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Investigation of electrochemical micromachining of tungsten microtools

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ABSTRACT

Tungsten tools are used in various advanced manufacturing industries owing to their excellent physical and mechanical properties. However, the material characteristics of tungsten, such as its hardness and brittleness, make it difficult to fabricate tungsten microtools using mechanical methods. Electrochemical micromachining (ECMM) is a potential method for machining tungsten microstructures, because the process is independent of the material physical and mechanical properties. In this paper, an investigation into ECMM of tungsten microtools using a rotary helical electrode is presented. The optimal process conditions, including electrolyte concentration, duty ratio, and frequency of pulsed voltage, are determined experimentally. A quantitative relation between the machining side gap and the applied voltage and electrode feed rate, which can be controlled online during the machining process, is calculated from the experimental results. A contour map is drawn to aid in selecting the optimum process parameters to achieve a specific slit width. Finally, a tungsten array microtool with variable cross-section is fabricated by adjusting the applied voltage online.

1. Introduction

Tungsten exhibits high hardness and the highest operating temperature of all metals [1,2]. The Young's modulus of tungsten is about twice that of steel, which allows tungsten products to be made in smaller sizes [3]. Thus, tungsten has come to be employed as a tool material in micro machining: tungsten micropin structures have been used as probes [4], tungsten micro-rods are used as electrodes in machining of fuel jet nozzles [5], and there are a number of engineering techniques that require the use of tungsten arrayed microtools with variable cross-section.

However, as a result of its otherwise desirable mechanical and physical properties, tungsten is difficult to cut by mechanical methods, especially when fabricating tungsten micro-devices. Generally, there is very high tool wear, in addition to the formation of a cold-hardened layer on the machined surface. Microwire electrical discharge machining (μ-wire EDM) has been used to produce planar tungsten-based microdevices such as collimators and detectors for medical computed tomography (CT) machines [1]. However, it generates significant surface damage and microcracks in the shaped parts, which may lead to fatigue failure [6].

In contrast to conventional mechanical methods and EDM, electrochemical micromachining (ECMM) removes material by controlled electrochemical anodic dissolution, and is a potential method for machining tungsten microstructures that is not subject to limitations arising from the physical and mechanical properties of the material. Its advantages include the absence of tool wear, residual stress, and metallurgical defects [7]. ECMM has consequently become an important method for machining microstructures with good surface integrity in difficult-to-machine materials [8].

A variety of tungsten microtools have been fabricated using electrochemical methods. Park et al. [5] described a microcarving technique combining laser beam machining and electrochemical etching to fabricate a tungsten micropin. Pan et al. [9] etched a tungsten wire of diameter of 1 μm in a two-step procedure. Lim and Kim [10] proposed a method in which the pin diameter is controlled via the current density and voltage, which determine the effect of the diffusion layer, and used it to fabricate a cylindrical micropin. Wang et al. [11] described a reproducible method based on liquid membrane pulsed electrochemical etching, and used it to fabricate sub-micrometer spherical probes with diameters as small as about 180 nm. Han and Kunieda [5] used a neutral electrolyte and ultrashort-pulsed bipolar currents supplied by an electrostatic induction feeding method to machine tungsten micro-rods. He et al. [12] studied the influence of some key parameters on the machining side gap in wire ECMM, and fabricated a tungsten microstructure with a slit width of 18 μm in a 100 μm thick plate. Liu et al. [13] investigated the fabrication of tungsten microtools of various shapes using wire ECMM, and fabricated a thin-slice tungsten microtool of length 224 μm and width 21 μm.

Although ECMM has many advantages, research on ECMM of

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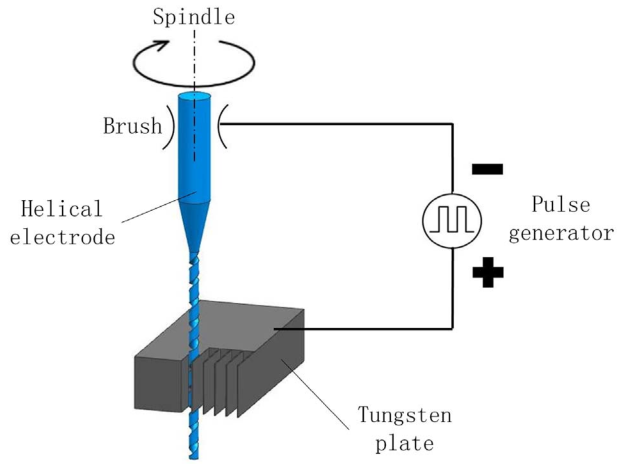

Fig. 1. Schematic diagram of ECMM using a rotary helical electrode.

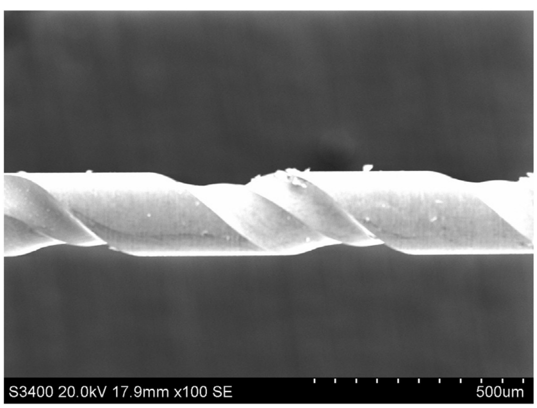

Fig. 2. The microdrill used as a helical electrode.

