Influence of abrasive particle movement in micro USM

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Abstract

Ultrasonic machining (USM) is known for its ability of processing hard and brittle materials such as silicon, glass and ceramics. Micro USM is used to generate micro features in these materials. In micro USM, material is removed using a tool that impacts abrasive particles into the workpiece, chipping material away from the workpiece. Abrasive particles are distributed randomly in the machining area. Their movement affects the profile of the machined surface. In this study, experiments are carried out to investigate the influence of abrasive particles on the profile of machined surface by micro USM. It was found that machined surface profiles show convex or concave shapes. The profile is affected by amplitude of vibration, diameter of tool and the depth of hole.

Keywords: Ultrasonic vibration; Micro machining; Profile of machined surface; Abrasive particle

1. Introduction

Hard and brittle materials such as silicon, glass, quartz crystal and ceramics are increasingly used in MEMS devices due to their excellent material properties such as resistance to high temperature, erosion and wear [1]. However, most of machining methods have difficulties in machining these materials. Electrical discharge machining (EDM) and electrical chemical machining (ECM) are not suitable processes because most of hard and brittle materials are not electrically conductive. Applying laser to machining these materials, cracks are easily generated due to their poor thermal conductivities or resistance to high temperature [2]. Some of ceramics are used as abrasive materials in grinding process. When traditional manufacturing processes such as milling and drilling are used to handle with those materials, tool wear occurs seriously, resulting in low machining accuracy, even the breakage of cutting tool. Ultrasonic machining (USM) is one of non-conventional mechanical material removal processes, which is mainly and uniquely used to machine hard and brittle materials by chipping. Micro USM is the downscaling of conventional USM for purpose of generating micro features which requires micro sized tool, small amplitude and abrasive particles of micrometer even nanometer order [3]. Applying the wire electrical discharge grinding (WEDG) on-the-machine to prepare micro tools with high accuracy, it enables Micro-USM possible to drill micro holes on a silicon wafer [4]. In micro USM, the workpiece is vibrated at an ultrasonic frequency instead of the tools in order to obtain high-precision tool rotation. As a result, micro holes as small as 5 \( \mu \)m in diameter were machined in quartz glass and silicon [5]. Integrating the uniform wear method with a CAD/CAM system, three-dimensional micro cavities have been generated layer-by-layer successfully [6].

There are two ways to generate micro features by micro USM. One is to use complex shape tool to do simple up-and-down movement [7, 8]. In this case, there is no tool rotation. The final surface is expected to have a good surface quality. The other one is to control a simple shape tool moving along a designed tool path [6]. In each layer machining, the flat surface is desired to form the final accurate 3D micro shape.

By observing the bottoms of micro holes machined by micro-USM, it was found that the bottoms of micro holes are uneven as shown in Fig. 1 [9]. USM process is
different from the grinding process in which abrasive particles are fixed on the tool or grinding wheel. In USM, abrasive particles are suspended in slurry. Movement of abrasive particles in the machining zone is so complicated that the distribution of abrasive particles is unknown.

Fig. 1 Machined surface by particles of 0.25μm without tool rotation [9].

To improve the quality of machined surface by micro USM, many methods were attempted. A non-contact USM method was proposed in order to ultra-precisely machine flat and complex surfaces. The material is removed by the impact of accelerated abrasives that are excited by ultrasonic energy instead of direct impacts [10]. It was also reported that smooth surface can be obtained by using oil based abrasive slurry instead of aqueous abrasive slurry [11]. H. Zarepour and S. H. Yeo studied experimentally the influence of processing parameters on surface quality and got surface roughness as small as Ra=24nm [12]. Different from the surface roughness, the surface profile machined by micro USM influences on the accuracy of final 3D micro shape, which is determined by the positions of abrasive particles during machining.

In this paper, the relationship between the profile of machined surface and the machining parameters including the tool diameter, abrasive size and the amplitude of ultrasonic vibration is studied. Experiments are carried out and results are discussed. The study is summarized in the final section.

