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Flow field design and process stability in electrochemical machining of diamond holes

Zhao Jianshe [a,*], **Wang Feng** [a], **Liu Zhuang** [a], **Zhang Xiangli** [a], **Gan Weimin** [b], **Tian Zongjun** [a]

[a] *College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[b] *Digital ECM Building Laboratory of Jiangsu Province, Changzhou Institute of Technology, Changzhou 213002, China*

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Abstract The metal grille, commonly composed of an amount of diamond holes, has been growingly used as a key structure on stealth aircraft. Electrochemical machining (ECM) promises to be increasingly applied in aircraft manufacturing on the condition that process stability is guaranteed. In this work, a flow field model was designed to improve the process stability. This model is endowed with a variety of flow channel features, together with vibrating feeding modes. The flow field distribution on the bottom surface of the diamond hole was discussed and evaluated as well. The numerical results show that a short arc flow channel could significantly enhance the uniformity of electrolyte velocity distribution and a vibrating feeding of the cathode enables to reduce both fluctuations of the electrolyte velocity and pressure on the bottom surface of the diamond hole. Consequently, the flow field mutations were eliminated. It is verified from the experimental results that a short arc flow channel, when combined with vibrating feeding, is capable of improving machining localization and process stability markedly. What is more, the side gap on the bottom surface of the diamond hole could also be reduced by the abovementioned approach.

1. Introduction

With modern technology's evolvement, great progress has been made in detection and attack technology. Therefore, better stealth performance is vital for a weapon to improve its self-protection capability and reduce the possibility of being detected.[1,2] Recently, metal grid, characterized by holes of special shapes such as square, diamond, and triangle, has increasingly become a common stealth structure in some critical parts of rockets and jet fighters. The machining precision and surface quality of special shaped holes matter a lot to the strength, stiffness and stealth performance of metal grid structures.[3] Compared with milling, electrical discharge machining (EDM), and laser material processing, electrochemical machining (ECM) is considered more suitable for special shaped holes on metal grid structures due to its advantages

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[*] Corresponding author. Tel.: +86 25 84891686.
E-mail address: zhaojs@nuaa.edu.cn (J. Zhao).

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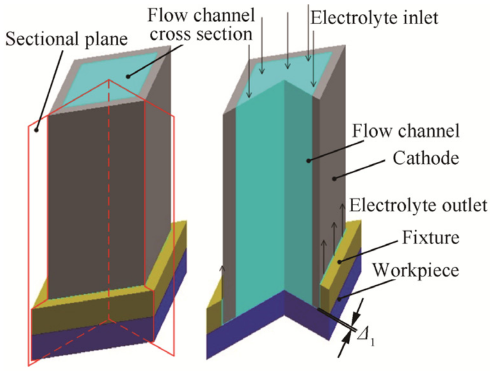
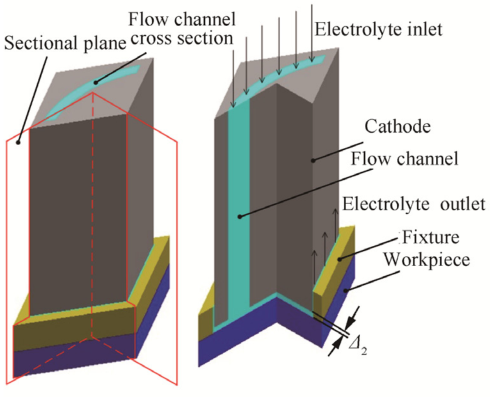
of no residual and thermal stress and also cathode wear free. However, improving the process stability of ECM has been proven to be a challenging task, because the physical features (e.g., electrical field and flow field) of a machining area are hard to control during the process.[4,5]

