High precision material removal of copper surface by jet electrochemical machining

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Abstract. High-precision machining technology has attracted increasing attention with the rapid development of modern industry. Jet electrochemical machining is a promising method for forming complex 3D shape surface by controlling the path and dwelling time of electrode nozzle moving over workpiece surface. The machining accuracy mainly relies on the stability of the material removal rate and the smoothness of the machined surface. In this paper, a new jet electrochemical machining method, which is based on a newly developed acid electrolyte, is proposed to improve its machining performance. The effects of voltage, interelectrode gap, electrolyte temperature and flow rate are discussed in this work. Stable machining can be achieved by selecting the optimum process parameters, and the surface roughness (Ra) can be reduced to 14.8 nm. Moreover, the obtained material removal rate distribution agrees well with the Gaussian function, which is recognized to have high capability to form complex 3D surface through controlling the movement of the tools.

1. Introduction

Copper is widely used in precision devices in the fields of aerospace, electronics, military products, instrumentation due to its good electrical and thermal properties [1]. Since the surface quality and structural accuracy of precision devices directly affect the performance of the device, the research on precision machining for high stability and high surface quality of copper is of great significance.

Electrochemical machining (ECM) is a controlled anodic electrochemical dissolution process, and the major advantages of ECM are its high material removal rate, almost no tool wear and good surface quality without the occurrence of re-solidified layers, heat-affected zone, or strain hardening [2, 3]. Liu et al. studied the ECM of γ-TiAl alloy through experiments, the surface roughness (Ra) of the micro-pores is about 1 μm by changing the voltage, the interelectrode gap (IEG), the flow rate and temperature of electrolyte [4]. Klocke et al. changed the current density of the machining region to obtain micro-pores with a surface roughness (Ra) of 0.4 μm for Ti-6Al-4V alloy [5]. Another investigation on technological capabilities of ECM by Klocke et al. revealed that the small frontal gap was an important factor in achieving high material removal rate and high machining precision [6].

Jet electrochemical machining (Jet-ECM) is an important variation of traditional ECM and is effective to manufacture complex structure with the help of multi-dimension mechanical motion [7]. Liu et al. studied the effects of process parameters of Jet-ECM of TB6 titanium alloy (Ti-10V-2Fe-3Al). The surface roughness (Ra) of the micro-pores and long grooves are 0.231 μm and 0.273 μm respectively [8]. Mitchell-Smith et al. studied the Jet-ECM of Titanium grade 5 (Ti-6Al-4V). In their
work, with the help of ultrasonic method the surface roughness Ra was reduced from 0.245 μm to 0.168 μm [9]. However, the existing Jet-ECM results cannot meet the processing requirements of high-precision devices with surface roughness of ten nanometers or several nanometers.

In this paper, a new type of electrolyte is used to investigate the effect of process parameters on the Jet-ECM machining performance of copper, such as machining voltage, interelectrode gap, electrolyte temperature and flow rate. And the optimum processing parameters are selected to achieve stable precision machining.

2. Experimental

2.1. Principle of Jet-ECM

As shown in figure 1, Jet-ECM removes material by jetting electrolyte from the nozzle toward the workpiece while applying voltage on cathode (nozzle) and anode (workpiece). Unlike traditional ECM, a jet of electrolyte is applied as a tool to selectively remove material on the workpiece [10]. With the help of multi-dimensional motion, it is possible for Jet-ECM to manufacture any 3D structure in theory [7].

![Figure 1. Schematic of Jet-ECM process.](image)

In Jet-ECM, the dissolution of anode is confined at the exposed surface directly below the electrolyte jet due to the localization of the machining current density [11]. This is achieved by the so-called hydraulic jump phenomenon [12]. When the rapid flowing electrolyte hits the workpiece, a fast thin layer of electrolyte is formed on the workpiece surface near the nozzle, and then, the thickness of electrolyte at remote area suddenly increases and becomes subcritical. With the help of this fast thin electrolyte layer, the current density is concentrated and good machining accuracy can be obtained in Jet-ECM [13].

2.2. Experimental equipment

The schematic diagram of the Jet-ECM experimental system used in this paper is shown in figure 2. The machining groove and the nozzle are fixed on the CNC XY two-axis and Z single-axis displacement platform by the fixture with the displacement accuracy of 100 nm respectively. The voltage is supplied by the high frequency pulse power supply. The electrolyte circulation system supplies the electrolyte and the flow rate and temperature can be controlled by it.

![Figure 2. Experimental equipment.](image)
In addition to excellent electrical conductivity, the nozzle material also needs to have good acid and alkali resistance, corrosion resistance and tensile strength. The metallic nickel meets these requirements and a cylindrical nozzle of nickel with an inner diameter of 1 mm is selected for this study. The fixture is made of polytetrafluoroethylene (PTFE) because of its excellent acid and alkali resistance and electrical insulation.

2.3. Electrolyte

In the Jet-ECM, the electrolyte not only transmits electrons as a conductive medium, but also performs a chemical reaction with the help of electric field, so that the anode dissolution can be performed smoothly and efficiently. At the same time, the electrolyte will also take away the electrochemical reaction products and heat in the interelectrode gap in time to ensure material renewal rate and cooling efficiency.

