Ultrasonic Vibration and Cavitation-aided Micromachining of Hard and Brittle Materials

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Abstract

This paper deals with the use of two types of ultrasonic-assisted micromachining methods for obtaining longer tool life and higher machining efficiency in the micromachining of hard and brittle materials. USV drilling is drilling that is aided by ultrasonic vibration in the direction axial to the tool. Cavitation machining is a method that is aided by ultrasonic vibration of the cutting fluid. We investigated the effects of USV, cavitation, and their combination on the micro drilling of SiC. Experimental results clearly showed an improvement in tool life and a reduction in tool wear. Furthermore, the accuracy was improved.

Keywords: Ceramic, Drilling, Micromachining, Ultrasonic, Cavitation

1. Introduction

Recently, the use of hard and brittle materials has spread widely in industrial fields such as the aerospace, automotive, optical component, and semiconductor industries, because of their special properties. The characteristics of hard and brittle materials, including their high hardness and particularly their high strength at elevated temperatures, high heat resistance, low wear rate, and light weight in comparison to metals \cite{1}, are valuable in the production of precision mechanical equipment. However, the machining of hard and brittle materials still remains a great challenge because of these superior characteristics, despite extensive developments in tools and cutting materials up to this point \cite{2}. These materials are hard and brittle; therefore, it is difficult to make tools that can machine without major damage from the cutting edge and to produce high accuracy on the machined surface. Further, the demand for micromachining has recently increased because of the miniaturization of mechanical, electrical, and optical components.

The conventional machining of hard and brittle materials produces high cutting forces and generally leads to tool wear and low quality of the machined surface \cite{3}.

In particular, micromachining techniques such as microdrilling and a micro-end-milling process have the problem of low rigidity in the cutting tool. As a result, many studies on hybrid manufacturing methods such as ultrasonic vibration cutting have been carried out. To machine difficult-to-machine materials, the ultrasonic vibration cutting method has been proposed as an effective cutting process in terms of cutting force, cutting instability, tool wear, chip generation, machining quality, and so on \cite{4}. The additional oscillation inside the drill causes a sawtooth-like trajectory at each point of the tool edge. Thus, drilling supported by ultrasound can also be seen as a drilling procedure involving the use of high-frequency oscillations \cite{2}.

In this study, the effect of the USV drilling of SiC was investigated to examine tool life and the cutting force. SiC is a key material in the semiconductor industry; it is hard and brittle. Another way of using
ultrasonic vibrations in the machining process is to apply ultrasonic vibrations to the cutting fluid.

Ogawa et al. [5] showed that cavitation resulted in the enhancement of chip removal and long tool life in the micro through-hole drilling of SUS304. It was suggested that cavitation in the cutting fluid was effective for the micromachining of hard and brittle materials. In this study, cavitation-assisted machining was applied to the microdrilling of SiC. Axial-directional USV drilling and the behavior of cavitation in the cutting area were observed with a high-speed camera. Several cutting tests were performed to investigate the validity of these methods.

2. Principles of USV-aided Micromachining

2.1. Axial-directional USV Micromachining

In this study, axial-directional USV was applied to a microdrilling tool. The conventional drilling process keeps the feed rate per revolution constant, and this leads to continuous cutting. Consequently, because the cutting edge and the work piece are engaged without any interruption [2], the cutting fluid is not efficiently supplied to the cutting point. When axial-directional USV is applied to drilling, the cutting process becomes intermittent. Therefore, the cutting fluid is supplied sufficiently to the cutting area, and, in addition, the effects of the sawtooth trajectory can be determined. Another important effect of the axial-directional USV cutting of hard and brittle materials is the fracturing effect, which is due to the high-speed beating of the tool. Work pieces are fractured by the tool tip, and this results in a reduction of the cutting force.

Figure 1 shows the reduction of the axial cutting force in the USV drilling of SiC. The axial cutting force obviously decreased immediately after USV was applied to the drilling process. It was clear that the cutting energy was reduced by the USV drilling.

2.2. Cavitation-aided Micromachining

When a very strong local shock wave is applied to a cutting fluid, an instance of rapid change in the stress occurs at each point in the fluid, and then, the eruption and evaporation of microscopic gas bubbles occur repeatedly. This phenomenon is called cavitation, and it provides sufficient power to overcome the particle-to-substrate adhesion forces.

In this study, a soluble oil was selected as the cutting fluid for the microdrilling of SiC because microscopic gas bubbles do not evaporate in oil-based cutting fluids with a high viscosity. As shown in Figure 2, ultrasonic vibrations were applied to the cutting fluids by the oscillator horn of a cavitation-generating device. Cavitation occurred around the processing point when a tool was inserted through the hole at the end of the oscillator horn.

3. Experimental Setup and Procedure

A three-axis vertical machining center (NVD-1500, Mori Seiki Co., Ltd.) was used for the cutting tests. Figures 3 and 4 show the experimental setup. A two-component force sensor that could be used to measure the cutting torque and thrust force was set between the work piece and the machine tool table. In the microdrilling of SiC, the synergistic effects of cavitation and axial-directional vibration were evaluated to examine the reduction of thrust force and the enhancement of tool life.

Figure 1. Reduction of the axial cutting force in USV drilling.

Figure 2. Illustration of cavitation-aided machining.
USV devices for axial-directional USV drilling and cavitation-aided machining (Sonic Impulse SD-50, 70 kHz) and an SC-450 cavitation generator (42.5 kHz, Taga Electric Co., Ltd.) were set up in the machining space. Diamond-coated drills were used for the cutting tests.

4. Observation of USV Drilling with a High-Speed Camera

Tool oscillation and the USV and cavitation drilling processes were observed with a high-speed camera (1,400,000 frames/s, Photron). An acrylic reign was used as a workpiece for this observation.

