TiO_2/EG [18], Al_2O_3-Cu [19] and SiO_2 [20], [21]. Toghraie *et al.* [18] reported that higher ZnO-TiO_2/EG nanofluids volume fraction resulted in lower temperature due to the enhancement of thermal conductivity. Suresh *et al.* [19] experimentally investigated that 10.94% enhancement of Nusselt number compared with pure water when Al_2O_3-Cu nanofluids used. Sayuti *et al*. [21] pointed out that using nano-lubrication system with 0.5 wt.% concentration of SiO_2 in the mineral oil as coolant could result in minimum tool wear and surface roughness in turning AISI 4140 steel. Besides nanofluids thermal conductivity, the friction between the cutting zone plays a critical role in heat generation at cutting zone [22]. The nanofluids decrease friction causing decreased tool tip temperature which in turn decreases the hardness and sharpness of the tool cutting edge. As a result, the surface roughness decreased and the tool wear is less. Different researchers have performed metal cutting operation with various nanoparticle enriched cutting fluid. Lee *et al.* [23] noticed that the graphite nanoparticles in the conventional coolant would increase its lubricant property due to size of nanoparticles, which promoted the lubrication and reduced friction force. Moreover, Iyappan *et al.* [24] found that MoS_2 and graphite nanofluids resulted in lower friction thereby reducing surface roughness and cutting force in turning. Williams *et al.* [25] also reported that there exists a sticking friction area at the tool rake face and formed chip surface and the main effect of coolant is to act on this area. Peng *et al.* [26] showed that dispersed nanoparticles could easily penetrate into the rubbing surfaces and have a great elasto-hydrodynamic lubrication effect. Hence, it can be concluded that nanoparticles added in base fluids could improve lubrication performance by preventing contact between the workpiece surfaces. Najiha *et al.* [27] found that TiO_2 nanofluids had better lubrication performance during the machining of aluminum alloy, whereas nanoparticles concentration of 2.5% appeared to have less tool damage compared with traditional fluids used.

This paper has discussed the turning of Ti-6Al-4V with polycrystalline diamond (PCD20) insert under different types of coolants. GO nanofluids and conventional coolant have been used. The cutting temperature and surface roughness were measured and analyzed. Additional cutting experiments using conventional cutting fluid were conducted in order to find the increase in cutting performance. The comparative analysis of cutting temperature in turning under between GO nanofluids and base fluids had been done.

II. Experimental Details

A. Experimental Setup and Design

A round titanium alloy bar (Ti-6Al-4V) with the dimension of 160 mm of length and 20 mm of diameters was used as workpiece. The chemical composition (wt.%) and the mechanical properties of the workpiece are listed in Table I and Table II, respectively. PCD20 tools (CCMW09T308F-L1 PCD20) manufactured by SECO TOOLS were used in the turning tests. The clearance angle is 7 degree and the insert included angle is 80 degree of the tool. The cutting parameters are listed in Table III. The experiment system included a small pumping system (Fig. 1) which was specifically designed to supply the GO nanofluids during the machining process.

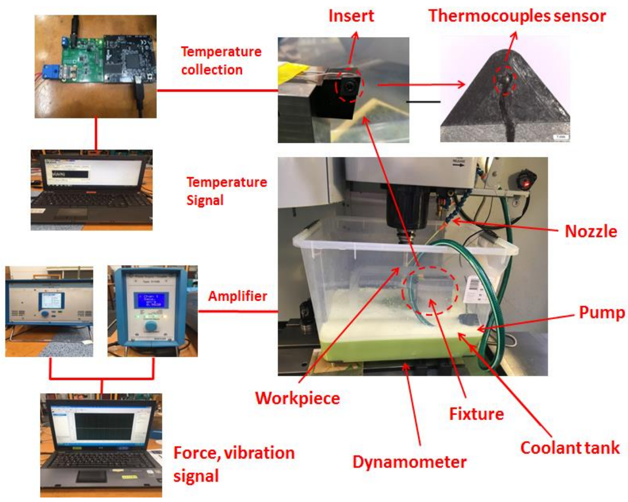

Fig. 1. Experiment setup for orthogonal cutting experiments.

