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Full Length Article

# Improving machining efficiency in wire electrochemical micromachining of array microstructures using axial vibration-assisted multi-wire electrodes

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ABSTRACT

Wire electrochemical micromachining (WECMM) is a promising approach for fabrication of high-quality microcomponents. However, its industrial applications remain limited owing to its relatively low machining efficiency, which is significantly affected by the efficiency with which electrolyte can be refreshed in the narrow machining gap. In this paper, a method of WECMM using axial vibration-assisted multi-wire electrodes with high traveling speed is proposed to improve upon the machining efficiency of WECMM. A flow-field model was established to simulate the flow field in the machining gap when the tool was traveling. A series of experiments are performed to optimize the machining parameters. Experimental results reveal that microstructures with negligible taper, high aspect ratio and good consistency can be effectively fabricated using this method. Finally, WECMM using 15-wire electrodes at a maximum feed rate of 5.0 $\mu$m/s is realized, at a total machining rate of 75.0 $\mu$m/s being achieved. With the optimal machining parameters, a multiple-slit microstructure with high aspect ratio of 20 is fabricated using 15-wire electrodes, and X-shape microparts of high surface quality ($Ra$ = 128.0 nm, $Rq$ = 162.0 nm and $R$max = 1.72 $\mu$m) are mass produced using 7-wire electrodes.



## 1. Introduction

Micromachining technology plays a vital role in the miniaturization of components [1]. The increasing use of a variety of difficult-to-machine materials, such as stainless steel, titanium, and superalloys, as basic materials for microcomponents has brought great challenges for micromachining technologies, especially traditional ones [2,3]. Electrochemical micromachining (ECMM), which is based on electrochemical dissolution, appears to be a very promising method for shaping these materials because of its ability to produce a bright surface finish without generating a heat-affected zone or residual stresses in the workpiece, together with the absence of tool wear and an independence of material hardness and melting point [4]. Recently, wire electrochemical micromachining (WECMM), a special type of ECMM, has come to be recognized as a flexible method for the fabrication of complex-shaped planar microstructures. It not only possesses the basic advantages of ECMM, but also does not require the fabrication of a complex-shaped cathode. WECMM is superior to wire electric discharge micromachining in that it neither suffers from surface defects nor wears out tool electrode. Thus, a thinner wire can be repeatedly used in WECMM. Using this method, diverse metallic microstructures have been produced, including microgrooves and microstars [5], microhelices [6], and X-shaped microparts [7], among others.

In WECMM, the machining performance (efficiency, accuracy, stability, etc.) is significantly affected by the mass transport rate in the machining gap. As a consequence, the possibility of enhancing mass transport in the machining gap during WECMM is of great interest [4]. Electrolyte flushing, a common method used in a typical electrochemical machining (ECM) process, has also been applied in WECMM. Qu et al. [6] investigated the shaping of a titanium alloy (TC1) using axial electrolyte flushing with a high flow rate. This method could be performed at a feed rate of 30.0 $\mu$m/s, but tapering of the machined feature was inevitable owing to frictional velocity loss of electrolyte along the flushing direction, especially when a thick workpiece was being machined. Moreover, the wire electrode had to be under sufficiently high tension to avoid swing vibrations caused by the flushing electrolyte. Therefore, the diame-

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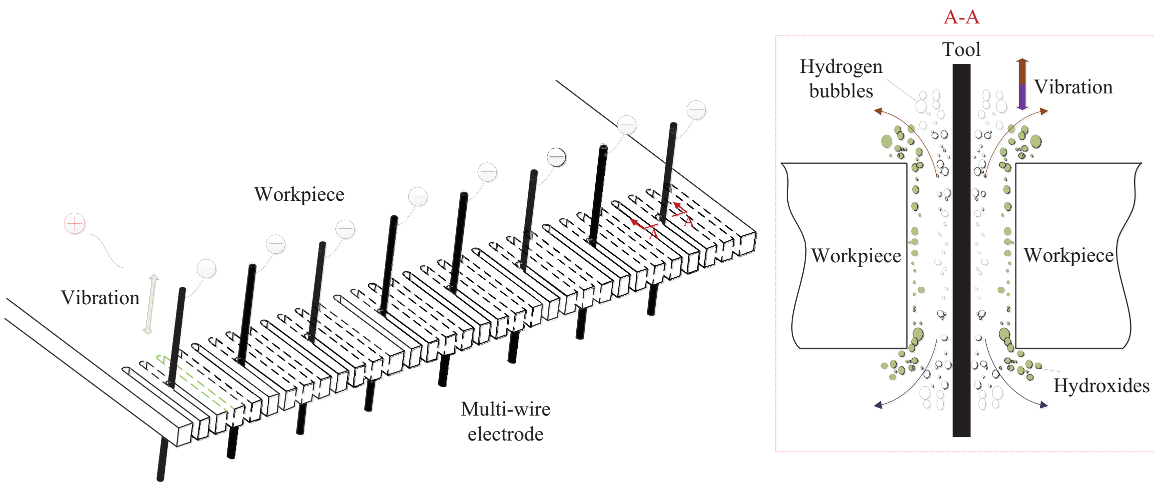