Over the past few years, enhancing the process stability and localization of ECM of special shaped holes has attracted great attention among researchers. Uchiyama and Kunieda[6] studied cathode optimized design and forming precision of curved holes based on analysis of the static electrical field and stress-strain analysis. Their study swirled around millimeter scale profiled hole machining and the results illustrated that the tip angle of the cathode and the feeding rate had great effects on the forming precision of curved holes. Wang et al.[7] established a multi-physical ECM model on the basis of an electrostatic, two-phase flow and temperature field, and verified the model by experiments of spiral hole machining. Li and Huang[8] studied the machining process of tapered holes of fuel jet nozzles, which had the size of micro/nano scale, and analyzed the influences of voltage, pulse duty cycle, pulse frequency, and cathode feed rate on the aperture distribution. Tapered holes with an inlet aperture of 181 μm and an outlet aperture of 203 μm were machined on a 1-mm Ni-based alloy plate. Chan et al.[9] investigated the forming mechanism of micro holes under the influences of pulsed power conditions, cathode insulation, and machining time. Barrel-shaped holes and reverse-tapered holes were machined successfully by regulating machining parameters.

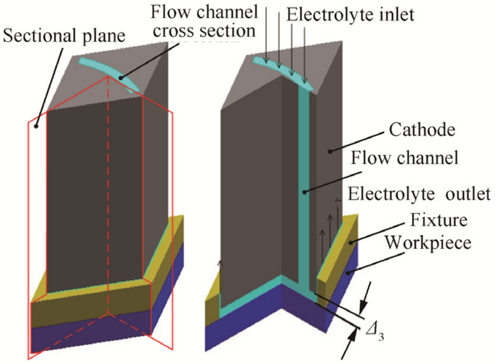
Current studies on ECM of profiled holes have been concentrated on shape forming such as inclined holes,[10] curved holes,[11] square holes,[12] and tapered holes,[13,14] whereas, the process stability of ECM is poorly studied. Specifically, during machining of a diamond hole, the flow paths of electrolyte in the machining gap differ a lot because of the two unequal diagonals. Therefore, electrolyte starvation and cavitation are inclined to occur at the opposite corners of the diamond hole, which will make stable machining impossible. In order to investigate and improve the stability of the ECM process of diamond holes, various flow channel structures of cathode and vibrating feeding modes were analyzed by numerical simulation and verified experimentally in a self-developed ECM system.



(a) Diamond flow channel



(b) Long arc flow channel



(c) Short arc flow channel

Fig. 1 Flow field models with various flow channel structures.

2. Flow field design

2.1. Cathode flow channel structure design

Three different-shaped flow channel models which are diamond, long arc, and short arc, respectively for machining a diamond hole with a side length of 9.9 mm and a sharp angle of 60° are shown in Fig. 1. In Fig. 1(a), the cross section of the diamond flow channel is obtained by isometrically offsetting from the cathode projection profile, and the cross-sectional area $A_1 = 49.89\ \text{mm}^2$ while the wetted perimeter $P_1 = 30.36$ mm, which is defined as the sectional profile length of the flow channel. In Fig. 1(b), the cross-sectional area of the long arc flow channel $A_2 = 12.81\ \text{mm}^2$ and the wetted perimeter $P_2 = 27.65$ mm. Similarly, the cross-sectional area of the short arc flow channel in Fig. 1(c) $A_3 = 7.83\ \text{mm}^2$ and the wetted perimeter $P_3 = 17.67$ mm. The cross-sectional area of a flow channel should be greater than the product of the frontal gap and the wetted perimeter in order to ensure an adequate electrolyte supply in the machining area, that is:

$$A_i \geqslant P_i\Delta_i \quad i = 1, 2, 3 \tag{1}$$

where Δ_i is the frontal gap (estimated as 0.08–0.3 mm).[15]

2.2. Selection of electrolyte velocity and pressure at gap entrance

It is requested that the flow state of the electrolyte should be turbulence under the condition of a steady distribution of the flow field; hence, the electrolyte velocity at the inlet should meet the following[16]:

$$u_i > 2300\frac{v_i P_i}{4A_i} \quad i = 1, 2, 3 \tag{2}$$