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Fabrication of high aspect ratio micro-rod using a novel electrochemical micro-machining method

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ABSTRACT

In this paper, a novel electrochemical micro-machining method is proposed to fabricate a tungsten micro-rod with a high aspect ratio. In this method, the periphery of the iron needle is surrounded by an insulator so that only its end face with the diameter of 50 μm is exposed on the electrolyte as the cathode of the tool electrode. A tungsten rod with a diameter of 200 μm is taken as the workpiece and the anode. These two electrodes are immersed to a depth of 3 mm in the electrolyte of 2 wt% sodium hydroxide. This small end face of the tool electrode is against the workpiece in vertically reciprocating motion with a certain stroke to conduct the electrochemical micro-machining under DC electric field. During the machining, since the diameter of the workpiece is gradually reduced, the tool electrode is adjusted so that the gap between its end face and the anode remains 30 μm. The effects of supply voltage or current, rotational speed and stroke of workpiece, and relative position between the end faces of electrodes on the geometry of one end of the workpiece are investigated. This relative position can be used to control the workpiece geometry at one end and its amount of the length reduction. When this relative position is adjusted to a preset position at each stroke, the ratio of the length to the diameter can be increased, but the average decreasing rate in diameter remains invariable. The novel method developed in this paper can fabricate an extremely thin straight rod in diameter of 2 μm with an aspect ratio of 120 from a tungsten rod with a diameter of 200 μm using a tool electrode with an end diameter of 50 μm under two-stage procedure.

1. Introduction

Today, in many micro precise process or measuring system, it is necessary to use micro electrode as the tool electrode [1,2] or as the probe [3–5]. To meet these demands, various methods to fabricate these micro electrodes have been proposed, such as a micro mechanical machining [6–8], a wire electro-discharge grinding (WEDG) [9,10], a reverse electro-discharge machining (EDM) [10,11], a scanning EDM [12], and a micro anode guided electroplating (MAGE) [13–15], etc. In recent years, an electrochemical micro-machining has received much attention in the fabrication of micro probe, since it offers several advantages including lower cost, no tool wear, higher machining rate, better precision and control, bright surface finish and absence of stress/burr in materials regardless of their hardness.

Electrochemical micro-machining is an anodic dissolution process in which a current is passed between a tool electrode (cathode) and a workpiece (anode) through an electrolyte so that material from the workpiece is dissolved to form the desired shape and the size in the workpiece. Lim et al. [16,17] investigated the effects of current and voltage on the appearance of tungsten pins and a mathematical model was derived for controlling the diameter of the pin. Based on this model to control the current and voltage, a straight micro-pin with a diameter of 50 μm and a length of 4 mm was fabricated. Choi et al. [18] fabricated a straight micro-pin with a diameter of 5 μm and a length of 3 mm by controlling the applied voltage and the concentration of the electrolyte. Fan and Hourng [19] thought that the micro-electrode with diameter less than 0.1 mm could be fabricated under low applied voltage, high concentration electrolyte and appropriate rotational speed of the electrode. A higher rotational speed would result in an electrode of conical shape. Fan et al. [20] discussed the effects of applied voltage, pulsed period, duty factor and temperature on the fabrication of microelectrodes under a pulsed voltage. The micro-pin with a diameter of 0.1 mm and various lengths could be fabricated by a linear decay of applied voltage or duty factor.

In the past, when the micro-part with the high aspect ratio was fabricated by the electrochemical micro-machining, the tool electrode of the cathode mostly paralleled the tungsten rod of the anode. Since the thickness of the diffusion layer [16] and the oxygen [19] formed around the tungsten rod are not uniform, the geometry machined is easily influenced by the operating conditions so that it is hard to fabricate a truly cylindrical micro-rod.

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On the other hand, using flat-end cathode against an anode workpiece to conduct the electrochemical drilling, the erosion gets deeper and the gap becomes larger, which will slow down the machining process by decreasing the electric field intensity [21]. Further, when the current density in the inter-electrode gap is higher than the one of the surrounding gaps, the workpiece is machined firstly at the inter-electrode gap [22]. Park et al. [23] investigated the effect of the tool electrode size on the machining rate. Hence, an insulation coating method was developed to reduce the tool electrode area. Their results showed that side insulation of the tool electrode is effective in minimizing size effects when the machining depth is high.

As mentioned above, it is easy to form the higher electric field intensity or current density in the gap between the electrodes, so that the machining rate is faster on a narrow area in the region with the smallest gap. Based on this idea, only the end face of the tool electrode with the diameter of 50 μm exposed on the electrolyte is proposed. The novel method of the electrochemical micro-machining is used to fabricate a tungsten micro-rod with a high aspect ratio which moves in vertically reciprocating motion with a certain stroke.