TABLE I: Chemical Compositions of Ti-6Al-4V Alloy (wt.%)

Ti	Al	V	Fe	O	C	N	H
89.464	6.08	4.02	0.22	0.18	0.02	0.01	0.0053

TABLE II: Mechanical Properties of Ti-6Al-4V

Hardness (HV_{20})	600
Melting point (°C)	1660
Ultimate tensile strength (MPa)	832
Yield strength (MPa)	745
Impact-toughness (J)	34
Elastic modulus (GPa)	113
Density (g/cm^3)	4.50
Thermal Conductivity at 20 °C (W/mK)	6.6
Elongation(%)	8

TABLE III: Cutting Parameters for Turning Experiments

Cutting speed (m/min)	80/160/240
Feed (mm/rev)	0.05/0.1
Cutting depth (mm)	0.1
Coolant pressure (Bar)	1/10
Concentration (wt.%)	0.1/0.3/0.5
Coolant	GO nanofluids/ CC coolant

B. Coolant Preparation

Cutting fluid ROCOL_Ultracut Clear manufactured by ITW Polymers & Fluids Co., Ltd Australia was used as base fluids, its composition was shown in Table IV. The solid particles used in this study were GO nanoparticles. The average particle size and purity of the GO was 50nm and 99%, respectively. The Transmission electron microscopy (TEM) micrograph of the GO nanoparticles was shown in Fig. 2. A 20KHz ultrasonic processor, (Rittal GmbH & Co., Germany, 500 W) was used to break particle agglomerates in mixing GO nanofluids. No surfactant was used due to its influence on the effective thermal conductivity of nanofluids. It was observed that GO nanoparticles were uniformly dispersed after 24 hours and the complete deposition occurred after one week.

TABLE IV: COMPOSITION OF ROCOL_ULTRACUT CLEAR COOLANT

Mineral oil (solvent refined)	10-30%
Saponified natural oil	10-30%
Corrosion inhibitor	<1%
Biocide	<1%
Fluorescein dye	<1%
Water	30%-60%
Density	0.95g/cm^3

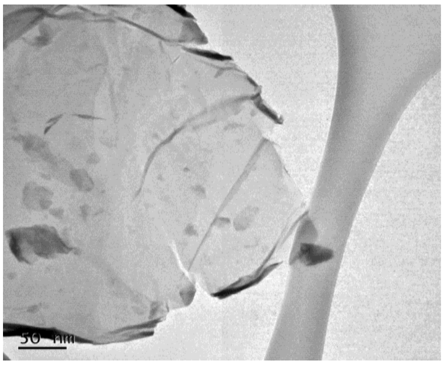

Fig. 2. TEM images of GO: Few-layer GO sheets.

III. RESULTS AND DISCUSSION

A. Cutting Temperature

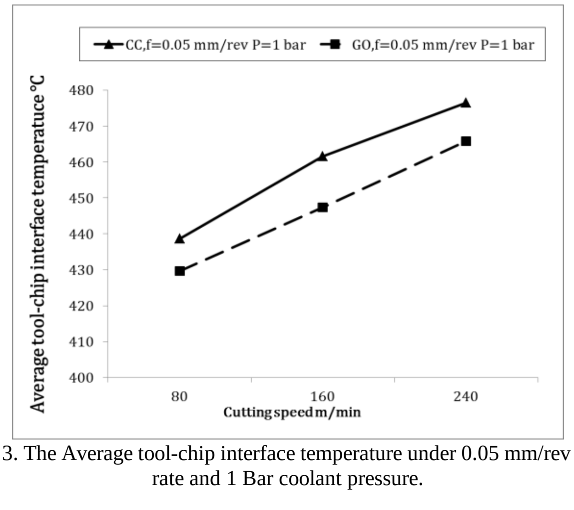

Fig. 3. The Average tool-chip interface temperature under 0.05 mm/rev feed rate and 1 Bar coolant pressure.

High cutting temperature may lead to dimensional errors of the machined surface and the elongation and increased wear of cutting tools. Lower cutting temperature not only contributes to the reduction in tool wear and machining errors, but also benefits the reduction in dimensional errors. The cooling effects of GO nanofluids were obvious according to the temperature measured in the cutting experiments. Fig. 3 shows the measured cutting temperature under 0.05 mm/rev feed rate and 1 Bar coolant pressure turning conditions. The active line stand for using CC coolant and the dotted line stand for using GO coolant. It could be obviously seen that when CC coolant was used, the cutting temperature was up to 476.414 ℃, which is higher than GO nanofluids were applied. This excessively high temperature led to galling of the workpiece to the inserts. The main reason of this high temperature is because much of coolant had been vaporized before reaching the cutting zone due to the increased temperature at the cutting edge. Moreover, with increased cutting speed, the cutting temperature is risen, due to the higher cutting speed resulted in higher cutting force. This increment of cutting force will lead to the amount of heat generated in the tool-chip interface, which cased to the higher cutting temperature.

