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Experimental Study of Tool Wear and Grinding Forces During BK-7 Glass Micro-grinding with Modified PCD Tool

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Abstract. This study focuses on the improvement in grinding performance of BK-7 glass using polycrystalline diamond micro-tool. Micro-tools are modified using wire EDM and performance of modified tools is compared with that of as received tool. Tool wear of different types of tools are observed. To quantify the tool wear, a method based on weight loss of tool is introduced in this study. Modified tools significantly reduce tool wear in comparison to the normal tool. Grinding forces increase with machining time due to tool wear. However, modified tools produce lesser forces thus can improve life of the PCD micro-grinding tool.

1. Introduction

Glass is a difficult to machine material which possesses very high hardness, no conductivity, high corrosion resistance and extremely fine aesthetic properties for which it is widely used in micro fluidics, optical lenses and beam splitting lenses [1, 2]. Glass and other hard and brittle materials are never easy to machine as they offer high resistance to tool and create large machining forces which results in rapid tool wear. In the recent concluded decades, mostly unconventional processes such as laser micromachining [3], electro discharge machining [4] and ultrasonic machining [5] were used to create micro-features in hard to machine material surfaces because they are non contact type machining processes where cutting tool does not come in direct contact with the workpiece and hence no problem of tool wear. However, these processes are also not one stop solution for the machining of all types of brittle and hard materials as some processes like EDM can machine only conductive materials whereas laser machining produces sever heat affected zone and surface damage. Due to above discussed limitations of unconventional processes; development of some mechanical micromachining process becomes inevitable. Due to high brittleness of glass, crack formation is very common during machining. To avoid brittle cracks during machining, it is desirable to achieve ductile mode failure in brittle materials. In the recent times, micro-grinding process emerged as a solution for the micro-machining of hard and brittle materials where diamond and cubic boron nitride (CBN) abrasive tools were used [6, 7]. Micro-grinding can be done at very small depth of cuts so that ductile mode material removal can be maintained. While choosing depth of cut, it is also to be considered that depth of cut should not be less than critical depth of cut otherwise more ploughing will take place without actual chip formation [8]. Two types of micro-grinding tools have been normally applied so far, one is coated and another is solid. Diamond coated tools were used to produce high quality surfaces in optical glasses [4, 9]. On the other hand, different shaped polycrystalline diamond solid tools e. g. square shape, D-shape, circular shape were applied for micro-grinding of BK-7 glass to produce different levels of surface finish [5]. Cavity or groove at the tool bottom was also observed as an effective technique to remove the micro-chips from the tool-workpiece interaction area during micro-grinding of quartz glass [10]. For the reduction of burrs and micro-cracks, coating of the workpiece surface with different types of resins was done before performing micro-grinding. Coating of the surface produces a restraining effect on the crack propagation [11]. Recently, ultrasonic vibration assisted micro-grinding of silica glass has been performed to reduce the grinding forces and to improve the surface quality. Normal and tangential forces also declined by at least 50% because of abrasive-work impact effect and interrupted cutting [12, 13].

Chip removal from the grinding area is a key factor for producing smooth surface and reducing grinding forces along with tool wear. As discussed above, different types of tool modification strategies were adopted to remove the chips effectively from the grinding zone and to prevent lodging of the tool. This study is focused on reduction of tool wear through tool modification. Two types of modified PCD micro-grinding tools are prepared through micro-WEDM. One tool has one groove on its end face while another one has two perpendicular grooves on its end face. Then, performance of three tools e. g. tool without any groove (NG), tool with one groove (1G) and tool with two grooves (2G) are observed in the micro-grinding of BK-7 glass based on grinding forces and tool wear.

2. Experiments

2.1. Experimental setup

All micro-grinding experiments were carried out on CNC hybrid micro machine tool- DT110 (Mikrotools Pte. Ltd, Singapore) having programmable multi axis controller (PMAC). Maximum allowable bed movements in x, y, z directions are 200, 100 and 100 mm, respectively. Position accuracy of the machine is 1 μm/ 100 mm. Range of spindle speed is 100 rpm to 60000 rpm and it uses AC servo motor controlled angular contact bearing for high precision rotation. The micro-grinding setup for grinding of BK-7 glass using different shaped PCD micro-grinding tools is shown in figure 1.

