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Fabrication of semi-circular micro-groove on titanium alloy surface by through-mask electrochemical micromachining

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A B S T R A C T

Titanium/silicon-carbide-fibre composites offer an excellent combination of weight-specific properties that make them ideal for many components in aeroengines. However, potential industrial applications are hampered by the need to fabricate semi-circular micro-grooves on the titanium alloy foils. Through-mask electrochemical micromachining (EMM) has been developed to fabricate micro-grooves on the surface of titanium alloy. The distribution of current density affects the micro-groove profile, and different mask aspect ratios can form different distributions of current density in through-mask EMM. Therefore, micro-grooves with semi-circular profiles can be fabricated by controlling the aspect ratio of the mask groove. In this paper, the effect of mask aspect ratio on the micro-groove profile during through-mask EMM is investigated by electric field simulation. From simulation results obtained in a series of experiments, the appropriate mask aspect ratio is found for fabricating semi-circular micro-grooves. Ultimately, a group of micro-grooves is fabricated successfully with the required accuracy by through-mask EMM.

1. Introduction

A critical component in future aeroengines will be bladed rings fabricated of titanium-alloy–metal-matrix composites (Klocke et al., 2015). Such composites, reinforced with continuous silicon-carbide fibre, offer attractive combinations of specific strength, stiffness and elevated temperature performance (Guo, 2016). The reinforcement is invariably silicon carbide (SiC) monofilament layered between the titanium alloy foils; alternate layers of metal foils and SiC fibres are hot pressed to give a fully dense product (Hooker and Doorbar, 2013). Because SiC fibres are cylindrical, they are prone to dislocation during the process of hot pressure (Carrère et al., 2001). To achieve satisfactory consolidation strength between the SiC fibres and the pre-processed titanium alloy foils, semi-circular micro-grooves must be fabricated on the latter. The SiC fibres then lie in these micro-grooves to ensure their proper positioning with respect to the titanium alloy foils. This challenging task requires a high level of machining accuracy: the micro-groove profile should be semi-circular, with a 50 μm radius and a roundness error of less than 10 μm. Several methods have been reported for fabricating metallic micro-grooves. Yan et al. (2010) proposed a high-speed rotating and moving electrode tool for generating micro-grooves by electro-discharge machining, and succeeded in fabricating multiple micro-grooves of various cross sections on stainless steel. Rao et al. (2007) achieved a 180 μm micro-groove and an etch factor of 1.36 by wet chemical etching. Xuan et al. (2009) researched the machining of micro-grooves on glass by electrochemical discharge machining, and succeeded in fabricating micro-grooves with a depth of 30 μm and a width of 40 μm.

Electrochemical micromachining (EMM) removes metallic materials by anodic dissolution via an electrochemical reaction. Because it is a contactless process, this machining method involves no residual stress, tool wear or metallurgical defects, and so is suitable for any metallic material regardless of material hardness or melting point (Rajurkar et al., 2013; Fang et al., 2015). Rathod et al. (2014) used a cylindrical micro-tool of 60 μm in diameter to machine EMM micro-grooves of uniform width, depth and cross section along their length. Chen et al. (2016) studied the influence of EMM parameters on the fabrication of a micro-groove array with a rectangular profile. Ghoshal (2013) fabricated a blind micro-groove of width 135 μm and depth 50 μm on an SS-304 plate by EMM. Lee et al. (2009) used EMM to machine micro-grooves on a bipolar plate, which is an important component in fuel cells. In addition to the micromachining on the metallic materials, EMM has also been applied to the microfabrication of microstructures in Silicon. Bassu et al. (2012) presented the silicon microstructures of high complexity can be effectively fabricated by EMM in HF-based aqueous electrolytes. Cozzi et al. (2017) revealed the synergistic cooperation of HF and H_2O_2 molecules in enhancing the controlled dissolution rate of silicon, which enables the fabrication of high-aspect-ratio (from

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10–100) microstructures by EMM.

As an EMM technology, through-mask EMM has been widely used to produce micro-structured components such as micro-dimples, hole arrays and micro-grooves (Volgin et al., 2015; Zhang et al., 2017). Specially patterned masks are used to localize the areas of anodic dissolution during through-mask EMM, and the throughput of this technology is considerable. Madore et al. (1999) researched the fabrication of micro-grooves on titanium in an acid electrolyte by through-mask EMM. Kern et al. (2007) investigated the shape evolution of micro-grooves during through-mask EMM. Different mask aspect ratios cause different distributions of current density. This facilitates different rates of material removal (West et al., 1992), and hence the ability to fabricate different microgroove profiles. In the present study, the effect of mask aspect ratio on micro-groove profile is simulated by finite-element analysis with the aim of fabricating a micro-groove with a semi-circular cross section. Through a series of experiments, the appropriate mask aspect ratio is identified for fabricating semi-circular micro-grooves. Ultimately, a group of micro-grooves is fabricated with the required accuracy by through-mask EMM.