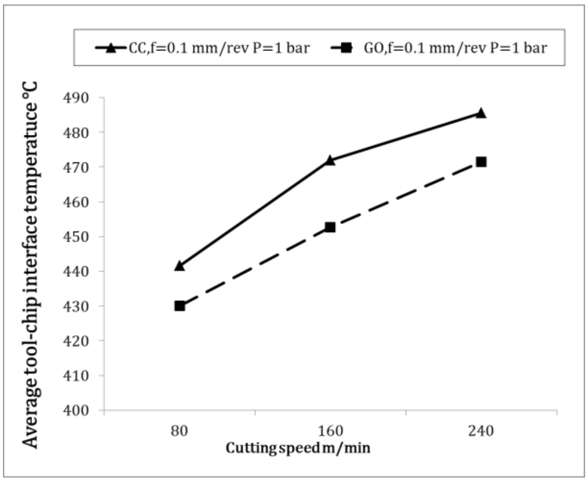

Fig. 4. The Average tool-chip interface temperature under 0.1 mm/rev feed rate and 1 Bar coolant pressure.

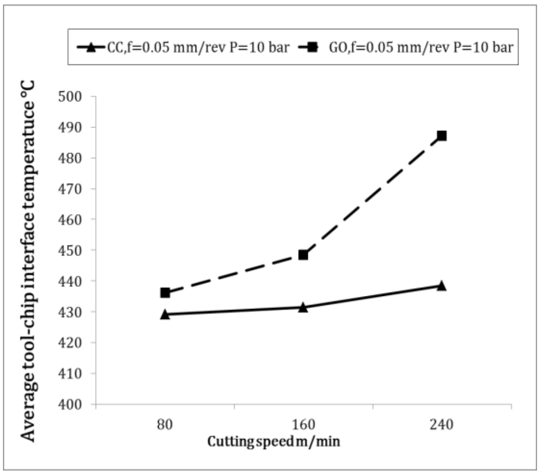

Fig. 5. The Average tool-chip interface temperature under 0.05 mm/rev feed rate and 10 Bar coolant pressure.

Fig. 4 shows the cutting condition of 0.1 mm/rev feed rate and 1 Bar coolant pressure was supplied. The feed rate is twice larger than Fig. 3 was used. It can be seen that cutting temperatures was extremely increase with larger feed rate, which is up to 485.475 ℃. This is owing to the large feed rate led to much more chip produced in the cutting zone. It would cause the chips accumulated and worse lubrication in the tool-chip interface, so that cutting temperature directly growth up. When GO nanofluids were applied, this is partially due to the increased thermal conductivity caused by the excellent thermal property of graphene oxide particles. The nanoparticles along the metal surface formed a thick, strong and durable film layer of lubricant [28]. The combined effect of GO nanofluids lubricant was the reason for reducing the cutting temperature.

Fig. 5 shows the cutting temperature under the condition of higher coolant pressure with different cutting conditions. It could be found that cutting temperature decreased up to 48.66 ℃ when the GO nanofluids were applied. Compared with previously results, higher coolant pressure and GO nanofluids were led to high efficiency of temperature reduction. The main reason was that higher pressure coolant could access the tool tip region more closely to ensure efficient lubrication of GO nanoparticles at the tool-chip area, which resulted in lower cutting temperature. Moreover, higher pressure coolant was able to remove the chips quickly from the cutting area, as in turning operation large amount of chips are generated in the cutting area, these chips could increase friction force and result in excessive cutting heat, if they are not removed from the cutting area [29].

IV. Conclusion

In this paper, several turning experiments were conducted to find effect of various concentrations of GO nanofluids and conventional coolant on tool wear, cutting forces, surface quality, cutting temperature, cutting vibration and the characterization of chip morphologies while turning titanium alloy. The following conclusions can were reached:

- When GO nanofluids were applied, the cutting temperature was decreased up to 48.66 ℃ under 0.05 mm/rev feed rate and 10 Bar coolant pressure.
- Lower cutting speed and higher feed rate yielded higher cutting temperature generated in the cutting zone.
- Higher coolant pressure led to lower cutting temperature efficiency, especially when GO nanofluids were applied.

Acknowledgment

The author would like to thank Mr Phil Francis, Mr Matthew Field and Mr Edwin Mayes of RMMF (RMIT Microscopy and Microanalysis Facility), Patrick Wilkins and Mark Overend of AML (Advance Manufacturing Lab) for their help in experiments. The authors' special thanks to China Scholarship Council for the scholarship provided (CSC Student ID: 201608240004).

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