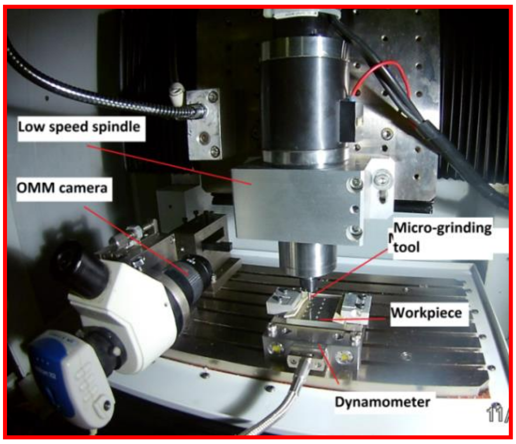

Figure 1. Experimental setup of micro-grinding.

2.2. Tool modification

Micro-tool used in this study is made up of polycrystalline diamond tip brazed on a 3 mm diameter tungsten carbide shank. Tip diameter of the tool is approximately 0.70 mm and it has included taper angel of 45°. Micro-grooves on the end face of the tools are fabricated through micro-WEDM using setup as shown in figure 2(a). Zinc coated brass wire of diameter approximately 0.07 mm is used as sacrificial electrode during WEDM. Operating parameters of micro-WEDM are given in figure 2(b). Three types of tools are used in this study. First tool has flat end face, second tool has one groove on the end face while third has two perpendicular grooves on the end face as shown in figure 2(b). Width and depth of the groove made is approximately 0.09 mm and 0.05 mm, respectively. Machining time for fabricating groves on the tool end face was captured using stopwatch. Machining time for tool type

1G is 32 minutes while for tool type 2G is 55 minutes. Machining time for tool type 2G is not exactly twice of tool type 1G, because for tool type 2G, when groove no 2 is fabricated, it has to remove less material as some of the material is already removed during fabrication of groove 1.

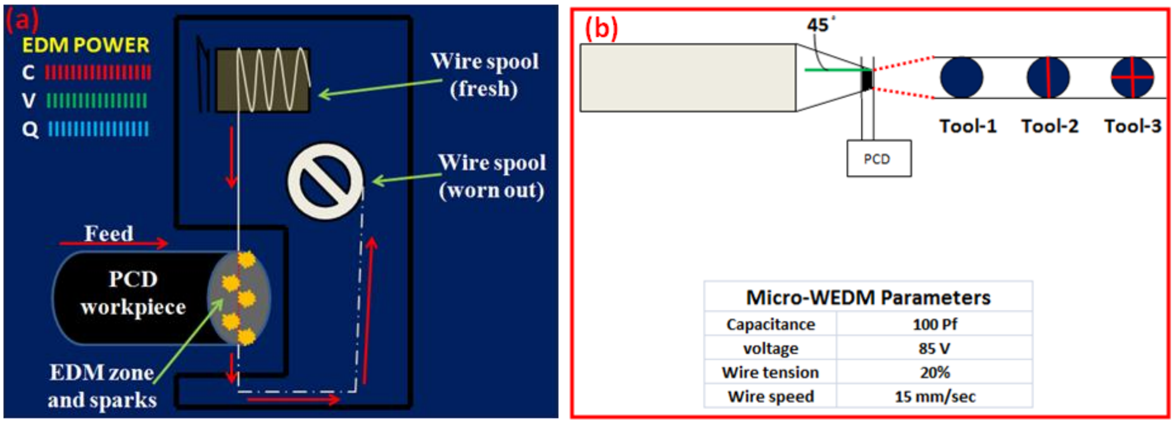

Figure 2. (a) micro-WEDM setup for tool modification; (b) Types of tool and micro-WEDM parameters

2.3. Micro-grinding experiments and measurements

After preparation of 3 types of tool, micro-grinding experiments are performed. Grinding parameters [14], conditions and different measurements adopted are presented in Table 1. Tool-workpiece orientation, feed direction and depth of cut direction during experiments are depicted in figure 3. Small pockets of 1.5 mm length are machined on BK-7 glass.

