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Fabrication of disk microelectrode arrays and their application to micro-hole drilling using electrochemical micromachining

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ABSTRACT

Minimal-taper microholes are widely used in modern industries. Electrochemical micromachining (EMM) has been demonstrated to be a feasible method to fabricate these microholes. In this study, based on its unique processing properties and productivity, a disk microelectrode array was fabricated via electrolysis for producing micro-holes. The dimensions of the cathode for hydrolysis were optimized by applying the finite element method to the constructed physical model. A 3 × 3 disk microelectrode array and a 5 × 5 cylindrical microelectrode array with uniform dimensions were then fabricated using the optimized cathode. Micro-holes were drilled on stainless-steel plates using both disk and cylindrical microelectrode arrays. The taper of the resulting micro holes obtained using the new disk microelectrode array was lower than that of the holes formed using the cylindrical microelectrode array. The effects of EMM parameters, including the applied voltage, feeding speed, and pulse-on time, on the hole diameter and taper were also investigated. The results suggest that appropriate machining parameters should be selected in consideration of the effects of these parameters on hole diameter, taper, localization, and material removal rate.

1. Introduction

With the development of modern industries for miniaturized components, micromachining has attracted considerable attention due to its ability to save energy, space, and material. The microstructures produced by micromachining include micro holes, slots, complex surface in larger numbers or in single workpiece. Nontraditional machining methods including microelectrical discharge machining (micro-EDM) (Ferraris et al., 2013; Tong et al., 2013), Lithographie Galvanoformung Abformung (LIGA) (Chang and Kim, 2000), laser beam machining (LBM) (Dubey and Yadava, 2008; Biffi and Tuissi, 2014), and electrochemical micromachining (EMM) (Sen and Shan, 2005; Fan et al., 2012; Ghoshal and Bhattacharyya, 2015) can be used to fabricate such micro holes and slots. However, because micro-EDM and LBM are thermal machining methods, the machined surface contains a heat-affected zone, and tool wear is inevitable in micro-EDM. LIGA has the advantage of processing two-dimensional microstructures, typically using nickel alloy or copper. Electrochemical machining (ECM), a nontraditional machining method, appears to be a promising micromachining method in the future because it can machine most metal materials regardless of their hardness, and the machined surface is free of tool wear and residual stress. In ECM, the material is dissolved from the workpiece surface into ions via electrochemical reaction; thus, ECM can be used to machine micro-holes on metal surfaces. The diameters of these holes range from several tens to hundreds of micrometers with numbers of dozens. The microelectrode plays a vital role in machining micro-holes using EMM, and microarray electrodes are the key to increasing the productivity of this method.

Hwang fabricated micropin arrays with circular cross sections, high hardness, and high density using a method that combines mechanical peck drilling and reverse electrical discharge machining (reverse-EDM) (Hwang et al., 2010). Hu fabricated a high-aspect-ratio electrode array by combining UV-LIGA with micro-EDM (Hu et al., 2009). Park drilled 120 micro holes in 40 min using arrays containing multiple tungsten carbide shafts machined by wire-EDM (WEDM) (Park and Chu, 2007). Zeng et al. (2012) reported a highly efficient technique for machining microelectrode and microhole arrays using hybrid micro-WEDM and ECMM methods. Wang and Zhu (2009) recommended a hybrid process combining EDM and electrochemical etching to prepare multiple microelectrodes. The literature review shows that the hole taper is inevitable in microhole drilling in ECMM by using the cylindrical microtool.

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Recent efforts have attempted to reduce the hole taper of machined microholes. Liu et al. (2011, 2015) fabricated a microelectrode with a spherical tip by combining electrochemical etching with single-pulse EDM, and then, drilled a microhole with no taper. However, the controlling process in this method is not facile. Kim et al. (2006) fabricated double disc-type electrodes with disc diameters of 45 μm, neck diameters of 20 μm, and neck lengths of 200 μm using a reverse-EDM method. Kuo and Huang (2003) processed microdisks of different thicknesses on a metallic pin using micro-EDM by precisely controlling the path of a wire tool electrode. However, the EDM method causes heat effects and wear on the machined surface. Rathod et al. (2013) used EMM to fabricate a microtool disk and machined microholes with diameters of approximately 480 μm and depths of 600 μm in a stainless-steel plate; this method significantly reduced the hole taper. As discussed above, disk electrodes and electrodes with spherical tips are effective for machining micro holes with minimal taper in EMM. The feature of these microtools is that the diameter is larger for the tip than that for the shank part, and is called "disk microtool." EMM is an effective method for preparing such disk microtool electrodes. Thus, in this paper, a method for the fabrication of disk microelectrode arrays is presented. To improve the consistency of the fabricated disk microelectrode arrays, finite element method (FEM) was employed to estimate the optimal dimensions of the cathode (a spherical surface). A physical model and an optimized equation for the interelectrode gap were constructed based on the Laplace equation of the electric field using numerical methods. The current density distribution on each electrode was computed and compared using the objective function. The optimized cathode and model dimensions were then utilized to prepare the disk microelectrode array. Finally, micro holes were drilled on the built set up by using the fabricated disk microelectrode array and the effects of variables such as applied voltage, feeding speed, and pulse-on time on the overcut and hole taper of the microholes were investigated. The results show that the proposed method can produce microholes with minimal taper and that the preparation method of the disk microelectrode array has significant effects on the resulting holes.

