STUDY ON MATERIAL REMOVAL MECHANISM IN MICROULTRASONIC MACHINING

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ABSTRACT

The material removal mechanism in microultrasonic machining (MUSM) was investigated for the first time. The removal mechanism in conventional ultrasonic machining (USM) has been reported by many researchers who have clarified that it is based on brittle fracture. However, in MUSM, the size of abrasive particles, the machining force and the ultrasonic vibration amplitude are so small that the removal mechanism cannot be analogized with that in conventional USM. Previous studies on erosion have shown that, in erosion of brittle materials, the brittle-ductile transition in the removal mechanism occurs when the size or the speed of abrasive particles becomes very small. In accordance with this research, it is possible that the brittle-ductile transition is observed in the removal mechanism in MUSM where the size of abrasive particles is smaller than 1μm and the velocity with which particles strike workpiece materials is very low because of the small vibration amplitude. Scanning electron microscope (SEM) observation showed that there was no evidence of brittle fracture, which can be identified as sharp edges, on the surface of glass machined using MUSM. The machining characteristics were investigated and the results indicated that the machining rate of brittle materials such as glass and silicon was only 1.5 - 2.0 times that of stainless steel, which is a ductile material, while conventional USM removes brittle materials 20 times faster than ductile materials. On the basis of these results we can conclude that the brittle-ductile transition also occurs in the case of USM, as in cutting or grinding.

1 INTRODUCTION

A new method for MUSM was developed to fabricate microholes on hard and brittle materials [1]. In order to obtain high-precision tool rotation, workpieces are vibrated during machining, while tools are vibrated in conventional USM. Using this method, it has become possible to machine microholes as small as 5μm in diameter in quartz glass and silicon. The experiments were carried out using a 0.2μm diamond abrasive with a vibration amplitude smaller than 1μm. The material removal mechanism in MUSM, however, has not been investigated yet.

Conventional USM is usually used for machining brittle materials and its tools are fabricated from ductile materials such as steel in order to avoid tool wear, since brittle materials are removed much faster than ductile ones. Many researchers have clarified that the material removal mechanism in conventional USM of brittle materials is based on brittle fracture. However, the size of abrasive particles and the vibration amplitude in MUSM are so small that it cannot be said that the removal mechanism is the same as that in conventional USM.

This work is aimed at studying the material removal mechanism in MUSM that has not been clarified before. The study will be carried out by considering previous studies on erosion and machining characteristics in MUSM.

2 STUDY ON MATERIAL REMOVAL MECHANISM

Conventional USM utilizes a colliding action between abrasive particles and a workpiece. Figure 1 describes the process of machining brittle materials. The ultrasonically vibrating tool hammers particles in the slurry into the workpiece surface and causes microcracks by brittle fractures in it. The workpiece surface is removed as chips are generated by the intersection of the cracks. The fracture type, brittle or ductile, is determined by the workpiece material, the size of abrasive particles and the speed of colliding particles. In most cases, brittle fractures are formed in brittle materials while ductile fractures in ductile materials.

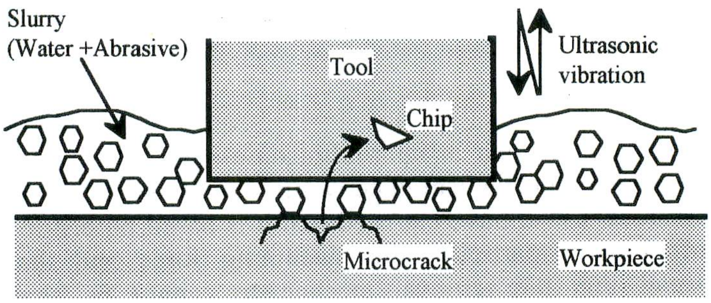


Fig. 1 USM process of machining brittle materials

However, previous studies on erosion have shown that ductile fracture can be seen on the surface of brittle materials when the size or the speed of abrasive particles is small [2][3]. After erosion with a 9μm abrasive, the surface of glass, which is a brittle material, had ripple patterns on it, indicating that the material removal mechanism was based on ductile fracture. Furthermore, the removal amount of glass was almost the same as that of aluminum, which is a ductile material, while the former was 50 times greater than the latter with a 127μm abrasive. This result also validated that, with a small-sized abrasive, not brittle fracture but ductile fracture occurred even on a brittle material, since the removal amount by ductile fracture is much smaller than that by brittle fracture. This phenomenon is referred to as the brittle-ductile transition, which can be seen in other machining fields such as cutting and grinding. Although the machining rate decreases with the occurrence of transition, the roughness of machined surfaces improves and high machining accuracy can be obtained.

In accordance with this research, it is possible that the brittle-ductile transition occurs in the material removal mechanism in MUSM where the size of abrasive particles is smaller than 1μm and the velocity with which particles strike workpieces is very low because of the small vibration amplitude. Results that confirm this assumption will be provided in the next section.