The neutral electrolyte is commonly used in modern industries produce hydroxide precipitates during processing, which can deteriorate the surface roughness and local short circuits [14, 15]. Using acidic electrolyte can cause the removed metal to dissolve into solution instead of forming precipitates [16], which will result in better surface roughness [17]. The acidic electrolyte require lower voltages than the neutral electrolyte [14] due to its good electrical conductivity. Moreover, the acidic electrolyte can achieve higher removal rate [18], so it is more suitable for precision machining [19].

In this paper, a new type of acidic electrolyte is used in the Jet-ECM, with phosphoric acid as the main electrolyte, assisted with a small amount of additives. The specific component and proportion of the new electrolyte are shown in Table 1.

| Phosphoric acid | Ethanol | Lactic acid | BTA | Ammonium acetate |
|-----------------|---------|-------------|-----|-----------------|
| 850 ml/L        | 90 ml/L | 60 ml/L     | 6 g/L | 3 g/L           |

When copper is removed in phosphoric acid, a soluble and viscous phosphate film layer is formed on the surface. The mucosa layer can act as a concentration polarization, which can slow down the dissolution rate of the depressions and accelerate the dissolution rate at the protrusions. And lower surface roughness can be achieved in this way. The removal process is the combination of an anodic electrochemical process and a phosphate film formed on the metal surface [20].

Ethanol as a hydroxyl additive is a good organic solvent, which can increase the fluidity of the electrolyte and promote the release of bubbles. As a carboxylic acid additive, lactic acid is a good acid-base buffer and reaction stabilizer. Benzotriazole (BTA) and ammonium acetate are good corrosion inhibitors [21], and if the anode is removed too quickly, it may cause erosion. However, the effects of different additives are not completely separated, and they can be matched to each other for multiple functional effects [22].

3. Results and discussion

The Jet-ECM experimental system is used with the new electrolyte for initial processing. The initial surface of the machined workpiece is very flat. In this paper, the depth of the pit is used to indicate the amount of material removed. The measurement of the pit profile is performed by the Keyence VK-X200 series 3D laser scanning confocal microscope. The surface roughness is measured by Zygo Nexview5022S 3D optical surface profiler.

A single pit processing experiment is performed. The two-dimensional height distribution of a single pit is shown in figure 3(a) and the three-dimensional topography distribution of the pit is shown in figure 3(b). As shown in figure 4, the longitudinal section of a single pit conforms to a Gaussian distribution by shape fitting, and the removal rate of single pit is about 10 μm/min.
Figure 3. Machining result of single pit. a. 2D height distribution. b. 3D topography distribution.

Figure 4. The longitudinal section in a Gaussian distribution.

3.1. Voltage

As shown in figure 5, when the voltage is 0.5 V, the current density in the interelectrode gap is too small to occur significant material removal. When the voltage is increased to 1.5 V, the material removal occurs in all low current density regions. The removal range is enlarged and the surface roughness is deteriorated from the initial surface. As the voltage increases, the current density increases gradually and the removal only occurs in the high current density regions. The longitudinal section of the pit agrees well with the Gaussian distribution. The removal depth is gradually increased and the surface roughness is gradually reduced.

When the voltage is increased to 3.5-4.5 V, the removal is in a saturated state. The removal depth is no longer increased and the surface roughness Ra is stabilized at about 17 nm. However, when the voltage is increased to 5.5 V or more, the influence of the cathode on the current density distribution is remarkably increased which causes the change of removal profile and the deterioration of surface roughness. Moreover, cavitation appear on the machined surface, which can cause some energy to be lost, so that the depth of removal is reduced.

3.2. Array pits processing
With comprehensive consideration of the effect of process parameters on the machining performance, the optimal parameters such as voltage 3.5 V, IEG 500 μm, electrolyte temperature 45 °C and flow rate 50 mL/min are selected. The processing of 3×3 array pits are performed with the optimal processing parameters, and the processing time of each pit is 60 s.

The Corning Tropel FlatMaster 200 is used to measure the machining results of the array pits. The macro profiles of the pits with top-view and reverse-view are shown in the figure 6. The removal profile and removal depth of the 3×3 array pits are very stable, and the error of the removal depth is within the range of 0.3 μm. The average value of the surface roughness is 14.19 nm.

![Figure 6. Macro profiles of the pits. (a) 2D depth of array pits (top-view) (b) 3D profile array pits (reverse-view).](image)

4. Results and discussion

In this paper, the Jet-ECM with a new type of acidic electrolyte is studied through experiments. The influence of process parameters such as voltage, IEG, electrolyte temperature and flow rate on the machining performance of copper are analyzed. According to the experimental results, the following conclusions are as the following:

1. Jet-ECM using the new acidic electrolyte proposed in this paper can further reduce the surface roughness, thereby enable the machining of high precision and ultra-smooth surface of copper. Changing the voltage causes the current density to change, which affects the removal rate, removal profile, and surface roughness.

2. With comprehensive consideration of the effect of process parameters on the machining performance, optimal parameters of voltage 3.5 V, IEG 500 μm, electrolyte temperature 45 °C and flow rate 50 mL/min are selected. The machining results show high accuracy (Ra=14 nm) combined with relatively high removal stability (depth error within 0.3 μm), which is acceptable from the viewpoint of high-precision machining industry.

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