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Drilling of microholes using electrochemical machining

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ABSTRACT

Few studies have been reported on the drilling of microholes with a diameter of approximately 10 µm or less by electrochemical machining (ECM). The ECM of such holes was therefore attempted using ultrashort voltage pulses. Stainless-steel sheets were drilled using cemented tungsten carbide tool electrodes. As a result, a microhole of 4.5 µm entrance diameter and 4 µm exit diameter was successfully drilled in a 5-µm-thick sheet with a pulse width of 60 ns using a tool electrode 3 µm in diameter. This is the smallest-diameter hole drilled by ECM, to the best of our knowledge. A microhole of 5.5 µm entrance diameter and 4.5 µm exit diameter was also drilled in an 8-µm-thick sheet. Furthermore, the machining properties were investigated. The effect of the tool electrode shape, pulse width, pulse frequency, high-level and low-level voltages, and electrolyte concentration on the drilling speed and hole diameter was examined. The results suggested that a semicylindrical tool electrode, long pulse width, high pulse frequency, high low-level voltage, and high electrolyte concentration were preferable for high-speed drilling without widening the lateral gap between the tool electrode and hole.

1. Introduction

There has been strong demand for the further development of micromachining technology to realize micron-size features as a result of the continuing miniaturization of industrial products and parts. One of these features is microholes, which are found in various applications such as fuel injection nozzles, spinneret holes, filters, grits, and optical apertures [1]. Cutting, laser processing, electrical discharge machining (EDM), and chemical etching, for example, are usually employed for microhole drilling. Although electrochemical machining (ECM) has not been used for such drilling because of its wide interelectrode gap, recent studies have demonstrated that it can be applied to micromachining using ultrashort voltage pulses [2–8]. One of the many advantages of ECM is that it does not cause any thermal stresses or heat affected zones to the workpiece compared with laser processing and EDM. No tool electrode wear is another important advantage that cannot be achieved by cutting or EDM [9–11]. In addition, the material removal rate and machined shapes are more easily controlled than chemical etching [12]. It is expected that these advantages of ECM can be utilized in the field of micromachining.

With regard to the ECM of concave microshapes, it has been reported that a microslot approximately 2 µm in width and 5 µm in depth was fabricated in a Ni sheet, during which the tool electrode was moved sideways as well as fed vertically [5]. The ECM of a microhole is more difficult than that of a microslot because the clearance between the tool electrode and the hole/slot inner wall is smaller for the hole, thus preventing electrolyte circulation. The reported smallest-diameter hole with an aspect ratio of more than one is an 8-µm-diameter through microhole drilled in a 20-µm-thick stainless-steel sheet [6], to the best of our knowledge. The drilling speed was 0.67 µm/s and the machining time was 30 min. However, the drilling of a smaller-diameter hole has not been reported so far, while EDM, in which electrical machining is carried out using a tool electrode similarly to in ECM, can drill such microholes. Furthermore, a high drilling speed, which is one of the important advantages of ECM, has not been obtained. In the present study on the ECM of microholes, we therefore attempted to drill smaller-diameter holes and to increase the drilling speed with the aims of further minimizing the machinable size and employing the ECM of microholes in industry in the future.

2. ECM using ultrashort voltage pulses

Micromachining by ECM can be performed using ultrashort voltage pulses. Its principle is as follows [2].

Fig. 1 shows a simplified equivalent circuit of the tool electrode and workpiece immersed in electrolyte. When voltage is applied across them, electrical double layers develop on their surfaces. The double layers constitute electrostatic capacitance, which is represented as C_{dl} in the figure. Because the electrolyte resistance is proportional to the interelectrode gap length, the resistance at a close gap (R_{close}) is smaller

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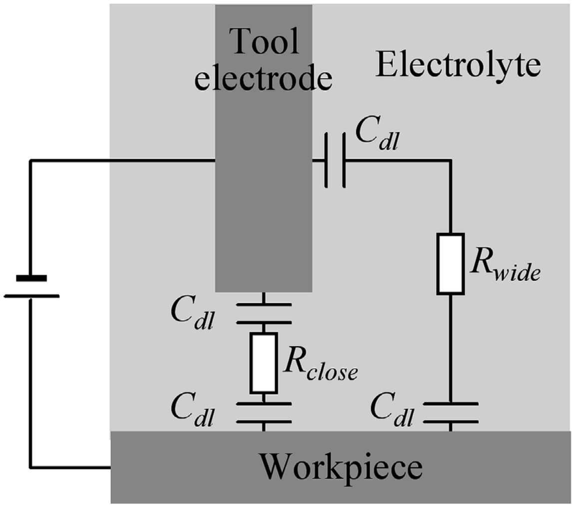

Fig. 1. Equivalent circuit using electrical double layer capacitance and electrolyte resistance.

than that at a wide gap (R_{wide}). Electrochemical dissolution occurs when the double layer voltage exceeds a certain threshold. The double layer voltage at a close gap increases faster than that at a wide gap with R_{close} being smaller than R_{wide}. If the pulse duration of the voltage applied across the tool electrode and workpiece is long enough for the double layer voltage at the close gap to exceed the threshold and is short for that at the wide gap, dissolution occurs only at the close gap. In this way, ECM with a micron-size gap is possible using ultrashort voltage pulses.

