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Effect of air blow pressure in ultrasonic vibration cutting of steel using PCD tools

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Abstract

Ultrasonic vibration has already been proven effective in suppressing the diamond tool wear when machining of steel since more than two decades ago. It has already been successfully applied by industry to fabricate optical molds made of stainless steel, and longer mold life has been achieved compared to nickel plated mold in plastic injection molding. Although it has been understood that chemical tool wear in the machining process is suppressed by ultrasonic vibration motion of the tool, the inherent reason for this suppression mechanism is still not clear. In the authors' previous study, it has been concluded that the generally speculated reason for the suppressed diamond tool wear by researchers (i.e. reduced cutting temperature) may not be correct. Instead, the coolant media, air or mist, could play an important role in suppressing the chemical wear. The expected mechanism is that the gap generated by the ultrasonic vibration between the tool and workpiece will allow the air or mist to penetrate to pollute the freshly machined steel surface and hence slow or prevent its chemical reaction with diamond. In this study, the authors investigated the effect of air blow pressure on the cutting performance. Dry air coolant without any mist is used to exclude the effect of atomized oil or water. It was found that increased air blow pressure to a certain extent is able to further reduce the PCD tool wear in ultrasonic vibration cutting of steel. Such phenomenon could be caused by the enhanced pollution of the freshly machine steel surface at higher air blow pressure with higher air density.

Ultrasonic vibration-assisted cutting; Ultra-precision machining; PCD; Tool wear

1. Introduction

Diamond turning is widely used in optics manufacturing industry to produce optics components and molds made of plastics or metal alloys. Unfortunately, only a few metal alloys (Al, Coper, etc.) can be directly cut using diamond tools with acceptable cutting distance. There are various metal alloys which cannot be directly machined using diamond (Steel, Nickel, Tungsten, etc.). Paul et al. [1] studied the chemical aspects of diamond tool wear in diamond turning, and identified that the chemical affiliation between diamond and the non-diamond-turnable metals is caused by the unpaired *d*-shell electrons of the metal element.

Steel is the mostly widely used engineering metal alloy, and it is necessary to note that iron has 4 unpaired *d*-shell electrons. The industry usually plates a layer made of nickel-phosphorus alloy on a steel substrate, and then conducts the cutting process on such diamond-turnable material. But the nickel alloy will start recrystallizing when the temperature is above 400°C, and its mold life is also much less than steel mold [2]. In order to directly cut steel using diamond without additional plating of nickel alloy, researchers have invented two major alternative methods to realize it: ultrasonic vibration cutting (UVC) [3] and surface nitriding [4]. Between these two technologies, UVC is the most promising one and has already been successfully adopted by industry for injection molding of plastic optical components with directly machined steel molds [2].

Although UVC has already been applied in machining of steel for 26 years, there is no research paper studying the effect of coolant media on the tool wear condition and cutting performance. In the authors' previous study [5], we have identified that the generally speculated reason for the suppressed diamond tool wear by researchers (i.e. reduced cutting temperature) may not be correct. Instead, the coolant media (air or mist) could play an important role in suppressing the chemical wear. Hence, it is necessary to conduct more experiments to investigate and understand the effect of coolant media.

In this paper, we have conduct experiments to study the air blow pressure on the cutting performance in terms of tool wear and surface roughness during UVC of steel. It has been found that an appropriately higher blowing air pressure would mostly lead to reduced diamond tool wear and better surface finish. Speculated explanations have been provided for the phenomenon observed.

2. Experimental investigation

The UVC tests are conducted on a 5-axis ultra-precision machining system (Moore Nanotech 350FG). Polycrystalline diamond (PCD) tools manufactured by Sumitomo are used, with a 0° rake angle, 11° clearance angle and 0.2mm nose radius. The workpiece is made of stainless steel (STAVAX), provided by ASSAB with a hardness of 49 HRC. During the experiments, an UVC system generates a 2D elliptical vibration with 4µm peak-to-peak amplitudes (a=b=2µm) on both directions, as shown in Figure 1(a). The depth of cut and feed rate are set to be 5µm and 3µm/rev. Each face cutting round starts from the workpiece edge (40mm diameter) and ends at 28mm diameter, with a cutting distance of 200m approximately, as shown in Figure 1 (b) and (c).

Four rounds of cutting tests for each PCD tool are conducted for every air blowing pressure condition (20, 40, 80 and 100 PSI), and a total cutting distance of 800m for each tool has been reached. Furthermore, as the gas density and instant pressure of blowing air quickly drops once the air is out from the nozzle, two locations of the nozzle (far and close) to the insert are studied to investigate its effect on tool wear and cutting performance.

