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A study of the diamond tool wear suppression mechanism in vibration-assisted machining of steel

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ABSTRACT

Inability of machining steel strongly inhibits the application of diamond machining in manufacturing industry, especially in the fields of ultra-precision and micro machining. In recent years, vibration-assisted machining (VAM) has been proved to be capable of efficiently suppressing the diamond tool wear in cutting steel. Currently, the prevailing speculation claimed by most researchers for such suppression is that the tool–workpiece flash temperature was reduced in VAM, which would slow the chemical reaction between iron on steel and carbon on diamond. However, the correctness of this speculation has not been proved by any experimental or theoretical research. In this paper, in order to understand the true wear suppression mechanism of diamond tools in VAM of steel, a study is conducted by measuring the workpiece temperatures and modeling the cutting energy consumption in both VAM and conventional cutting (CC). Based on the comparison results, it is concluded that the cutting temperature and energy consumption in VAM are not smaller than in CC, and hence the reduced diamond tool wear in VAM should not be caused by the claimed reduced temperature, especially when the material removal rate is very small. Finally, based on the EDS analysis and the comparison of experimental results under different air pressure, two probable reasons are proposed for the significantly reduced diamond tool wear in VAM of steel: (i) increase of gas pressure at the tool–workpiece interface and (ii) generation of an oxide layer on the freshly machined surface.

1. Introduction

The tool wear condition strongly affects various machining performances in ultra-precision diamond machining. After the diamond tool is worn, it is more likely to obtain bad surface quality, larger cutting force, chatter, and larger form error. All of them are harmful or even detrimental to the machined surfaces/parts, and definitely should be avoided in most cases. Generally speaking, in diamond turning of most non-ferrous metal materials (copper, aluminum, electroless nickel, etc.), the tool is worn very slowly if the cutting conditions are well controlled. Stable and good surface quality can be kept even after several hundreds of kilometres cutting length. Wear of diamond tools can be caused by several different mechanisms, and multiple mechanisms may work together under particular circumstances. Evans and Bryan (1991) used four categories to classify the wear mechanism: (1) adhesion and formation of a built-up edge, (2) abrasion, micro chipping, fracture and fatigue, (3) tribothermal wear and (4) tribochemical wear. Most of them can be minimized or eliminated by carefully choosing the machining conditions, but tribochemical wear occurs in diamond turning of some particular materials (like steel), and causes very fast tool wear, which is difficult to avoid. Paul et al. (1996) did an extensive study on the diamond-turnable materials and, based on their investigation, explained the chemical wear of diamond tools using the formation of carbon-metal complexes with unpaired *d*-shell electrons from the workpiece. For example, all the diamond-turnable elements have no unpaired *d*-shell electrons, while all the non-diamond-turnable elements must have unpaired *d*-shell electrons ranging from 1 to 5. It is necessary to note that iron, which is highly non-diamond-turnable, has 4 unpaired *d*-shell electrons.

In machining those non-diamond-turnable materials like steel, tribochemical wear mechanism plays the leading role. Evans and Bryan (1991) distinguished three types of possible tribochemical wear: oxidation, diffusion wear, and catalyzed graphitization. In fact, Thornton and Wilks (1979) have found that diamond oxidation does not happen for common situations in ultra-precision machining, because the tool tip temperature in an ultra-precision cutting process is considered much lower than the diamond oxidation temperature (900–1000 K). Shewmon (1963) stated that diffusion wear occurs when the carbon atoms of the diamond lattice enter the workpiece, during which atoms move into the vacancies in a solid metal lattice until vacancies are filled. Graphitization

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Nomenclature

a	tangential amplitude
b	thrust amplitude
x	x-axis coordinate
y	y-axis coordinate
t	time
ϕ	phase shift
ω	angular frequency
v_c	nominal cutting speed
$(v_t)_{\max}$	maximum tool vibration speed
R_s	speed ratio in VAM
γ	tool rake angle
θ	transient tool velocity angle
t_o	instantaneous undeformed chip thickness
t_c	critical undeformed chip thickness for ductile–brittle transition
a_p	nominal uncut chip thickness
t_A	time instant when the tool edge passes point A
t_B	time instant when the tool edge passes point B
t_C	time instant when the tool edge passes point C
t_D	time instant when the tool edge passes point D
t_F	time instant when the tool edge passes point F
t_G	time instant when the tool edge passes point G
t_H	time instant when the tool edge passes point H
R_{max}	maximum resultant force
F_p	principal force
F_t	thrust force
L_c	cutting distance
W_{CC}	cutting energy consumption in CC
$W_{1D\text{-}VAM}$	cutting energy consumption in 1D VAM
$W_{2D\text{-}VAM}$	cutting energy consumption in 2D VAM
ΔT_{CC}	temperature rise in CC
$\Delta T_{1D\text{-}VAM}$	temperature rise in 1D VAM
$\Delta T_{2D\text{-}VAM}$	temperature rise in 2D VAM

is the most frequently reported chemical wear mechanism of diamond tools in machining steel. From the view of chemistry, graphitization is actually the reverse process of diamond synthesis. During the graphitization process, carbon atoms of the diamond lattice revert to the stable graphite form. The uncatalyzed process is extremely slow, because the sp^3 hybrid orbitals are tightly interlocking the carbon atoms. Similar to the diamond synthesis process, the graphitization process can be catalyzed to a much faster rate using particular metals, by providing a path with a much lower energy barrier than the uncatalyzed process.