Table 1. Micro-grinding conditions and measurements adopted

Experimental conditions		**Measurements adopted**	
Speed	2000 rpm	Before experiments	WEDM machining time for tool NG, 1G and 2G
Feed rate	25 µm/min		Tool profile and weight measurements
Depth of cut	5 µm	During experiments	Grinding force
Lubrication	Dry	After experiments	Grinding surface morphology inspection using optical inspection
Environmental temp.	25 °C		Surface roughness measurement Tool inspection using microscope Tool wear

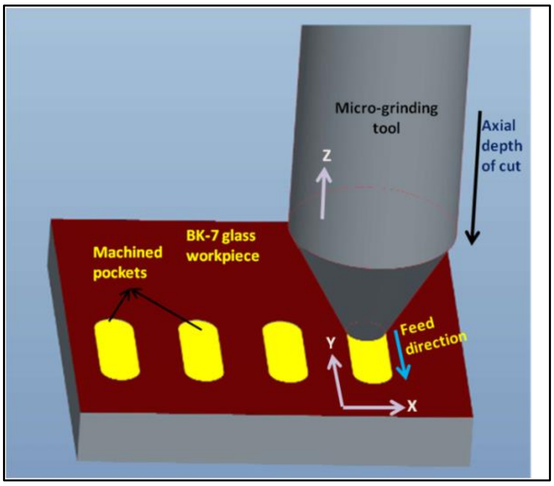

Figure 3. Tool-workpiece orientation and machining directions during machining

3. Results and discussions

3.1. Tool wear study

Significant tool wear is one of the few negative aspects of micro-grinding process. But it is very difficult to characterize the tool wear phenomena in micro-grinding because of multiple and random cutting edges. In this study, tool wear pattern of three types of tools (NG, 1G and 2G) are observed through microscopic images of the end face. Weight loss of the tools during grinding is also taken as a measure of tool wear. Tool wear were analyzed after grinding of 4.5 mm length. Microscopic images of the tool end face taken at different magnification level can be seen in figure 4. Enlarged views of the craters and pitting marks are shown using 50X magnification. End face morphology of tool type NG after grinding is shown in figure 4(a). Big craters as well as lot of pitting marks can be observed on tool face. Length and width of the crater are measured and found to be 85.34 μm×57.04 μm. Wear pattern is also non-uniform when going from centre to periphery. For tool type 1G, edge craters developed are not as severe as compared to that of tool type NG but are very significant to damage the edges of the machined pockets. Size of the cracks is around 58.58 μm×49.79 μm. End face of tool type 2G after grinding is shown in figure 4(c). Craters developed are not as deeper or wider as of tool types NG and 1G because two micro-grooves on the face provides enough space for chip removal from grinding zone. Crater size is found to be 30.11 μm×14.38 μm.