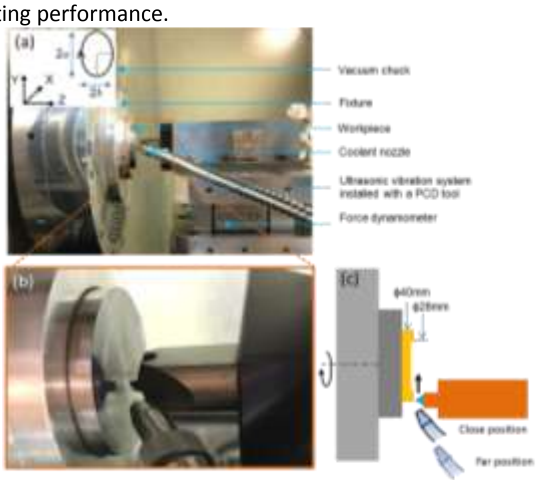


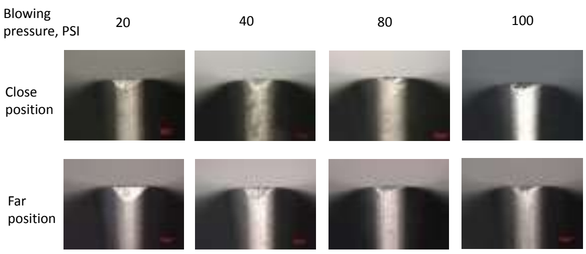
Figure 1. Experimental setup of the UVC test.

3. Results and discussion

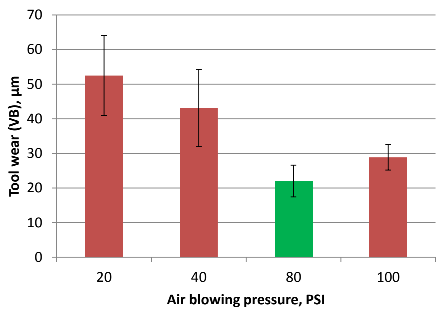
2.1. Tool wear conditions

The tools are taken out from the tool holder for tool wear investigation using microscopes every round of cutting test (200m cutting distance), and then put back on the tool holder with the identical position. Total cutting distance is 800m, and four times of investigation is conducted for each PCD tool.

Figure 2(a) and (b) show the tool flank wear condition after 800m cutting distance. It can be observed that increased air blowing pressure generally lead to a decreased tool flank wear, for both close and far positions of the coolant nozzle. But it is interesting to find that 100 PSI air blowing does not give further reduced tool wear compared to 80 PSI. It is necessary to note that the commonly utilized air blowing pressure by the industry for mist coolant in diamond turning is around 20~30 PSI.



(a)



(b)

Figure 2. (a) Tool flank wear condition for different air blowing condition; (b) Averaged flank tool wear (VB).

2.2. Surface roughness

The roughness of the machined workpiece and the cutting force are also investigated for every 200m cutting as well. A Taylor Hobson stylus profilometer is used to measure the surface roughness of the machined surface, using a single crystal diamond stylus tip of 2µm and 90° included angle. The cut-off length for the roughness calculation is set to be 0.08mm for all the roughness measurement. Figure 3 shows the average surface roughness with respect to the cutting distance for the close position. It can be observed that 80 PSI leads to the lowest surface roughness compared to all the other 3 air blowing conditions. It is interesting to note that 100 PSI does not lead to better surface finish, which could be caused by the induced tiny impact and vibration of the tool tip due to the significantly large air blowing velocity.

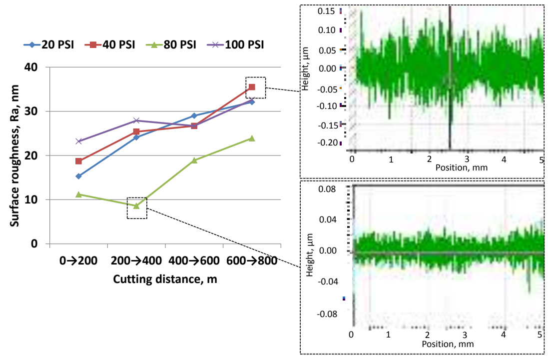


Figure 3. Surface roughness (*Ra*) results for the machined region.

3. Discussion

Based on the observed experimental results above, it can be derived that air blowing pressure has significant effect on the tool wear speed in UVC of steel using PCD tools. Generally speaking, increased air blowing pressure will slow down the tool wear rate. Two reasons could be explained for this phenomenon: i) increased air blowing pressure take away the heat generated during the cutting process and hence reduced the cutting temperature as well as the rate of chemical wear; ii) increased air blowing pressure lead to increased oxygen partial pressure for the cutting region, and hence increase the oxide generation speed and thickness on the freshly machined steel surface, which separate the direct contact between active iron atoms and the diamond atoms [5].

5. Conclusion

Based on the experimental results, conclusions can be compiled as follows: i) increased air blowing pressure to a certain extent (80 PSI in this study) will significantly slow the chemical tool wear rate of PCD tools in UVC of steel; ii) an extraordinarily higher air blowing pressure (100 PSI in this study) will introduce worse surface roughness as well as slightly increased tool wear compared to the optimal pressure value.

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