2. Fabrication of disk microelectrode array

2.1. Principles for the fabrication of the disk microelectrode array

Considering the stiffness, heat resistance, electrical conductivity, and breakability of the microelectrode array, tungsten carbide (WC) was selected as the electrode material and the disk microelectrode array was prepared. First, a small microstructure with square micropillars was processed from a small rectangular body of WC via WEDM (Fig. 1). The workpiece (the rectangular body of WC) was clamped on the spindle and gradually fed downward against the moving wire by using a pulse power of 100 V, cutting the workpiece into slices. Subsequently, the workpiece was rotated 90° and the process was repeated to produce a second cut orthogonal to the first. In this way, the squared microelectrode was fabricated. The fabricated squared microelectrode was then immersed in the KOH solution at a certain depth and gradually eroded into cylindrical sectional electrodes under the conditions listed in Table 1.

Table 1
Conditions of electrochemical etching.

Parameters	Value
Applied voltage	2–7 V
KOH solution	2 mol/L
Temperature	25 °C
Immersing depth	1–4 mm

The simulated current density distributions on the bottom of each electrode obtained using the parallel plate opposite the bottom of the microelectrode as the cathode is shown in Fig. 2a. The current distribution on each electrode bottom was nonuniform and basin-like. The current on the corner was larger than that on the central section. The scanning electron microscopy (SEM) image of the microelectrode array (Fig. 2b) clearly shows that the pillar sizes were different.

Based on the simulation results discussed above, the spherical cathode was selected and the optimal dimensions were determined using FEM. The sphere radius (R), distance between the center of the sphere and the bottom of the microelectrode (L), and sphere radiation angle (β) were selected as the optimization variables (Fig. 3).

As shown in Fig. 3, the squared microelectrode (anode) and a stainless-steel ball (cathode) located above the anode were connected to the positive and negative terminals of a DC power supply, respectively. When power was applied between the anode and cathode, metal dissolution occurred. The material at the edges of the squared electrodes was first dissolved due to the strong electric field distribution in these places, and the squared electrode became cylindrical. According to the discussion in Wang and Zhu (2009), the changes in electrode shape along the longitudinal axis were determined primarily by the applied voltage. In this study, a voltage of approximately 5.9 V resulted in the formation of a cylindrical micropin (Fig. 4). The microelectrode tended to be conical in shape at voltages less than 5.9 V and assumed a reverse-conical shape at applied voltages exceeding 5.9 V. Next, the disk microelectrode array was fabricated by protecting the tips of the prepared cylindrical microelectrodes using the same electrochemical etching method.

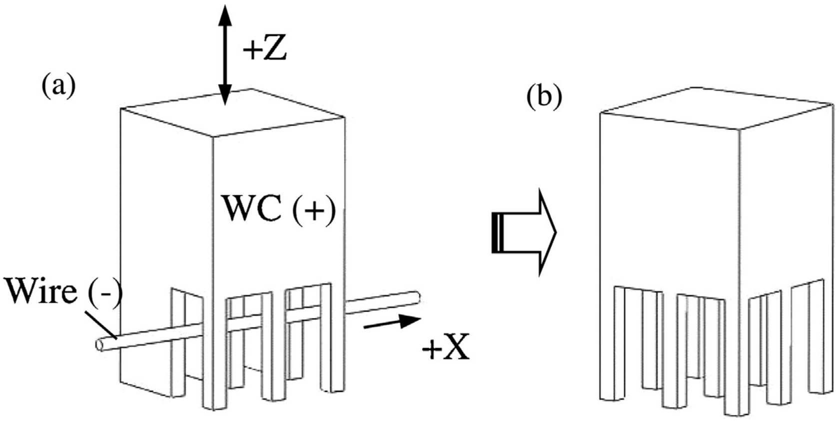

Fig 1. Squared electrode array processed by WEDM: (a) multielectrode by WEDM and (b) machined square electrode array.

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