MICROULTRASONIC MACHINING USING MULTITOOLS

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Abstract Multitools have been fabricated and then been used in microultrasonic machining (MUSM) of arrays of microholes. MUSM with a single tool had so far been carried out on hard and brittle materials, however, it is time-consuming for drilling lots of holes, which is often required for the applications of microholes. The multitool fabrication process include: (1) shaping a small-diameter tungsten electrode by wire electrodischarge grinding, (2) drilling arrays of microholes in copper foil by electrodischarge machining (EDM) using the fabricated electrode and (3) fabricating a multitool by EDM using the foil as the electrode with an assistance of ultrasonic oscillation. The multitool consists of 16 single tools arranged in a square array. MUSM has been performed in soda-lime glass using a tungsten carbide abrasive 0.6μm in grain size with oscillation amplitudes of 0.4 to 1.6μm, machining loads of 0.025 to 0.2N and an oscillation frequency of 40kHz. As results, arrays of microholes have been successfully drilled, with few holes having chippings around their entrances. The drilling speed and the tool wear ratio have also been investigated. Using cemented carbide tools, the drilling speed rises with increases in the machining load as that for a single tool does. In contrast, it decreases as the oscillation amplitude increases. The tool wear ratio varies widely and does not show clear relationships with the machining load or the oscillation amplitude. Polycrystalline diamond tools have excellent wear resistance, while they are apt to break under high machining loads.

Key words ultrasonic machining, micromachining, multitool, microhole, EDM

1 INTRODUCTION

There are heavy industrial demands for fabricating three-dimensional (3D) microshapes of various materials. Many methods fulfill these requirements, however, hard, brittle and non-conductive materials such as glass and ceramics are still difficult to machine. Cutting is not suitable for hard and brittle materials; electrical discharge machining (EDM) has a problem in processing non-conductive materials. Even laser machining or chemical etching, which are not mechanical or electrical removal processes, cannot deal with all of these materials.

In contrast, ultrasonic machining (USM) is a unique method in that it is employed especially for processing such difficult-to-machine materials. It can deal with hard and non-conductive materials because its machining mechanism is based on the material-removing action of hard abrasive grains. Although the impact pressure at the machining points is high owing to the ultrasonic oscillation of a high frequency and the small sizes of grains, the machining load is small enough to prevent the generation of large cracks in brittle materials.

One of the authors has carried out studies on microultrasonic machining (MUSM). Equipping a USM apparatus with a unit for wire electrodischarge grinding (WEDG) has enabled the on-the-machine fabrication of microtools and thus MUSM of various shapes [1]. Oscillating workpieces instead of tools has allowed processing much smaller shapes [2]. As results, microholes 5μm in diameter and other 3D microshapes have been successfully fabricated. However, for example, drilling lots of holes, which is often necessary for the applications of microholes, is very time-consuming work because of low material removal rates in MUSM. Furthermore, under conditions where a tool wears fast, the tool has to be repeatedly reshaped, leading to inefficiency of the total machining procedure. Using a tool capable of drilling lots of holes in one process is preferable, therefore, multitools that consist of many single microtools are used as the MUSM tools in the present study. A multitool fabrication process presented by Masaki et al. [3] is adjusted to work with our experimental setup and then employed. Improvement in the total machining time can be expected using the multitools.

2 EXPERIMENTAL

2.1 Setup

The experiments are carried out on a MUSM setup. Its schematic configuration is shown in Fig. 1. The setup has three numerically controlled axes driven by stepping motors, which have a minimum increment of 0.05μm. A unit for WEDG is installed with a brass wire 90μm in diameter. The wire running speed is 3mm/min. WEDG is a micro-EDM method capable of processing micropins several micrometers in diameter [4]. The EDM circuit is a RC type. Kerosene-type machining fluid is dropped into the gap between the wire and the WEDG workpiece (electrode material). The WEDG workpiece is held by a mandrel mounted on a V-shaped sliding bearing. A DC motor drives the mandrel whose rotation speed and run-out are 3000rpm and less than 0.5μm, respectively. Copper foil or a MUSM workpiece is fixed on the tip of an ultrasonic transducer by a both-sided adhesive tape. The transducer resting on a transducer holder oscillates at a frequency of 40kHz. The holder is placed on an electronic balance with a minimum index of 0.01gf (approximately 0.1mN). The balance measures the machining load in a MUSM process.