Inability of machining the non-diamond-turnable materials significantly reduces the application area of diamond machining in manufacturing industry, and researchers have never stopped paying efforts to develop new methods in order to apply diamond turning in machining those materials. The effective methods people have tried to suppress the quick diamond tool wear mainly include: (1) modifying chemical compositions of work material, (2) cooling the cutting process, and (3) applying ultrasonic vibration-assisted machining. Among these methods, ultrasonic vibration-assisted machining has been found to be the most promising technique for industry in terms of economical machine setup, few negative effects on machining accuracy, and long diamond tool life.

The vibration-assisted machining (VAM) technology was first introduced in the 1960s and has been progressively applied in the manufacturing industry. Based on the number of vibration modes, two main types of the VAM methods could be identified: 1D VAM (i.e. conventional vibration cutting), and 2D VAM (i.e. elliptical vibration cutting). Various experimental studies have shown that better cutting performance can be achieved in VAM of various materials compared to conventional cutting (CC). Such superior cutting performance includes smaller cutting forces, better surface quality, longer tool life, suppression of chatter, larger critical depth of cut in machining brittle materials, etc. Direct machining of steel using diamond is always a critical concern in manufacturing industry, especially in the field of mold/insert fabrication for optical lenses. Although electroless nickel plating acts as a substitute nowadays, its mold life and product quality are still much lower compared to the steel mold. It is because that, during the molding process, the amorphous layer of electroless nickel starts to re-crystallize when exposed to high temperatures (approximately >400 °C), which will degrade surface roughness of the molded plastic product. By employing VAM, it has been found by Moriwaki and Shamoto (1991) that diamond tools can be used to cut steel sustainably, with significantly extended tool life compared to CC.

For the reason of the reduced diamond tool wear in VAM of steel, Brehl and Dow (2008) have stated that most researchers attributed it to the experimentally measured reduced cutting force, which they believe will lead to smaller heat generation and reduced temperature in VAM. Such explanation seems to be reasonable because a reduced temperature possibly leads to a lower chemical reaction rate and a lower diamond graphitization rate. However, few people have analyzed the cutting energy consumption and tool–workpiece temperature variation in VAM, let alone understanding their true role in the catalyzed diamond graphitization rate.

In order to estimate and compare the temperature rise in VAM of steel using diamond, it is necessary to evaluate the temperature variation in comparison experiments, CC of steel using diamond. As VAM of steel using diamond is mostly conducted using ultra-precision machines and at a very low cutting speed (e.g. below 0.06 m/s for 40 kHz VAM), the evaluation of temperature rise for the comparison case should be under low-speed ultra-precision diamond machining of steel. Loladze and Bokuchava (1967) measured the temperature of diamond tool rake face in turning steel using an optical pyrometer, and recorded the temperature ranging from 600 K to 1300 K at cutting speeds between 2.5 m/s and 10 m/s. Sagarda and Khimach, quoted by Thornton and Wilks (1979), have also observed temperatures of this order when grinding steel using diamond grit. It should be noted that the temperature at the tool–workpiece contact zone (i.e. first few atomic layers at the interface between the workpiece and the diamond tool) could be higher than the temperature measured by most measurement instruments, but they are still proportional to each other. When conducted at a very low cutting speed (e.g. <0.06 m/s), the temperature must be much lower than the above mentioned values. As an example, if the temperature rise is 1000 K for 10 m/s cutting speed, it should be less than 10 K for 0.06 m/s by applying a conservative extrapolation which is provided by Shaw (1987). Moreover, Lucca and Seo (1989) have predicted that the cutting temperatures are only a few degrees above ambient in ultra-precision machining, where feed rates and depths of cut are usually maintained at tens of microns in rough cutting and several microns in finish cutting. Therefore, in low-speed ultra-precision diamond machining of steel, it can be derived that the rise of cutting temperature should be less than several degrees with no doubt.

As mentioned above, most researchers assumed lower temperature in ultrasonic VAM, and claimed it to be the main reason for the diamond tool wear suppression in machining steel. Even if such assumption was correct, since the temperature rise in low-speed ultra-precision diamond machining of steel is already very small, the difference between the temperature rise in VAM and non-VAM should be negligibly small. Furthermore, Thornton and Wilks (1979) found that the wear rate of diamond tool in machining steel is not affected as the workpiece temperature is artificially heated from 20 °C to 220 °C, which implies that the catalyzed