**Fig. 1.** Schematic diagram of WECMM using axial vibration-assisted multi-wire electrodes with high traveling speed.

ter of the wire electrode in WECMM using axial electrolyte flushing with high flow rate cannot be too small, which has a great influence on the minimum feature size that can be produced by WECMM. Zeng et al. [8] fabricated microstructures on stainless steel 304 with a thickness of 5.0 mm using electrolyte flushing with a low flow rate. A thinner wire of 20.0 μm diameter was used in their research, but the maximum feed rate that they were able to use was only 0.5 μm/s. Several other methods employing assisted axial movement of the electrode have been introduced in WECMM. Qu et al. [9] investigated WECMM with a reciprocating electrode. They were able to produce a microstructure on stainless steel with a slit width of 177 μm, a standard deviation of 1.5 μm, and an aspect ratio of 113 at a feed rate of 1.0 μm/s. Zeng et al. [5] introduced a unidirectional traveling wire into the WECMM process to remove the electrolysis products and refresh the electrolyte in the machining gap and were able to fabricate microstructures with uniform slit width at a feed rate of 1.2 μm/s. Compared with electrolyte flushing, the two methods mentioned above can effectively avoid tapering of the machined feature.

Although there have been many investigations of WECMM, its application in industry is still limited because of its relative low machining efficiency. In WECMM using ultra-short pulses, axial vibration of the tool has been demonstrated to be an effective way to enhance mass transport [10]. Compared with the use of a reciprocating or unidirectional traveling electrode, this approach allows more effective control of the tension of the axially vibrating tool, and a thinner wire electrode can be used. However, in previous research using this method, it was only possible to machine a thin workpiece a few hundreds of micrometers in thickness (<0.5 mm) at a quite slow feed rate (<0.7 μm/s) because of limitations on the vibration velocity and amplitude.

In many high-precision devices, array microstructures are commonly used to perform specific functions, such as comb structures in micro-actuators [11] and multiple slits in X-ray phase-contrast imaging systems [12]. The main limitation on the use of WECMM to produce these microstructures is that the process is very time-consuming owing to the long machining length. WECMM using multi-wire electrodes, in which multiple features of the same shape are fabricated in one process, is a perfect method to improve machining efficiency when fabricating array microstructures, and it can effectively increase throughput when producing microparts at high demand.

In this paper, a method of WECMM using axial vibration-assisted multi-wire electrodes with high traveling speed is firstly proposed. A flow-field model is established to simulate the flow field in the machining gap when the electrode in WECMM is traveling. Experimental investigations are undertaken, and several parameters affecting machining accuracy and efficiency are discussed. Finally, a multiple-slit microstructure with high aspect ratio and good quality is successfully produced in a stainless steel workpiece using 15-wire electrodes. Compared with other methods in previous reports, the total machining rate of this method is improved many times, even as much as more than tenfold.

**Table 1**
Parameters used in flow-field simulation.

| Parameter | Value |
|---|---|
| Wire diameter | 50 μm |
| Vibration direction | +$Z$ |
| Travel speed | 0.01–0.05 m/s |
| Workpiece thickness | 3 mm |
| Slit width | 200 μm |
| Machined length | 2 mm |

## 2. Principle of WECMM using axial vibration-assisted multi-wire electrodes with high traveling speed

Fig. 1 shows the principle of WECMM using axial vibration-assisted multi-wire electrodes. The workpiece acts as the anode, and multi-wire electrodes connected in parallel with each other act as the cathodes. In the process, the tool vibrates along its axial direction with high traveling speed ($U$), which is the linear speed of moving wires up and down. The electrode motion causes fresh electrolyte to be dragged into the machining area while dirty electrolyte containing electrolysis products (hydrogen bubbles and hydroxides) is dragged out, resulting in the improvement of mass transport rate in the narrow machining gap. The tool traveling speed can be calculated by

$$U = 2Af \tag{1}$$

where $A$ and $f$ are the vibration amplitude and frequency, respectively.

A flow-field model of this process can be established as shown in Fig. 2. To simplify the proposed model, two assumptions are made [14]. The first one is that the scale of bubbles in the electrolyte is small enough to neglect its impact on fluid flow, and the electrolyte flow is simplified as single-phase flow. The second one is that the electrolyte dynamic viscosity is assumed to be constant value. The parameters of this model are listed in Table 1. Sections A and B are chosen to illustrate the velocity distributions in the $XOY$ and $XOZ$