3 VERIFICATION OF BRITTLE-DUCTILE TRANSITION

3.1 SEM Observation of Machined Surfaces

It is useful to observe workpiece surfaces after machining in order to see whether brittle fracture or ductile fracture occurred. The observation here was carried out using a SEM. Figure 2 shows a surface of glass machined with a 50μm silicon carbide abrasive using conventional USM. Sharp edges, which are typical of brittle fracture, can be seen on the surface.

However, as can be seen in Fig. 3, a surface of glass machined using MUSM with a 0.2μm diamond abrasive does not show any sharp edges, but instead shows wave patterns. This result implies that the brittle-ductile transition occurred, where the brittle fracture is not formed and only ductile deformation remains because of the small abrasive particle size.

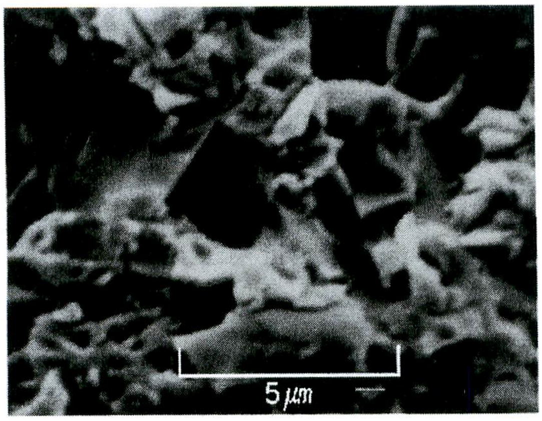


Fig. 2 Surface of glass machined using conventional USM (Abrasive: silicon carbide, 50μm)

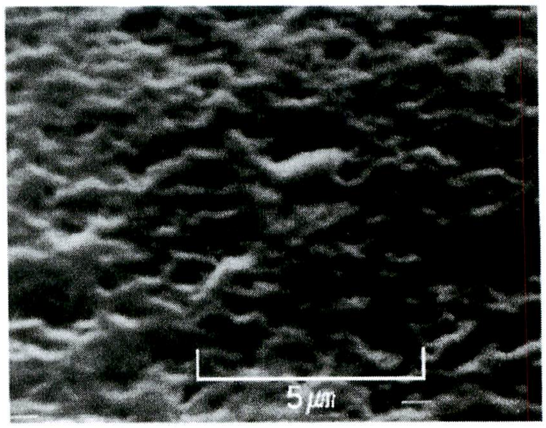


Fig. 3 Surface of glass machined using MUSM (Abrasive: diamond, 0.2μm)

The surface roughness Ra was measured for the surface in Fig. 3 using a scanning laser microscope. It was from 0.1μm to 0.5μm. This is slightly high considering the abrasive size of 0.2μm.

3.2 Machining Rate and Tool Wear Ratio

The machining rate and the tool wear ratio were investigated and compared with those in conventional USM. Here the machining rate is defined as hole depth per machining time and the tool wear ratio as the ratio of the length of tool wear to hole depth.

In a study on the machining rate and the tool wear ratio in conventional USM, it was reported that the machining rate of brittle materials such as glass and silicon was 20 times that of stainless steel, a ductile material [4]. The tool wear ratio of brittle materials was only 1 % of that of stainless steel. These results are due to the fact that brittle fracture removes materials much faster than ductile fracture.

MUSM, however, has a different tendency in terms of the machining rate and the tool wear ratio, as indicated in Fig. 4. The machining conditions are shown in Table 1. The machining rate of brittle materials is only 1.5 - 2.0 times that of stainless steel. The machining rate difference between brittle materials and ductile materials is much smaller than that in conventional USM. This result can be explained by the brittle-ductile transition. With the transition, even brittle materials are removed by ductile fracture, by a removal amount which is very small compared with that of brittle fracture.

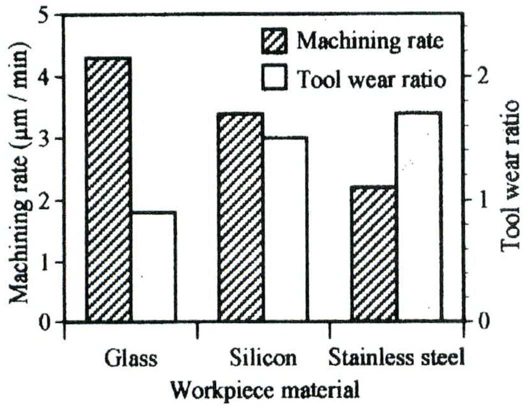


Fig. 4 Machining rate and tool wear ratio in MUSM

Table 1 Machining conditions

Tool material	Piano wire
Tool diameter	10.5μm
Tool feed depth	35μm
Machining load	0.2 – 0.4mN
Vibration amplitude	0.8μm
Abrasive material	Diamond
Abrasive particle size	0.2μm

The wear ratio of glass and silicon is 50 - 90% of that of stainless steel, which is much higher than that in conventional USM. This result can also be attributed to the brittle-ductile transition. In conventional USM, a tool is made of ductile materials in order to avoid tool wear, since the removal amount of ductile materials is much smaller than that of brittle materials. Therefore, the tool wear ratio of brittle materials is very small in conventional USM. However, when the brittle-ductile transition occurs, the removal amount of brittle materials markedly decreases and the difference in the removal amounts of brittle materials and ductile materials becomes small, leading to the high tool wear ratio of brittle materials in MUSM.