2.2 Procedure

Figure 2 illustrates the multitool fabrication process. First, as shown in Fig. 2 (a), a tungsten electrode is fabricated by WEDG. Its diameter depends on that of holes to be drilled by MUSM. The fabricated electrode then drills holes by EDM in 30μm-thick copper foil mounted on the transducer tip (Fig. 2 (b)). The holes are arranged in a 4x4 array format. The circuit for WEDG is also used in this drilling. The electrode polarity is here changed from the anode to the cathode. A few drops of working fluid are placed on the foil.

After this the drilled foil is employed as a plate cathode electrode for fabricating a multitool as shown in Fig. 2 (c). Cemented carbide with a grain size of 0.6μm and sintered diamond (polycrystalline diamond, PCD) made of submicron-size grains are used as the tool materials. The mandrel is replaced by another holding a tool material, which is then processed into a multitool by EDM. Since the mandrel cannot be rotated, removing debris from the machining regions becomes difficult when the material penetrates deep into the foil. The transducer therefore oscillates the foil, easing debris removal. Figure 3 shows a fabricated multitool made from a 300μm-diameter cemented carbide rod. The diameter of its single tools (hereafter simply referred to as the diameter) is

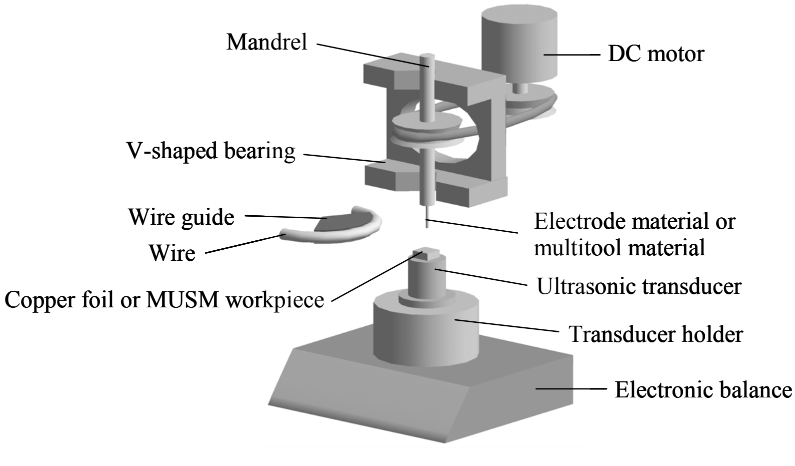


Fig. 1 Schematic configuration of MUSM setup

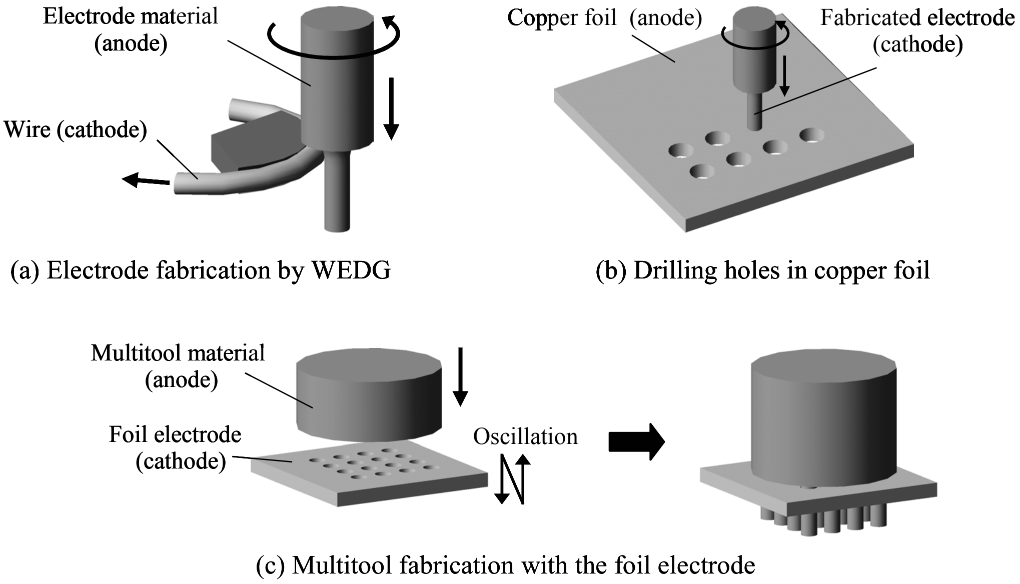


Fig. 2 Multitool fabrication process

approximately 25µm. The single tools are arranged in a square array with a pitch of 60µm.