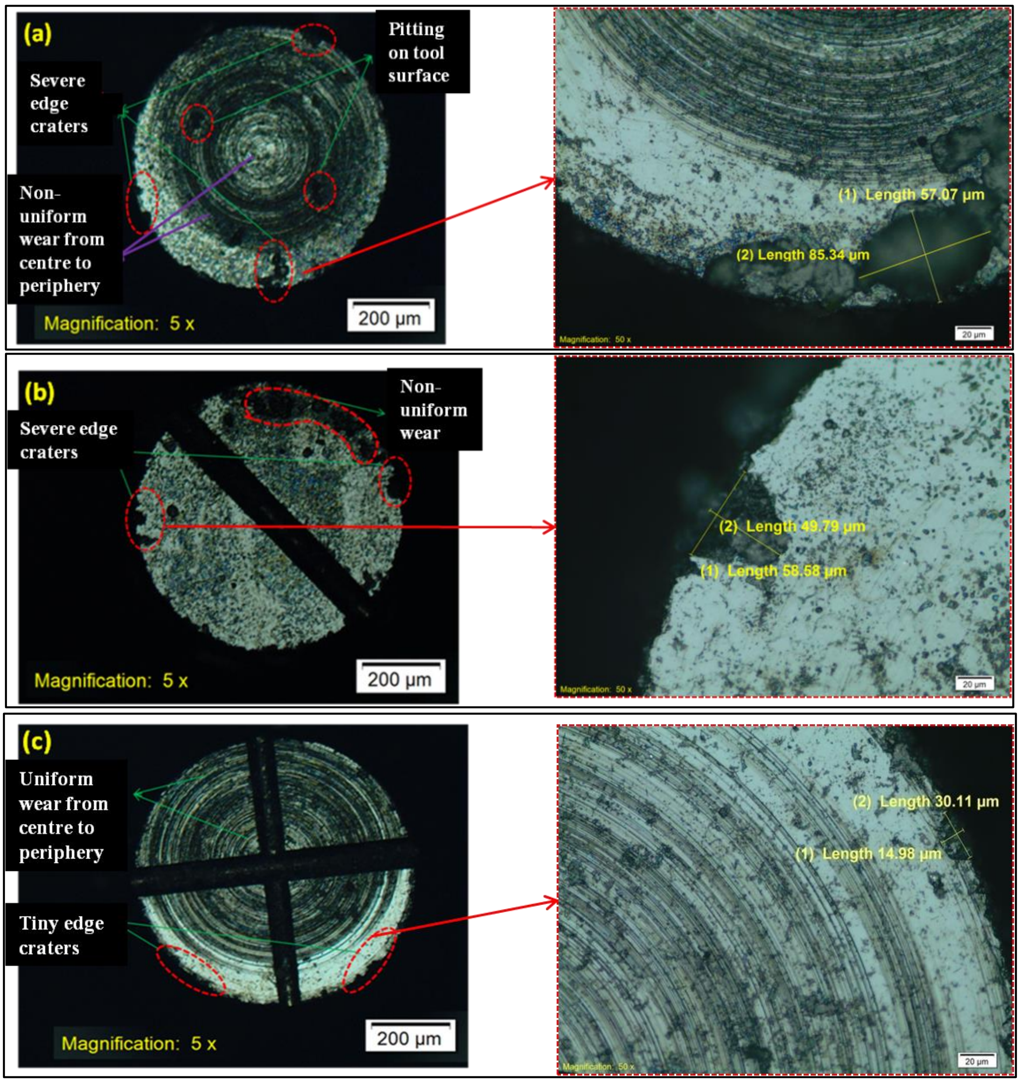

Figure 4. Worn out end faces of tool types (a) NG, (b) 1G, (c) 2G

Amount of tool wear is approximately quantified through weight loss measurement. Highly precise micro weighing machine (Make- Mettler Toledo, Resolution- 1 µg) is used to measure the weight of the tool. Tools were thoroughly cleaned in ultrasonic cleaner before measuring weight so as to remove any adhered microchips on the tool face. Weight of the tool before and after micro-grinding is measured and difference in the weight is the approximate amount of tool wear. Since grinding length is only 4.5 mm, expected amount of tool wear is very less. As shown in figure 5, weight losses of tool types NG, 1G and 2G during micro-grinding are 29 µg, 19 µg and 16 µg, respectively. It is clear that amount of tool wear is least for tool type 2G because of less contact area between tool and workpiece as well as reduced rubbing of microchips on tool surface. However, cleaning of the tool is carried out before measuring weight of the tool; still some microchips may be there on the tool surface which leads to error in the weight measurement of the tool as weight of these microchips are neglected. This problem should be taken care of in the future studies.

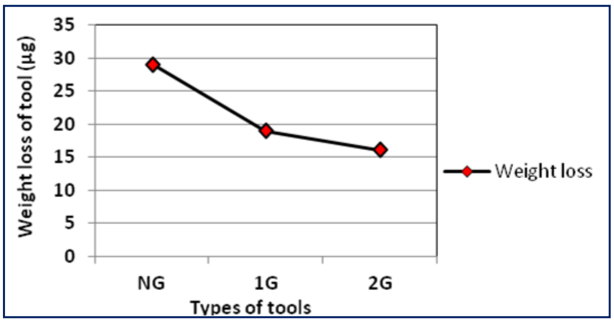

Figure 5. Weight loss of the tools (amount of tool wear) during micro-grinding.

