Analysis of Chip Morphology in Drilling Ti-6Al-4V by Using Graphene Oxide Nanofluids

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Abstract. Titanium and its alloys have been widely used in various areas due to their superior mechanical properties. However, Titanium and its alloys have low elastic modulus and low thermal conductivity, which lead to extreme high temperature during the machining process and result in poor workpiece quality. The main objective of this paper is to investigate the effectiveness of graphene oxide (GO) nanofluids in drilling process of Ti-6Al-4V by using tungsten carbide tools. The spiral chips were obtained when GO nanofluid was used and squeezed string chips were obtained when conventional coolant was applied. By analysing the back surface of the chips, it was found that the high coolant pressure resulted in better chip formation, which had less scratch and plunking. In addition, by using higher concentration of GO nanofluids, the adhesion phenomenon was found significantly reduced.

1. Introduction
Titanium and its alloy have high specific strength, better corrosion resistance and relatively lighter weight. Hence, it has been widely used in bioengineering and aerospace industry for medical implants and turbine blades [1, 2]. However, titanium and its alloys are hard-to-machine because of their low elastic modulus, low thermal conductivity and high chemical reactivity, which result in welding during the machining process. The welding phenomenon and low thermal conductivity of the work piece lead to significant reduction of tool life and machine quality.

Chip formation is a critical characteristic which reflects the surface quality and machining stability. The chip formation is governed by tool geometry and cutting parameters. The well-broken chips imply a smooth drilling process. In addition, well-broken chips are preferred because long chips would block the flutes which require more torque, possibly damage the drill bit [3]. Generally, four different types of chips will be generated during the drilling process, which are segmented chips, lamella chips, string chips and spiral chips. The chips are broken when the drilling process is smooth. However, the chips will not break when drilling the ductile materials [4]. In addition, the poor lubrication of coolant could result in more scratch and plunking on the back surface of the chip. The lamella structure of the free surface could deform due to the high temperature during the machining process [5].

Cutting temperature play an important role in machining processes. High cutting temperature may increase the tool wear rate and reduce the tool life. Also, the high cutting temperature would increase
the chemical reactivity and cutting stress which cause crater wear, flank wear and chipping failure. These problems can lead to the reduction of machining quality. As a result, reduce the cutting temperature is important in machining process [6, 7]. The coolant pressure has huge influence on cutting temperature especially when using the internal cooling approach [8]. The low-pressure jet cannot get into the cutting edge due to the vapor blanket formed by high temperature, but high coolant pressure can reduce the cutting temperature significantly. The low coolant pressure can only provide a little lubrication because most of the cooling fluid is not directed to the interface, therefore, high pressure coolant is able to overcome the chip flow to reach the secondary shear zone and provides a better lubrication. In addition, high pressure coolant has advantage in chip breaking to block the excessive contact between the chip and rake face of the tool.

Nanofluids consist of small amounts of nano-sized particles in the base fluid. Most studies have shown that nanofluids can improve the heat transfer rate, due to the increment of thermal conductivity [9]. Metal-based nanoparticles have been used as additives to increase the thermal conductivity and lubricant of the conventional coolant. However, graphene-based nanoparticles are introduced only in recent years although its thermo conductivity is even higher than metal-based nanoparticles, which is around 5500W/mK. This excellent thermal property makes graphene oxide an outstanding media in conventional coolant [10]. The graphene-based nanoparticles in the conventional coolant would promote its lubricant performance because the small size of nanoparticles promote the lubrication and reduce the friction force. The dispensability and stability of the nanofluids would be influenced by different particle concentration; the optimal concentration of graphene can improve the performance of the coolant remarkably [11].

It has been concluded in many researches that nanoparticles added into the conventional coolant can improve the quality of metallic workpiece. However, how the graphene oxide (GO) nanofluid would affect drilling process of titanium remains unclear. In addition, only a little research has investigated how the GO nanofluid coolant pressure and concentration affect the machining quality. Hence, this paper is focused on how GO nanofluid, GO nanofluid coolant pressure and concentration increase the machining performance of Ti-6Al4V.