4.1. Observation of Axial-Directional USV Drilling

A carbide drill (φ 1.5) was used in this experiment for clear observation of the tool’s oscillations. The oscillation of the tool tip was confirmed, and the drilling process was also observed. Remarkable differences between conventional drilling and axial-directional USV drilling in the evacuation of the chips were observed, as shown in Figure 5. During conventional drilling, the chips were evacuated continuously, whereas the chips were fractured into fine pieces during USV drilling.

4.2. Observation of the Cavitation Effect

A microhole (φ 0.3) was drilled into the clear acrylic substrate, and the space between the hole and the helical flute of the drill was filled with fine chips that were dispersible in the cutting fluid. Then, the chip evacuation behavior was observed when cavitation was generated in the cutting fluid. As shown in Figure 6, the chips that had accumulated at the helical groove were instantly evacuated by the effect of cavitation. It was clear that cavitation-aided drilling enhanced chip evacuation remarkably.

5. Application of the Microdrilling of SiC

Four types of drilling experiments were performed: conventional drilling, axial-directional USV drilling, cavitation-aided drilling, and hybrid drilling (axial-directional USV drilling + cavitation-aided drilling). For each experiment, the maximum number of holes drilled without a tool change was counted. The cutting conditions are summarized in Table 1. In this experiment, the center holes were machined with a diamond-center drill before the drilling tests. The drilling process was carried out according to the NC step feed program. And piezoelectric dynamometer was used to observe the cutting process.

| Type of condition          | Condition                  |
|----------------------------|----------------------------|
| Axial-directional USV      | 70 kHz/3.5 μm              |
| Cavitation device          | 42.5 kHz/2–3 μm            |
| Tool                       | Diamond-coated drill (φ 0.22) |
| Cutting fluid             | Soluble type               |
| Rotational speed           | 8000 min⁻¹                |
| Feed rate                  | 6.0 mm/min                 |
| Step feed rate             | 0.01 mm                    |
| Hole depth                 | 1.0 mm                     |
The results of the drilling tests are summarized in Table 2. The tool life was successfully increased by axial-directional USV drilling and cavitation drilling. Compared with axial-directional USV drilling, cavitation drilling was more effective in increasing tool life. Furthermore, hybrid drilling enabled the tool life to be significantly enhanced.

The causes of these positive effects of cavitation-aided drilling on tool life are explained in Figures 7 and 8. There was no chip adhesion to the tool tip with cavitation-aided or hybrid drilling.

The tools were effectively cleaned by the cavitation-aided drilling process, whereas strong chip adhesion occurred with axial-directional USV drilling. The amount of chip adhesion was greater with USV drilling than with conventional drilling. However, the maximum number of drilled holes reached with USV drilling was about three times greater than that with conventional drilling. This was due to the beater effect of the dynamic movement of the tool tip in axial-directional USV drilling. We suppose that the repeated USV movement of the tool compressed the cutting chips and resulted in strong adhesion to the tool tip and side face. However, the positive effects of USV drilling, such as the decrease in the thrust cutting force and the fracture of the work piece at the tool tip, were dominant. Additionally, the influence of negative factors of axial-directional USV-aided drilling (i.e., the compression and adhesion of cutting chips to the tool tip) could be successfully reduced by the combination of axial-directional USV drilling and cavitation cleaning.

6. Additional Experiments with the Cavitation-Aided Drilling of SiC

The experiments described previously were all performed with a low spindle rotational speed because the maximum permissible rotational speed of the USV equipment installed on the spindle was 8,000 min⁻¹. The cavitation device shown in Figure 3 is the noncontact external attachment to the spindle. The effects of the application of cavitation on drilling were tested at higher cutting speeds. The cutting conditions are summarized in Table 3. The same tools as former experiment (Fig. 7) were used. A shorter cutting hole depth were set to machine holes for certain. In this experiment the tool run out was adjusted up to 3μm at each time.

Table 3: Cutting conditions of drilling (SiC).

| Type of condition | Condition |
|-------------------|-----------|
| Rotational speed  | 20,000 min⁻¹ |
| Feed rate         | 0.50 mm/min |
| Hole depth        | 0.4 mm     |
When the center holes were prepared, no significant difference in the thrust force was found between conventional drilling and cavitation-aided drilling at the beginning of the drilling tests. However, when the center holes were not prepared, large differences in the cutting resistance appeared. As shown in Figure 9, there were large differences in the cutting resistance between conventional drilling and cavitation-aided drilling, and the differences became even greater with the number of drilling holes. In addition, the tool that was used for conventional drilling showed chipping in the middle process of the fourth hole. While more than four holes could not be machined in conventional drilling, the tool used in cavitation-aided drilling was in good condition after five holes drilling and seemed to be possible to drill more holes.

We also evaluated the effect of cavitation-aided drilling on the accuracy of the machined hole entrance; this is shown in Figure 10. Chipping was observed at the edges of the drilled holes with conventional drilling, whereas chipping was successfully suppressed with cavitation-aided drilling. When cavitation was added to drilling, we could create the machined hole precisely without premachining center holes.

As a future plan, evaluation of the surface quality of the machined holes is under consideration to reveal the effect of cavitation-aided drilling on machining accuracy.

7. Conclusion

Axial-directional USV and cavitation were applied to the microdrilling of SiC, and the validity of these methods was evaluated. The results showed some positive effects, which are summarized as follows:

1) The thrust force decreased when axial-directional USV and cavitation were applied to the tool or cutting fluids.
2) Cavitation-aided machining enhanced the performance of chip evacuation and led to longer tool life.
3) Drilling assisted by USV and cavitation showed potential for improved tool life.
4) The occurrence of chipping at the entrance of the machined hole was effectively suppressed by the application of cavitation-aided drilling.

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