2. Model of micro-groove machining by through-mask EMM

Through-mask EMM is shown schematically in Fig. 1(a). The workpiece is covered by a mask with a micro-groove pattern, whereupon the exposed area of the workpiece is dissolved by electrochemical reaction. The electrolyte flows at high speed through the gap between the cathode and the workpiece (anode), transporting away the dissolved material (usually metal hydroxide) and any gas bubbles and Joule heat generated in the process. Evolution of the micro-groove profile is controlled by the distribution of current density on the surface of the workpiece, and the aspect ratio mask can affect the distribution of current density. Therefore, the effect of mask aspect ratio on micro-groove profile is simulated by finite-element analysis to ensure the appropriate aspect ratio and machining time for fabricating micro-grooves with a semi-circular cross section.

A geometrical model of through-mask EMM can be obtained via the cross section *P* shown in Fig. 1(b). In the geometrical model, *d* is the width of the groove in the mask, *h* is the thickness of the mask, and *a* is the distance between the cathode and the anode; *D* and *H* are the width and depth, respectively, of the micro-groove. The aspect ratio (*AR*) of the mask groove is the ratio of the thickness *h* of the mask to the width *d* of the groove:

$$AR = h/d. \tag{1}$$

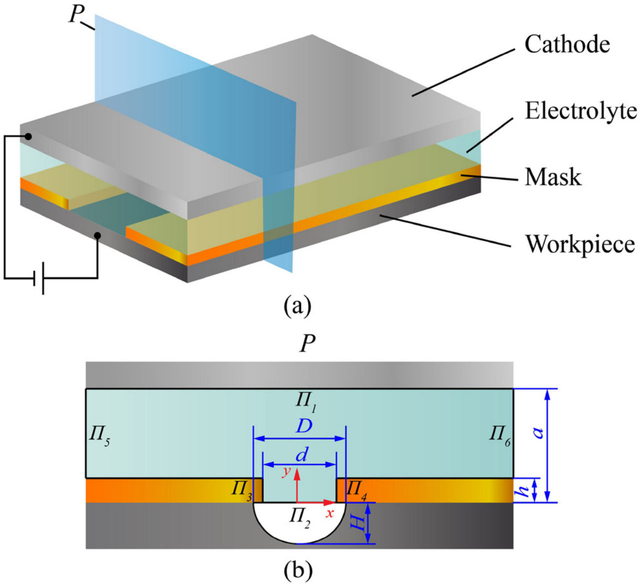

Fig. 1. Model of micro-groove machining by through-mask EMM: (a) schematic; (b) geometrical model.

Table 1
Values of h and AR investigated.

h (mm)	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
AR	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0

In the geometrical model, *a* is held constant at $a = 0.2$ mm. The machining goal is a micro-groove with a semi-circular profile of radius 50 µm. Hence, the groove in the mask should be less than 100 µm wide. In this study, a 50-µm-wide mask groove is chosen for the simulations and experiments. To research the appropriate *AR* and machining time for fabricating semi-circular micro-grooves, the mask thickness *h* is varied according to Table 1 to give *AR* as an arithmetic progression from 0.2 to 2.0. All the conditions of the electric field are simulated at each different value of *AR*.

To simplify the analysis of the electric field established in the micro-groove machining process, the following assumptions are made:

1 The distribution of current density on the workpiece surface is determined by considering only ohmic effects;
2 The conductivity *k* of the electrolyte is uniform;
3 The electrodes are defined as equipotential surfaces.

According to electric field theory, the distribution of electric potential is given approximately by the Laplace equation (Chen et al., 2015):

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

where ϕ is the electric potential. The boundary conditions are as follows:

$$\varphi\Big|\prod\nolimits_1 = 0 \quad \text{(cathode tool)} \tag{3}$$

$$\varphi\Big|\prod\nolimits_2 = U \quad \text{(workpiece)} \tag{4}$$

$$\frac{\partial\varphi}{\partial n}\Big|\prod\nolimits_{3,4} = 0 \quad \text{(insulating boundaries)} \tag{5}$$

$$\frac{\partial\varphi}{\partial n}\Big|\prod\nolimits_{5,6} \approx 0 \quad \text{(free boundaries)} \tag{6}$$

where *n* is the unit vector normal to the surface. The relationship between current density *i* and electric potential ϕ is given by Ohm's law:

$$i = k\frac{\partial\varphi}{\partial n} \tag{7}$$

The anode dissolution rate *v* can be determined using Faraday's law:

$$v = \eta\omega i \tag{8}$$

where η is the current efficiency and ω is the volume electrochemical equivalent of the material. The parameters η and ω are constants. The initial conditions of the finite-element analysis are a machining pulse voltage of $U = 15$ V and a conductivity of $k = 10.5$ S/m. The on–off time of the pulsed power is $t_{on} = 0.5$ ms and $t_{off} = 2$ ms.

3. Simulation results

The material removal rate is proportional to current density; the distribution of the latter on the workpiece surface will affect the evolution of the micro-groove profile. The initial distribution of current density is shown in Fig. 2 for different values of *AR*. Fig. 2(a) shows clearly that the current density increases at the margins of the machining zone as *AR* is decreased. As *AR* is increased, the current density