2. Effect of abrasive particle movement on machined surface

In micro-USM, the mechanism of material removal is that workpiece material is chipped away under repeated impacts of abrasive particles at an ultrasonic frequency. It was confirmed that the material removal and the tool wear occur only when both of ultrasonic vibration and abrasive particles exist [13]. The profile of machined surface by micro USM has a closed relationship with number of particles and its distribution in machining area. When abrasive particles are uniformly distributed in working area, the material removal rate in the whole area is same, resulting in a flat surface. However, abrasive particles are not evenly distributed in working area. The more the abrasive particles are, the more material is removed. The generated surface turns to be concaved. Reversely, the surface is machined into convex shape where there are less abrasive particles. The movement of abrasive particles suspended in slurry is influenced by ultrasonic vibration. In a micro hole drilling by micro USM, a particle moves reciprocating to the center and the boundary of a hole with the up-and-down movement of tool or workpiece. This movement of abrasive particles is complicated and leads to uneven distribution of abrasive particles in working area, resulting in the different profile of machined surface. In this paper, the movement of abrasive particles in micro USM and its effect on the profile of machined surface are studied experimentally. Experimental results are discussed.

3. Experimental equipment and procedure

To study the movement of abrasive particles in micro USM, experimental procedure is designed and experiments are carried out.

3.1. Experimental equipment and machining conditions

Fig. 2 shows the experimental equipment used in micro ultrasonic machining. The experimental setup consists of XYZ stages with a resolution of 0.1μm, a wire electrical discharge grinding (WEDG) unit used for preparing micro-tools, an ultrasonic vibration unit and an electronic balance with a resolution of 0.01mN served as the force sensor. The experimental conditions are listed in Table 1.

![Fig. 2 Structure of Micro USM equipment.](image-url)
Table 1. Experimental conditions

| Parameter                        | Conditions          |
|----------------------------------|---------------------|
| Ultrasonic vibration frequency   | 35 kHz              |
| Ultrasonic vibration amplitude   | 0.5 μm, 1 μm, 1.5 μm|
| Abrasive particle material       | Polycrystalline diamond (PCD) |
| Abrasive particle concentration  | 3 wt% to water      |
| Abrasive particle size           | 0.5 μm, 1.5 μm, 3 μm|
| Tool material                    | Tungsten            |
| Tool diameter                    | 200 μm, 300 μm      |
| Static load setting             | 10 mN               |
| Workpiece material              | Silicon <100>       |
| Tool rotation                    | 0 rpm               |

3.2. Date processing

The machined surface of a micro hole by micro-USM is scanned by an interferometer. The profile of machined surface is analyzed. When the center of the machined surface is higher than the surrounding as shown in Fig. 2, it is identified that the bottom profile of the micro-hole is convex. When the profile of the cross-section is low at the center as shown in Fig. 3, it is identified that the bottom profile of the micro-hole is concave. The height, $H$, in Fig. 3 is the height of the convex contour, while the height, $h$, in Fig. 4 is the height of the concave contour. The positive value implies convex, while the negative value implies concave.

Fig. 3 Profile of convex machined micro-hole.

Fig. 4 Profile of concave machined micro-hole.

4. Experimental results and discussion

Experiments under the conditions in Table 1 are carried out to study the relationship between the bottom profile of micro-holes and tool diameter, amplitude of ultrasonic vibration and tool feed depth.

Fig. 5 shows heights of bottom profiles of micro-holes drilled by micro USM using micro tools with diameters of 300 μm, different tool feed depths, amplitude of ultrasonic vibration of 1 μm and various sizes of abrasive particles. It can be seen that bottom of micro holes are almost convex except the conditions of tool feed depth of 100 μm and abrasive sizes of 1.5 μm and 3 μm. During machining, the chipped out material in the center of micro hole is not quickly removed from the working area. The accumulated debris in the center part of micro hole may block the material removal, resulting in the convex shape of bottom profile of a micro hole.

When a micro hole is drilled over 70 μm in depth, the machining time is long enough that the abrasive particles move towards the center of micro holes. The number of abrasive particles in the center of a micro hole increases, resulting in the increase of the material removal. This leads to the concave shape of the bottom profile of a micro hole.

Fig. 5 Heights of bottom profiles of micro holes.