3.2. Variations of grinding forces and ground surface morphology with time

Variations of grinding forces F_x, F_y and F_z with respect to time are shown in figures 6 (a), (b) and (c), respectively. Increase in machining time causes tool wear and hence increase in grinding forces in all the directions. Grinding forces are observed for three types of tool at the machining times of 0, 60, 120 and 180 minutes. From the figures, it can be observed that grinding force is generally increasing with machining time except some exceptions. At the machining time of 60 minute, there is a sudden rise in F_x and F_y values for tool type 2G. This is due to clogging of chips or re-sharpening of tool for any particular case [15]. Tool re-sharpening at any instant may lead to sharp cutting edges, which in turn increases the chip load and grinding forces. Overall, grinding forces has an increasing tendency with machining time and grinding forces for tool type 2G is always lesser as compared to tool types NG and 1G. Surface of the pockets at different machining times is shown in figure 7. Initially, brittle fractures and damage at the edges and surface of the pockets are more due to very sharp edges of the tool. After some time, surface obtained is smoother and damage free as compared to initial surface under balanced stage of the tool. But the pocket surface again starts deteriorating after some time because of the progressive tool wear.

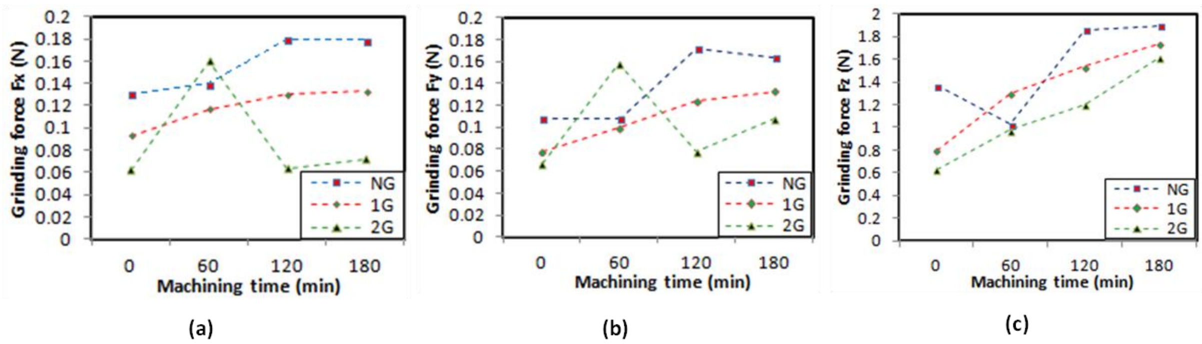

Figure 6. Variation of cutting force with time for all tools (a) F_x (b) F_y (c) F_z

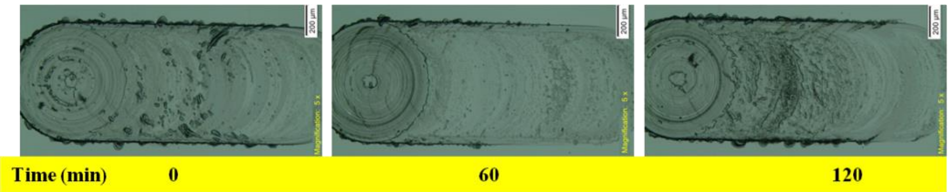

Figure 7. Pocket surface obtained at different machining times for 2G tool.

4. Conclusions

Following conclusions can be made from this study

- Wire-EDM is an efficient and precise technique to machine PCD tools which is very difficult to machine with conventional machining processes.
- Modified tools are able to flush away the microchips from the grinding zone.
- It is observed from the microscopic images of the tool that modified tool suffers less wear as compared to that of normal tool during micro-grinding of BK-7 glass.
- Weight loss measurement technique is used to quantify the amount of tool wear where amount of tool wear is minimum for tool type 2G.
- Grinding forces first decrease with time due to rounding of sharp edges and then increase due to progressive wear of cutting edges.
- Effects of tool wear can also be visualized from the grinding surface morphology.

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