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Investigation of the hole-formation process during double-sided through-mask electrochemical machining

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ABSTRACT

Through-mask electrochemical machining has been developed to fabricate hole-array in titanium alloys that are difficult to cut using traditional mechanical machining. The taper angle of hole-array is an important criterion to estimate the quality of machined hole-array. Due to the isotropic nature, the machined holes have taper angles by using through-mask electrochemical machining, and it is still a challenge to reduce these taper angles. In this paper, a double-sided through-mask electrochemical machining process is investigated in order to fabricate hole-array with low taper angle. A model of the double-sided through-mask electrochemical machining is established to simulate the hole-formation process. The simulation results indicate that the electric field of the double-sided through-mask electrochemical machining is beneficial to reduce the taper angles of machined holes. In order to verify the simulation results, experimental investigations of hole-formation are implemented. The experimental results indicate that the sidewall of machined hole could be close to the straight at a certain machining time. Finally, a 6×50 hole-array is machined by double-sided through-mask electrochemical machining onto Ti-6Al-4V sheet with thickness 0.5 mm. The maximum taper angle of the hole-array is only 2.52°.

1. Introduction

Hole-array in metal parts is used in many fields, including aeronautical engineering, automobile manufacturing, and electronics industries. The materials comprising these parts are usually difficult-to-cut metal, because these parts are used in special environment (Bao et al., 2008; Pavlinich et al., 2008). Meanwhile numerous of these parts included a large number of holes in the thin metal plate (<1 mm) will lead many problems in generating these parts, such as low processing efficiencies, high processing costs, and easy deformation of the materials (Pattavanitch and Hinduja, 2012). Electrochemical machining (ECM) is a very important technology in the processing of difficult-to-cut materials because it is independent of material hardness and has no heat-affected layer, no residual stresses, and no cracks (Kern et al., 2007; Rajurkar et al., 2013). It is popular for the foregoing advantages in machining hole-array by ECM.

The common ECM technologies of machining hole-array could be divided into two classes: multiple electrode drilling holes using ECM and through-mask electrochemical machining. Many researchers have focused on the multiple electrodes using ECM technique for machining holes in arrays. Bo et al. (2006) reported that a micro-hole-array (3×7) with 50 μm in diameter was machined on stainless steel (SS) 304 with 100 μm thickness by the multiple electrodes ECM technique. The fabricated hole had sharp edge which shown that the dissolution is localized only around the electrode. Wang and Zhu (2009) investigated micro machining gap to fabricate hole-array on SS 304 by the multiple electrodes ECM process, and the machining gap could be decreased down to as low as 10 μm. Min and Chong (2007) obtained a micro-hole-array (30×4) on an SS 304 workpiece with a thickness of 50 μm by the multiple electrodes ECM process. The multiple electrodes do not wear during the ECM process, and the machining accuracy is good. However, the preparation process of multiple electrodes is complex.

Through-mask electrochemical machining (TMECM) selects metal dissolution from unprotected areas of a mask-patterned workpiece that is made an anode in an electrolytic cell. TMECM is a high-throughput process and has low processing costs for fabrication of hole-array. Datta (1995) used the TMECM to fabricate a hole-array of precision nozzles metal foils for ink-jet printer heads. The taper angle of hole is an important criterion to estimate the quality of machined hole. The isotropic nature of the metal removal process during TMECM will cause the sidewall to have certain taper

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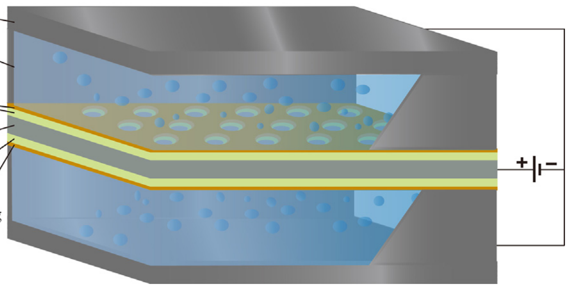

Fig. 1. Schematic diagram of modified double-sided through-mask electrochemical machining.

(Shenoy and Datta, 1996). It is still a challenge to reduce the taper angle of machined hole. Many researchers have presented various methods of reducing the taper angle of machined hole. Alan et al. (1992) reported that the taper angle of machined hole in SS 304 was less than 20° by optimizing the electric field during TMEC Li et al. (2011) demonstrated that the taper angle of hole-array in SS 304 would be reduced when the mask wall angle was larger than 90°.

TMECM involves dissolution of the metal workpiece either from single side or from double sides simultaneously. The double-sided TMECM dissolves the metal workpiece from double sides simultaneously, and this technology has been used in some occasions such as machining low taper angle hole-array. The double-sided TMECM has long been considered a simple symmetry with single-sided TMECM, and researchers concentrated the machining process analysis of single-sided TMECM (Alexey et al., 2014). To our knowledge, it has not been done to analyze the machining process of the double-sided TMECM by numerically simulation and experiment.