Finally, MUSM of holes is carried out using the multitool. A workpiece replaces the foil and is oscillated during the MUSM process. The workpiece material is soda-lime glass. A few drops of slurry are placed on the workpiece surface. The slurry is mixture of water and a tungsten carbide abrasive with a grain size of 0.6µm. The weight concentration of the abrasive in the slurry is 20%. The tool feed motion is controlled by measuring the machining load using the electronic balance. The tool is fed or retracted, as the load is under the preset minimum load or over the maximum load, respectively. The depth of a drilled hole is calculated as the tool feed length minus the tool wear length.

Compared to MUSM using a single tool, this experimental procedure includes additional processes such as fabricating a tungsten electrode and drilling holes in copper foil. However, the total operation time is expected to be largely reduced because EDM is generally much faster than USM.

3 RESULTS AND DISCUSSION

3.1 Drilling example

Figure 4 shows microholes drilled in MUSM using a cemented carbide multitool 18µm in diameter.

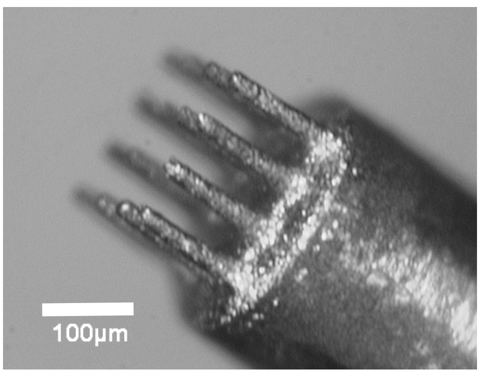


Fig. 3 Cemented carbide multitool made from a 300µm-diameter rod (diameter of the single tools = 25µm)

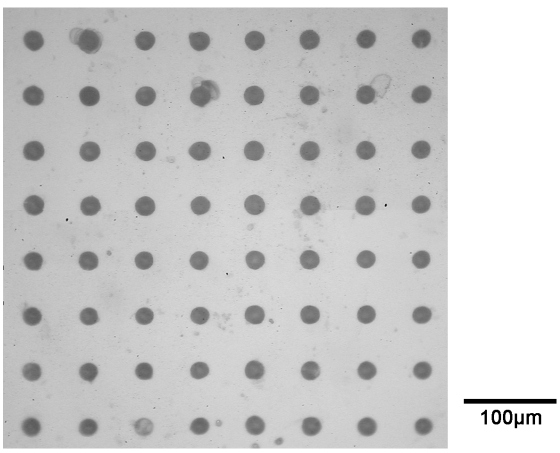


Fig. 4 Microholes 20µm in diameter (tool diameter = 18µm, oscillation amplitude = 0.8µm, machining load range = 0.05 - 0.1N)

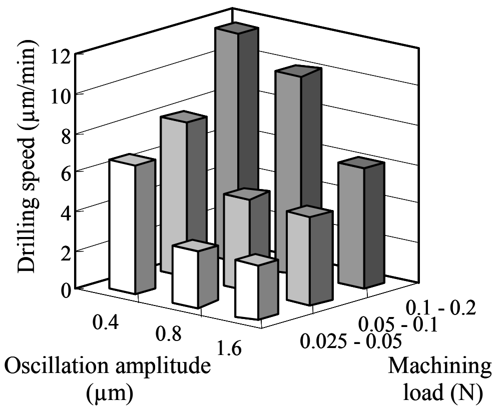
The drilling was performed four times and fabricated a total of 64 holes with an oscillation amplitude of 0.8μm and a machining load range of 0.05 to 0.1N. Most holes were well drilled without chippings around their entrance, although a few have some chippings. The feed length and the average tool wear length were 30μm and 5μm, respectively. The average hole depth is therefore 25μm. The diameters of the holes are around 20μm. With the average drilling time of approximately 3min, the drilling speed, which is defined as the hole depth divided by the drilling time, is approximately 8μm/min. This speed is comparable to that for drilling one hole using a single tool [1][2], indicating that the drilling time per hole fairly decreases.