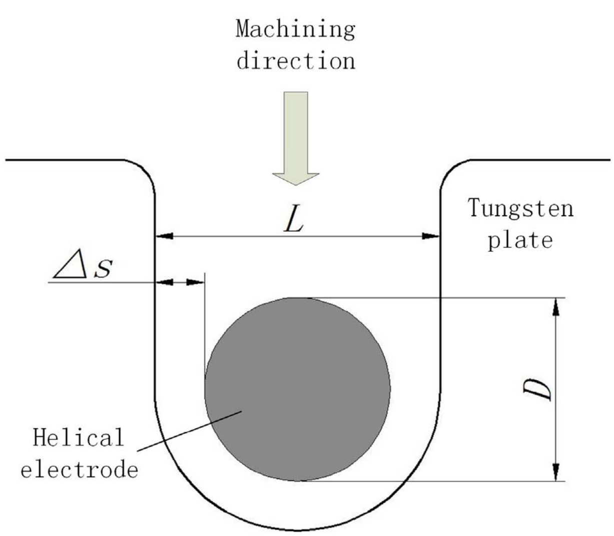

Fig. 3. Relative positions of the workpiece and electrode in ECMM.

tungsten microtools is lack and there are still some problems that remain to be solved. The machining gap between the cathode and the anodic workpiece is too tiny to allow rapid removal of electrolysis products and renewal of electrolyte, leading to frequent electric short circuits and a low process efficiency when fabricating thick structures [14]. Thus, the current research focused on enhancing the removal of electrolysis products to improve the machining efficiency. Natsu et al. [15] proposed the application of ultrasonic vibrations to the tool electrode to enhance removal of electrolysis products from the machining area and improve the machining efficiency. Bhattacharyya et al. [16] investigated the influence of microtool vibrational frequency on the material removal rate and machining accuracy in ECMM. Zeng et al. [14] proposed three approaches, namely, flushing of electrolyte along the cathode wire, unidirectional motion of the wire, and micro-vibration of the wire, and studied these both theoretically and experimentally. Fang et al. [8] proposed an ECMM method using a rotary helical electrode to enhance electrolyte refreshment in the depth direction of the machining gap and were able to fabricate two complex microstructures at a spindle speed of 20,000 rpm/min.

Recently, tungsten microtools have come to be used in precision micromachining where it is necessary to produce complex structures with variable cross-section. However, to date, there has been a lack of relevant research. This paper describes an investigation of ECMM of tungsten microtools with variable cross-section. Experiments are conducted on 500 μm thick tungsten plates, with the aim of investigating the influence of process parameters on machining accuracy. Furthermore, a quantitative relationship between the machining side gap and specific parameters (applied voltage and feed rate) is determined and discussed. Finally, an arrayed tungsten microtool with variable cross-section is fabricated through adjusting the applied voltage at different machining positions.

2. Principle

In acidic or weakly alkaline solutions, the total anodic oxidation reaction of tungsten can be expressed as follows [17]:

$$W + 3H_2O = WO_3 + 6H^+ + 6e^- \quad (1)$$

The oxide phase may accumulate in the machining gap, causing a blockage and leading to machining failure. However, in strongly alkaline solution, the oxide phase can be dissolved with the assistance of OH^- ions as follows [18]:

$$WO_3 + 2OH^- \rightarrow WO_4^{2-} + H_2O \quad (2)$$

Therefore, for the experiments reported here, KOH solution was chosen as the electrolyte.

In ECMM, an electric potential is applied between the workpiece, which acts as the anode, and the tool, which acts as the cathode [3]. It has been shown that the machining stability and the material removal rate in ECMM can both be significantly improved by enhancing the mass transport process, which facilitates removal of the products of electrolysis and refreshment of the electrolyte [14]. One way to do this is to use as the tool a rotary helical electrode, a cylinder with spiral grooves on its surface. This approach was adopted in this investigation.

Fig. 1 shows a schematic diagram of the setup for ECMM using a rotary helical electrode, for which a microdrill of diameter 200 μm (shown in Fig. 2) was used. The electrode was attached to a spindle and rotated at high speed. The workpiece was a pure (99.9%) tungsten plate and was immersed in the electrolyte. During the machining process, the helical electrode was fed along a predetermined path to produce the desired structure.

As the helical electrode rotates, the electrolyte in the processing gap between workpiece and electrode is forced to flow from bottom to top. Thus, electrolyte containing electrolysis products is removed from the narrow machining gap to the top surface of the workpiece. Meanwhile, fresh electrolyte is forced from the bottom of the workpiece into the machining gap. In this way, the use of a rotary helical electrode enhances refreshment of electrolyte in the machining gap, thereby improving process stability and efficiency.

In this study, the machining accuracy is evaluated by the width of the machining side gap and the machining efficiency is evaluated by the maximum achievable feed rate of electrode. The maximum achievable feed rate is defined as the maximum value of electrode feed rate at which no short circuit occurs during the process with a machining