In the conventional TMECM, the photoresist as a mask adheres to the workpiece. The photoresist is adhered to the workpiece surface is quite strong, and the photoresist mask cannot be reused after once TMECM. Therefore, the photoresist coating and exposure must be repeated. Zhu et al. (2009) presented a modified TMECM, in which a patterned insulation plate coated with metal film was used as mask instead of photoresist. The modified process had short lead time and low cost because the mask could be reused. Chen et al. (2015) developed the uniformity of shape evolution during the modified TMECM by optimizing the electric field and controlling the processing voltage. In this paper, the mask of the double-sided TMECM makes reference to the aforementioned modified TMECM. A copper coating onto a patterned insulation plate is used as mask and the mask can be reused.

The purpose of this investigation is to study the hole-formation process during double-sided TMECM in order to fabricate hole-array with low taper angle. In the double-sided TMECM, a copper coating onto a patterned insulation plate clad and a fixture were employed as dual cathodes to constitute the unique model of electric field. A mathematical model of the double-sided TMECM is established to evaluate the machining process of hole-array and acquire hole-array with low taper angle, and verified experiments were also done.

2. Model of double-sided TMECM

The schematic diagram of double-sided TMECM is shown in Fig. 1, where copper clad laminate is used as a mask. The hole-array in the mask is machined using computer numerical control drilling. A special fixture as shown in Fig. 1 is used to avoid that the electrolyte diffuses between the workpiece and the mask. The special fixture has a lot of convex columns around mask holes. The fixture with these columns presses the mask onto the workpiece, and electrolyte is pumped out at a high speed between the fixture and

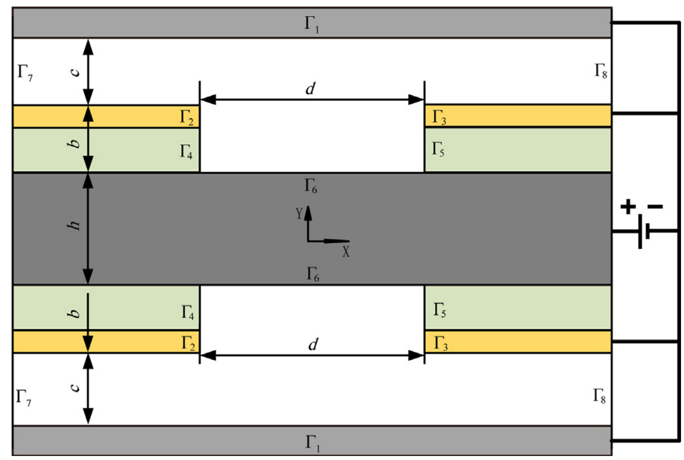

Fig. 2. Geometric model of double-sided through-mask electrochemical machining.

the mask. The area of the workpiece exposed in the electrolyte can be dissolved from double sides simultaneously when 30 V voltage is applied. The dissolved material (usually metal hydroxide), the generated gas bubbles, and the Joule heating generated are flushed away using the flow of the electrolyte.

The copper coating and the fixtures constitute dual cathodes in order to improve the electric field distribution during the double-sided TMECM. The mask with a lot of holes can be fabricated within a short time, and the mask can be reused. In addition, the workpiece is dissolved from double sides simultaneously. Therefore, the double-sided TMECM can efficiently create hole-array at low cost.

The simplified two-dimensional (2D) geometric model of the double-sided TMECM is shown in Fig. 2. In the geometric model, d is the diameter of the holes in the mask, c is the distance between the cathode and the mask, and b and h are the thickness of the mask and the workpiece, respectively. The geometric parameters are as follows: d = 2 mm, c = 1.2 mm, b = 0.3 mm (the copper layer is 0.1 mm thick), and h = 0.5 mm. The following assumptions are made:

1 The distribution of current density on the workpiece surface is only determined considering ohmic effect;
2 The conductivity of the electrolyte, k, is uniform;
3 The temperature of the electrolyte, T, is uniform;
4 The electrodes are defined as equipotential surfaces.

According to electric field theory, the electric potential distribution can be approximately described using the Laplace equation (Filatov, 2001):

$$\nabla^2\varphi = 0 \tag{1}$$

where φ is the electric potential.

The boundary conditions are as follows:

$$\varphi|\Gamma_{1,2,3} = 0(\text{cathodetool}) \tag{2}$$

$$\varphi|\Gamma_6 = U(\text{workpiece}) \tag{3}$$

$$\frac{\partial\varphi}{\partial n}|\Gamma_{4,5} = 0(\text{insulating boundaries}) \tag{4}$$

$$\frac{\partial\varphi}{\partial n}|\Gamma_{7,8} \approx 0(\text{free boundaries}) \tag{5}$$

where n is the unit normal vector surface.

The relationship between the current density, i, and the electric potential, φ, is given by Ohm's law:

$$i = k\frac{\partial\varphi}{\partial n} \tag{6}$$