2. Experiment Setup

The titanium alloy workpiece (Ti-6Al-4V) has the dimension of 250 mm × 30 mm (L×D). The workpiece was mounted on the spindle of a CNC milling machine (HASS VF1-HRT160 3-axis vertical CNC machine). The chemical composites and material properties of workpiece are shown in Table 1 and Table 2, respectively. The tungsten carbide drill was selected for drilling experiment. The drill bit has diameter of 8mm with point angle of 140-degree. The detailed experiment parameters are shown in Table 3. A coolant circulation system was designed to pump the coolant. A power supplier was used to drive the rotary pump. A valve was connected between the pump and outlet pipe to regulate the coolant pressure. The coolant pressure varies from 10psi to 150 psi (0.69bar to 10.34bar). A tank has used to contain the coolant and collect the backflow of the coolant. The inlet pipe has plugged into the tank to draw the coolant. The aluminum block has a hollow path inside to deliver the coolant to the oil hole. A reservoir was fixed on the aluminium block and surrounds the drill and chunk to collect the sprayed-out coolant (Fig. 1).

| Ti (wt. %) | Al (wt. %) | V (wt. %) | Fe (wt. %) | O (wt. %) | C (wt. %) | N (wt. %) | H (wt. %) |
|------------|------------|-----------|------------|----------|----------|----------|----------|
| 89.464     | 6.08       | 4.02      | 0.22       | 0.18     | 0.02     | 0.01     | 0.0053   |
Table 2. Work piece Ti-6Al-4V Mechanical Properties

| Property                        | Value   |
|--------------------------------|---------|
| Hardness (HV20)                | 600     |
| Melting point (°C)             | 1660    |
| Ultimate tensile strength (MPa)| 832     |
| Yield strength (MPa)           | 745     |
| Impact-toughness (J)           | 34      |
| Elastic modulus (GPa)          | 113     |
| Density (g/cm³)                | 4.50    |
| Thermal Conductivity at 20 °C (W/mK)| 6.60 |
| Elongation (%)                 | 8       |

Table 3. Drilling Experiment Cutting Parameters Setting

| Parameter                      | Setting                              |
|--------------------------------|--------------------------------------|
| Tool Material                  | Tungsten Carbide Drill               |
| Cutting Depth                  | 8mm                                  |
| Pressure                       | 1Bar/10Bar                           |
| Coolant                        | 0 wt. % GO/0.1 wt. % GO/0.3 wt. % GO |
| Feed Rate                      | 0.05mm per rev./0.1 mm per rev.     |
| Cutting Speed                  | 60m per min/120m per min            |

Figure 1. Schematic Drawing of Drilling Experiment Setup

The Graphene Oxide (GO) nanoparticles are supplied by Hengqiu Graphene Science Co., Ltd, China. Base fluid used was ROCOL-Ultracut clear coolant. The properties of GO nanoparticles and base fluid are shown in Table 4 and Table 5, respectively. Nanofluids were formulated by adding GO powder into base fluid at 0.1 wt. % and 0.3 wt. % of concentration. To avoid agglomeration and obtain uniform suspension, the fluids were placed into an ultrasonic bathtub for a period of 30 minutes.

Table 4. Graphene Oxide Parameter

| Purity (wt. %) | Thickness | Layer Diameters (μm) | Layer (m²/g) | Specific Surface Area |
|----------------|-----------|----------------------|--------------|-----------------------|
| >95            | 1.0-1.77  | 0.5-5                | 1-5          | 300-450               |

Table 5. ROCOL Ultracut Clear Coolant Properties

| Component                  | Content   |
|----------------------------|-----------|
| Saponified Natural Oil     | 10-30%    |
| Corrosion Inhibitor        | <1%       |
| Biocide                    | <1%       |
| Fluorescein Dye            | <1%       |
| Water                      | 30-60%    |
| Density                    | 0.95 g/cm³|
3. Discussion