2. The machining characteristic of workpiece with mathematical model at fixed position

In the Coulomb's law, the electric field intensity, E, applied to the workpiece is proportional to the charge density, q, and inversely proportional to the square of the distance between the tool and the workpiece, R, as illustrated in Eq. (1).

$$E \propto \frac{q}{R^2} \tag{1}$$

Based on the Coulomb's law, a 2D mathematical model has been studied in the previous research [24], and a modified 3D mathematical model is developed in this study, as shown in Fig. 1. In this model, the removal amount of the workpiece machined at a fixed position is assumed to be proportional to E, as mentioned above. An imagined circle which has diameter, r', is located on the end face of the electrode. P is one of the points on the circle. θ is the angle between $\overline{O'P}$ and Y'-axis. On the other hand, another imagined circle, A_3, which has diameter, r, is located under the surface of the workpiece. Q' is one of the points on the circle A_3, which is also located on the surface of the workpiece. α is the angle between $\overline{UU'}$ and $\overline{UQ'}$. δ is the shortest distance between the electrode and the workpiece. x' is the distance between the point on the workpiece surface, T, and the center, U of the circle A_3. It can be shown in Fig. 1 that

$$R^2 = (r' \sin\theta - r \sin\alpha)^2 + (r' \cos\theta - r\cos\alpha)^2 + (\delta + x')^2 \tag{2}$$

and

$$x' = \rho - \sqrt{\rho^2 - r^2 \sin^2\alpha} \tag{3}$$

where ρ is the diameter of the workpiece.

The removal amount of the any point on the workpiece surface is influenced by all points on the electrode. An integral of the points from the electrode is carried out to add up the removal amounts of the single point on the workpiece surface, and a new gap, x_{i+1}, between the electrode and the workpiece is also predicted at the first moment of the machining. Substituting this new gap into the model, and the total removal depth per unit time, m_i, along the X-direction can be calculated by iteration with increasing machining time.

$$x_1(r,\alpha) = \delta + x' \tag{4}$$

$$x_{i+1}(r,\alpha) = x_i(r,\alpha) + \Delta t \cdot m_i(r,\alpha), \quad i \geq 1 \tag{5}$$

$$\begin{aligned} m_i(r,\alpha) &= -\int_0^{r'}\int_0^{2\pi} \frac{c}{R^2}\,d\theta\,dr' \\ &= -\int_0^{r'}\int_0^{2\pi} \frac{c}{r'^2 + r^2 - 2r'r\cos(\theta-\alpha) + x_1^2(r,\alpha)}\,d\theta\,dr' \end{aligned} \tag{6}$$

where c is a constant of electrical efficiency and Δt a time increment.

When the iteration of the single point on the workpiece is finished, a new iteration at another point on the workpiece is carried out. The new topography of the workpiece is sketched after the total removal amounts of all points on the workpiece are iterated. Hence, the development of the machined surface of the workpiece in the ECM process is described using this model. Fig. 2 shows the predicted micro-machining profile under the inter-electrode gap of 30 μm, the workpiece diameter of 200 μm, the electrode diameter of 50 μm, and the machining time of 10 s. This figure makes clear that only the region of the workpiece near the end face of the electrode is machined.

Moreover, an independently experiment is conducted to verify the model, as shown Fig. 3. Fig. 3 shows how the micro-machining depth increases with the machining time. The comparison of the experimental data and the 3D model shows that the predicted value is in good agreement with the experimental one under the supply voltage of 15 V, the machining time of 150 s, and the other operating conditions remain the same as Fig. 2.

Based on the results mentioned above, the machined areas are focused at certain position where the end face of the tool electrode is fixed. If the tool electrode is moved along the Y-axis with certain inter-electrode gap, and the workpiece is rotated, the electric field or machined areas can be uniformly distributed on the surface of the workpiece. Hence the micro-rod can be achieved using the electrochemical machining (#3).

3. Experimental apparatus and procedure

An electrochemical micro-machining apparatus is designed and set up to fabricate a micro tungsten rod with high aspect ratio, as shown in Fig. 4(a). This apparatus is located on a plate of vertical worktable so that it is easy to adjust its position of the vertical direction. In the present experiment, a tungsten rod with a diameter of 200 μm is taken as the workpiece, and it is attached to a jig which is precisely chucked to a rotating spindle mounted by a bearing support. The conductive wire is connected to the anode of the DC power supply and carbon brush, respectively, and then the carbon brush is in contact with the rotating spindle, so that the tungsten rod becomes the anode. The distilled water containing 2 wt% NaOH is taken as the electrolyte and an iron needle is used as the cathode. The rotating speed of the tungsten rod is controlled and adjusted by the first motor. In this experiment, the rotating speed is set to be 200 rpm and 500 rpm. The bearing support and the first motor are attached to the linear slider, and this slider is driven by the screw of a non-rotating spindle type micrometer head. A synchronous belt is used to connect the gear in the spindle of the second motor and the gear mounded on the spindle of micrometer head so that the slider can be driven by the second motor. When the spindle of the second motor rotates at 1 rpm and reverses its direction of rotation at a certain period, the first motor and the tungsten rod mounded on the slider move a vertically reciprocating motion at a certain stroke. For convenience, the cycle number per minute for the tungsten rod under the reciprocating motion is defined as the frequency.

On the other hand, the iron needle is surrounded by a layer of the epoxy resin of an insulated material so that its end face with a