3. Experimental procedure

3.1. Preparation of tool electrodes

Ultrasmall-diameter tool electrodes are required for the ECM of microholes. EDM was employed here for tool electrode fabrication. It is suitable for fabricating micropin tool electrodes because the mechanical force exerted on an EDM workpiece is minute and because minimizing the unit removal is possible under machining conditions where the electrical discharge energy is very low. Wire electrodischarge grinding (WEDG) [13], an EDM method, was used for the fabrication. A wire tool electrode is used in WEDG, as in wire electrical discharge machining (WEDM). However, a wire guide supports the electrode at the machining point to reduce wire vibration in WEDG, unlike in WEDM, leading to high dimensional accuracy. Straight pins with micron-order diameter can be fabricated by WEDG.

WEDG was carried out on a micro-EDM machine (MG-ED72, Panasonic Corp.). Its spindle system includes a V-shaped sliding bearing and a mandrel made of stainless steel. A ceramic capillary inserted in the mandrel tip guides a tool blank. The rotation runout of the mandrel is principally determined by the circularity of the cross sections of its parts in contact with the bearing surfaces. The mandrel was fabricated such that this circularity was approximately 0.2 μm. A relaxation-type pulse generator was employed for the electrical discharge circuit. This type of pulse generator is preferable for micromachining because it can generate electrical discharge with a very short pulse width and thus minimize the unit removal per discharge.

Cemented tungsten carbide (WC) of 0.6 μm grain size (FM10K, A.L.M.T. Corp.) was used as the tool electrode material. Its high electrical conductivity allows it to be processed by EDM. This material with high hardness and high fracture toughness was selected because an ultrasmall-diameter tool electrode easily bends or breaks when it comes in contact with a workpiece. Such contact is apt to occur in the drilling of microholes because of a narrow interelectrode gap. Fig. 2 (a) and (b) show an example of fabricated cylindrical tool electrode 10 μm in diameter and the semicylindrical tool electrode geometry, respectively. R in Fig. 2 (b) indicates the radius of the wire tool electrode used for WEDG. The tool electrodes were finished at an electrical discharge circuit open-circuit voltage of 50 V and an electrostatic capacitance of the stray capacitance only.

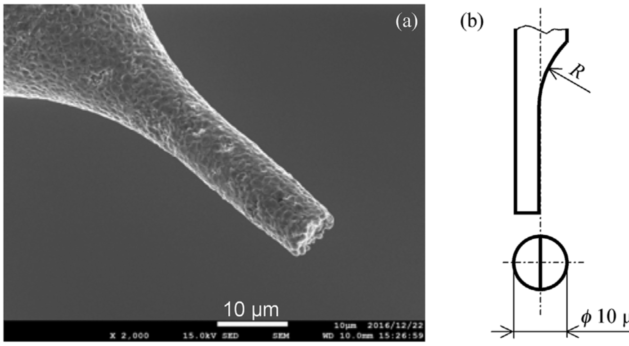

Fig. 2. (a) Example of fabricated cylindrical tool electrode and (b) semi-cylindrical tool electrode geometry.

3.2. Experimental setup

Experiments were performed using a machine originally designed for micro-ultrasonic machining (ASWU-1, Creative Technology Corp.) that has three axes, each driven at a step feed of 0.05 μm [14]. Fig. 3 shows a schematic configuration of the main parts of the machine. It employs the same spindle as that used in the micro-EDM machine. After tool electrode fabrication using the micro-EDM machine, the mandrel holding the tool electrode is mounted on the V-shaped sliding bearing on the micro-ultrasonic machine. The advantages of using the same spindle system on both machines are that high precision of the mandrel rotation can be maintained and that an operator can avoid directly handling a tool electrode, which is a difficult task when tool electrodes have a small diameter.

A workpiece was attached with adhesive tape to the tip of an ultrasonic transducer originally installed for ultrasonic machining. The workpiece can be ultrasonically oscillated using the transducer; however, it was not oscillated in the present study. The transducer was held by a transducer holder, which was mounted on an electronic balance (EB-430H, Shimadzu Corp.) with a minimum increment of 1 mgf (approximately 10 μN) and a time resolution of 50 ms. The electronic balance was employed so that a very low contact load between the tool electrode and workpiece could be detected. A drop of electrolyte was supplied at the interelectrode gap because no working tank was

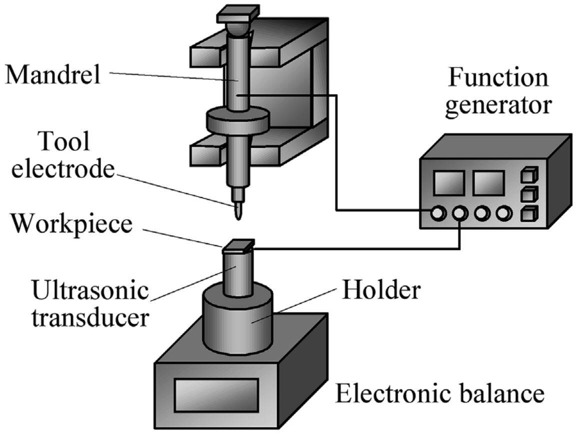

Fig. 3. Schematic configuration of main parts of experimental setup.