When the diameter of a micro tool decreases to 200 μm, bottom profiles of micro-holes by micro USM become concave, with the exception of conditions using abrasive particles of 3 μm in size and tool feed depth of 50 μm as shown in Fig. 6. These phenomena might be caused by the decrease of tool diameter. When a small diameter tool is used, the initial evenly distributed abrasive particles move easily and quickly towards the center of a micro hole under ultrasonic vibration. The number of abrasive particles in the center area is more than that in the boundary area of a micro hole during machining. Therefore, the material removal rate in the center is larger than that of the boundary, leading to the concave shape of machined bottom profile of a micro hole.

Fig. 6 Heights of bottom profiles of micro holes.

To study the influence of the tool feed depth on the profile of machined surface, micro holes are drilled to
different depths using tools with diameter of 200 μm and abrasive particles of different sizes. Table 2 lists different combinations of tool feed depths and sizes of abrasive particles used for experiments. All results are summarized in Fig. 7. Different from the experimental results in Fig. 6, the vibration amplitude increases from 1 μm to 1.5 μm. It is clear that all bottom profiles of machined micro holes are concave. It indicates that the abrasive particles move to the center of a micro hole in a short time under a large vibration amplitude, leading to the material removal in the center is faster than that in the boundary of micro holes. Therefore, the surface profiles of micro holes are concave.

Table 2. Feed depth of micro-holes (μm)

| Serial No. | 1  | 2  | 3  | 4  | 5  | 6  |
|------------|----|----|----|----|----|----|
| 0.5μm      | 20 | 40 | 60 | 80 | 100| 140|
| 1.5μm      | 30 | 50 | 70 | 90 | 110| 150|
| 3μm        | 40 | 60 | 80 | 100| 140| 180|

To further investigate the influence of the vibration amplitude on the abrasive particle movement, experiments under different vibration amplitudes are carried out. Fig. 8 shows the influence of vibration amplitude on the bottom profile of micro hole. Usually, the bottom profile of a micro hole generated using small particles and small tool feed depth has a convex shape as shown in Fig. 5. It can be seen that the surface profile changes from the convex to concave with the increase of the vibration amplitude under same other machining conditions. The bottom of a micro hole generated by large amplitude of 1.5 μm is concave. It is further confirmed that the increase of vibration amplitude accelerates the movement of abrasive particles towards the center of the micro hole, resulting in the number of abrasive particles in the central part of a micro hole increases.

To investigate the machining time on the surface profile of machined micro hole, three holes were drilled to different depth under a small vibration amplitude of 0.7 μm. The machining times are 341 seconds, 389 seconds and 452 seconds, respectively. The heights of surface profiles are shown in Fig. 9. The number of abrasive particles in machining area is calculated as 59 [9]. Initially, the abrasive particles are distributed in the machining area randomly. The debris in the center of micro hole blocks abrasive particles moving towards to the center. The surface profiles are convex. Even under large vibration amplitude of 1 μm and the tool feed depth of 70 μm. As shown in Fig. 5, the bottoms of micro holes are convex. When the tool was fed into the workpiece to 80 μm in depth, the machining time is long. The particles move to the center of machining area. Therefore, the obtained profile of machined surface is concave.

![Fig. 7 Heights of bottom profiles of micro holes with different feed depths using different sizes of abrasive particles.](image)

![Fig. 8 Heights of bottom profiles of micro holes generated under different vibration amplitudes.](image)

![Fig. 9 Heights of bottom profiles of micro holes generated with different tool feed depths.](image)

5. Conclusions

In micro USM, the profile of machined surface has a closed relationship with the distribution of abrasive particles, which suspends in slurry during machining. In this study, it was found that the abrasive particles move towards to the center of machining area during vibration and the debris accumulated in the center of machining blocks the movement of abrasive particles, resulting in convex or concave bottom shape of a micro hole.

At the initial stage of machining, the debris accumulated in the center blocks the abrasive particles move to the center. The surface profiles are convex. Under the same conditions, the bottom surface is generated to concave shape easily with the increase of particle size. When the vibration amplitude increases, the moving speed of particle increases, resulting in concave bottom shape. Using a tool with a small diameter, the time of a particle moving to the center is shorter than that using a large size tool, leading to the concave bottom shape. When a deep hole is drilled, the machining time is long enough for the particles moving...
to the center of micro hole, leading to the formation of concave bottom shape.

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