3.3 Particle Approach Angle

Figure 5 shows the material removal/deformation mechanism in ductile mode when an abrasive particle strikes a target surface. If a particle approaches at a shallow angle to the surface, as in Fig. 5 (1), it removes a part of the surface by a cutting action. In Fig. 5 (2), a particle vertically striking the surface causes a ductile deformation on it at impact. The surface is only deformed and not removed by this action. However, a previous experiment on erosion has shown that it is removed when abrasive particles approach at a right angle [5]. This can be explained as follows: a particle at impact makes a deformation on the surface. The deformed part is neither flat nor vertical to the direction from which other particles approach. Therefore, when another particle strikes the part, some amount is removed by the cutting action.

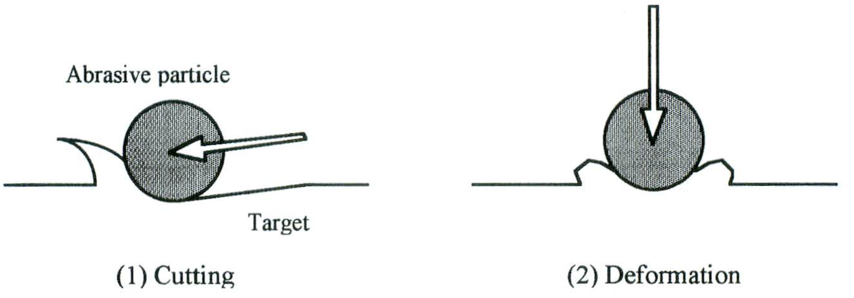


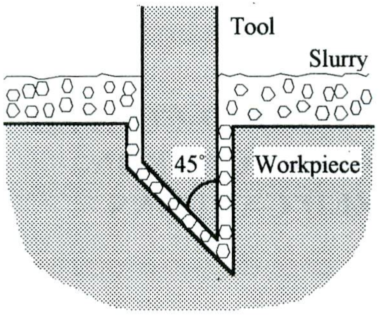
Fig. 5 Material removal/deformation mechanism in ductile mode

Although ductile fracture is dominant in the removal mechanism in MUSM, a machined surface has wave patterns, as indicated in Fig. 3, and is not as smooth as a lapped or polished surface. Furthermore, the surface roughness is slightly high for the abrasive size. These results can be attributed to the fact that in MUSM, abrasive particles strike a workpiece surface at a right angle to it, not at a shallow angle, as in lapping or polishing, leaving many deformed parts on it. Considering this, it is possible that if the particle approach angle is made shallow, a machined surface will be smooth even in MUSM. An experiment was carried out in order to verify this assumption. Figure 6 (1) describes the process. The tool tip is a flat surface with an inclination of 45 degrees to the tool axis, letting abrasive particles approach at 45 degrees to the surface. A 0.2μm diamond abrasive was used for the slurry. Figure 6 (2) is the photograph of the machined surface, which is much smoother than the surface shown in Fig. 3. This result indicates that cutting was more dominant than deformation.

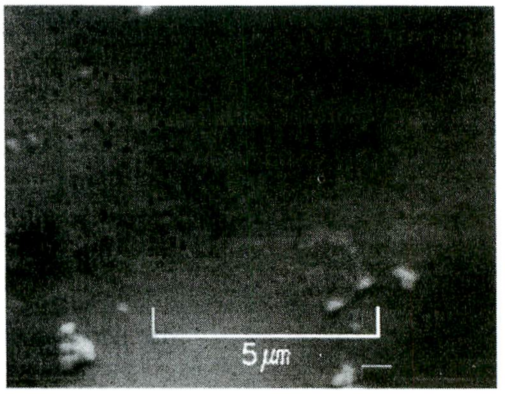
4 CONCLUSION

The material removal mechanism in MUSM was studied. Previous research on erosion suggested that the brittle-ductile transition occurs with a mechanism based on ductile fracture. This assumption was investigated and the following evidences that support it were found.

(1) No sharp edges caused by brittle fracture are observed on a machined surface.
(2) The difference in the machining rates of brittle materials and ductile materials is much smaller than that in conventional USM.



(1) Tool tip is a flat surface with inclination of 45 degrees to tool axis



(2) Machined surface

Fig. 6 Experiment with 45 – degree particle approach angle
(Abrasive: diamond, 0.2μm)

(3) The tool wear ratio of brittle materials is much larger than that in conventional USM.
(4) With an abrasive particle approach angle of 45 degrees, the workpiece surface was machined smooth as in lapping or polishing.

On the basis of these results we can conclude that the material removal mechanism in MUSM is based on ductile fracture, not on brittle fracture as in conventional USM.

5 REFERENCES

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