3.2 Drilling speed and tool wear ratio

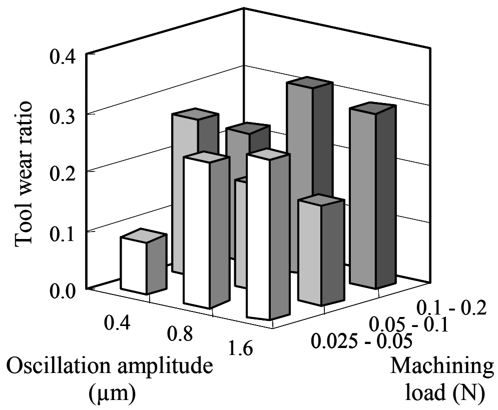
Figure 5 shows the drilling speed and the tool wear ratio for cemented carbide tools 25μm in diameter. The drilling was carried out with machining load ranges of 0.025 to 0.05N, 0.05 to 0.1N and 0.1 to 0.2N and amplitudes of 0.4, 0.8 and 1.6μm. The tool wear ratio is given as the ratio of the tool wear length to the hole depth. The drilling speed increases with an increase in the machining load, as reported in the previous work [1][2]. However, it decreases as the oscillation amplitude increases, contrary to the preceding work and many of other researchers' reports on USM. Further investigations are necessary to fully understand this discrepancy.

The wear ratio varies greatly and does not show clear relationships with the machining load or the oscillation amplitude. In the previous work in which workpieces are oscillated instead of tools, the wear ratio is independent of the machining load and the oscillation amplitude, however, it is almost the same without a wide variation [2]. This result for the tool wear ratio may be attributable to debris trapped at the drilling regions. Since slurry circulation is hindered among the single tools of a multitool, debris is localized there. The debris from the cemented carbide tools is similar in hardness to the abrasive and thus works as abrasive grains, raising the slurry concentration to certain values higher than 20%. The previous work has reported that, with slurry concentrations of over 20%, the wear ratio increases as the concentration rises while the drilling speed hardly changes [1]. The slurry concentration raised by trapped debris may differ in each drilling and thus vary the wear ratio widely.

The hardness of the cemented carbide tools is almost the same as that of the abrasive, hence a problem of high wear ratios is posed. PCD multitools have therefore been fabricated and then been employed. PCD can be processed in EDM because of its electrical conductivity. Figure 6 shows the drilling speed for PCD tools 25μm in diameter with a machining load range of 0.025 to 0.05N and oscillation amplitudes of 0.4, 0.8 and 1.6μm. The drilling speed is highest with an amplitude of 0.4μm, as is the case with the cemented carbide tools. In this drilling the tool hardly wore owing to the high hardness of PCD, with wear ratios of approximately 0. In terms of tool wear, PCD is the most suitable tool material. One drawback is that the PCD tools endure lower machining loads than the cemented carbide tools. The PCD tools broke with machining load ranges of 0.05 to 0.1N or greater. Cemented carbide tools must be employed at these machining load ranges.



(a) Drilling speed



(b) Tool wear ratio

Fig. 5 Drilling speed and tool wear ratio for cemented carbide tools (tool diameter = 25μm, tool feed length = 50μm)

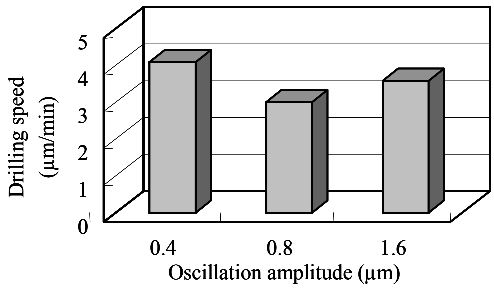


Fig. 6 Drilling speed for PCD tools (machining load range = 0.025 - 0.05N, tool diameter = 25μm, tool feed length = 50μm)

4 CONCLUSION

MUSM of holes was carried out using multitools fabricated by micro-EDM. The tools each consist of 16 single tools. The holes were drilled in soda-lime glass with an abrasive of tungsten carbide. The following results were obtained:

(1) The drilling speed is comparable to that for a single tool, indicating that the drilling time per hole can be greatly reduced.

(2) Using cemented carbide tools, the drilling speed rises with increases in the machining load as that for a single tool does. In contrast, it decreases as the oscillation amplitude increases.

(3) The tool wear ratio for cemented carbide tools varies widely and is not influenced by the machining load or the oscillation amplitude.

(4) With wear ratios of approximately 0, PCD tools have more excellent wear resistance than cemented carbide tools.

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