3.1. Chip Formation
The chip formation is an essential factor to analysis the roughness of the drilling process. The chips are broken when the drilling process is smooth. However, the chips will not break when drilling the ductile materials [2]. Thus, continues chips were observed in the experiment. It was observed that the squeezed string chips were generated when conventional coolant was used. In contrast, spiral chips were formed when GO nanofluids was used as the coolant. This is because the cutting temperature during the machining process when conventional coolant was applied was higher than that when the GO coolant was used. The high temperature softened the chips, which resulted in the formation of squeezed string chips. In contrast, the GO nanoparticles added into the conventional coolant increased the thermal conductivity of the conventional coolant dramatically, which dissipated more heat at the cutting edge during the machining process. As a result, the cutting temperature can be reduced by using GO nanofluid.

3.2. Coolant Pressure
Coolant pressure has a huge impact on surface quality especially when the wall of the workpiece is thin and internally cooling approach is used [12, 13]. Fig. 2 shows the chip generated under the same cutting condition (0.3%wt. concentration GO nanofluids, feed rate is 0.05mm/rev, spindle speed 120m/min) except coolant pressure (1 bar and 10 bar respectively). Less scratches and plunking were observed on the back surface of the chip, which generated under the 10bar coolant pressure. This is because when under low coolant pressure, the coolant vaporised before it reached the cutting zone due to the high temperature. Hence, the coolant can only provide a little lubrication at the cutting zone. However, at higher cooling pressure, the jet flow can get into the cutting zone. Hence, the coolant could provide a better lubrication compared with low coolant pressure. Since the lubrication was improved, less friction was generated during the machining process. As a result, the cutting temperature could be reduced. In addition, the temperature could reduce significantly by using high pressure jet of cutting fluid, due to the faster heat dissipation and higher heat transfer rate.

![Figure 2. Chip back surface by using different coolant pressures: a) 1bar; b) 3bar](image)

3.3. Concentration of Nanoparticles
The chip adhesion needs to be averted during the machinery process. The melt droplet could adhere on the workpiece, cutting edge and chips, which has a negative impact on cutting quality. The higher local cutting temperature, as a result, increase the chip adhesion tendency [14]. Fig. 3 shows that by using the 0.3wt. GO nanofluids, least chip adhesions were formed on the chip. This is because the GO nanoparticles which added into the base fluid enhanced the thermal conductivity of the cutting fluid. Thus, during the machinery process, the cutting fluid dissipated more heat from cutting edge, as a result, the cutting temperature was reduced. Moreover, the nanofluids have the ability to form a film between the cutting edge and workpiece which caused ball bearing effect [15], hence the lubrication effect of GO nanofluids was better than the conventional coolant. As a result, the friction during the machinery process is reduced, and less friction which result in less heat was generated. Furthermore, higher concentration of the GO nanofluids result in lower friction coefficient and higher thermal
conductivity of the nanofluids, thus less friction and heat were generated during the machining process. Therefore, 0.3wt. % resulted in a better chip formation among other fluids (0.1wt. % & conventional coolant).

Figure 3. Chip back surface by using different coolant and concentrations: a) Conventional coolant; b) 0.1wt. % GO nanofluid; c) 0.3wt. % GO nanofluids

4. Conclusion
Cutting experiments have been conducted to find how nanoparticle as an additive GO into the conventional coolant affect the machining process of Ti-6Al-4V. The effective of coolant pressure and concentration have also been investigated. It can be observed that by using GO nanofluid, the spiral chips were formed, which indicate the machining process was smoother compared with using conventional coolant which squeezed string chips were generated. By analyses SEM images, the scratch and plunking on the back surface was found to be less when 10 bar coolant pressure was applied. In contrast, the massive scratch and plunking was found on the back surface when 1 bar coolant pressure was applied. In addition, when 0.3wt. % GO nanofluid was used, the adhesion on the back surface of the chips was more significant than 0.1wt. % GO nanofluid, even more than conventional coolant.

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