CIRP Annals - Manufacturing Technology 61 (2012) 195–198

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

# Enhancement of mass transport in micro wire electrochemical machining

Yong-Bin Zeng, Qia Yu, Shao-Hua Wang, Di Zhu (1)*

*Research Center for Nontraditional Machining, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

ARTICLE INFO

*Keywords:*
Electro chemical machining
Micromachining
Wire

ABSTRACT

In micro wire electrochemical machining, the machining gap between the cathode wire and anode workpiece is so tiny that it is difficult to remove electrolysis products and renew electrolyte, leading to frequent electric short circuits and quite low processing speed. Three approaches of enhancing mass transport, electrolyte flushing along the wire, wire traveling in one direction and micro-vibration of cathode wire have been studied theoretically and experimentally in this paper. The results demonstrate that the proposed methods significantly enhance the mass transport and thus improve the machining stability, the productivity and the surface quality for micro wire electrochemical machining.

## 1. Introduction

Metal microstructures have been playing an increasingly important role in the microsystem industry because of its desirable properties, such as good mechanical strength, magnetic properties, and high electrical and thermal conductivity. For micro machining of three-dimensional metallic micro parts, a few manufacturing processes are available such as micro milling, micro electric discharge machining and laser beam machining. However, in these methods, the metal parts usually suffer from mechanical or thermal stress, and burr formation.

Electrochemical micromachining (EMM) is now receiving considerable attention to produce metal microstructures since it can electrochemically dissolves conductive materials at atomic sizes regardless of their hardness and toughness. Microfabrication by EMM might involve micro hole drilling [1], micro milling [2] and micro wire cutting [2–4], etc.

Micro wire electrochemical machining adopts micron scale wire as tool cathode since it does not wear out the tool. It is a promising issue in the fabrication of metal micro parts or devices by moving the wire electrode along a programmed path [3,4].

However, micro wire electrochemical machining is a transport-limited electrochemical dissolving process. For achieving higher machining accuracy, the machining balance gap should be maintained in several micrometers or even sub-micrometer dimensions in micro wire electrochemical machining. As the gap is deep and narrow, removing the electrolysis products, namely the hydroxides and the hydrogen gas, and renewing electrolyte in the gap become very difficult. The machining process is typically unstable since electric short circuits will frequently occur as the machining gap is accumulated by electrolysis products. Although it may be possible to improve the stability by reducing wire feedrate, which presently is less than 0.125 $\mu$m/s [3,4], the machining process is time consuming. These problems result from mass transport limitations that arise because the electrolyte in the deep narrow gap may remain nearly stagnant. The key to solve these problems is how to force the electrolyte in the machining gap to flow.

This paper presents three mass transport enhancing approaches of electrolyte flushing along the wire, ring wire traveling in one direction and micro-vibration of cathode wire for renewing the electrolyte in the machining gap. The proposed approaches demonstrated significant improvements in the machining stability, the material removal rate and the surface quality for micro wire electrochemical machining.

## 2. Importance of mass transport

In micro electrochemical processing, the machining balance gap $\Delta_b$ can be expressed as:

$$\Delta_b = \eta\omega\kappa\frac{U_R}{\upsilon_c} \qquad (1)$$

where $\eta$ is the current efficiency of anodic metal dissolution, $\omega$ is the volumetric electrochemical equivalent, $\kappa$ is the electrolyte conductivity, $U_R$ is the voltage of electrolyte in the machining balance gap and $v_c$ is the tool feedrate.

In an electrolytic process, the composition and concentration of the electrolyte in the gap will be changed by electrolysis product. Following the work of Thorpe and Zerkle [5] and considering the effect of electrolysis product on the electrolyte conductivity, the actual electrolyte conductivity, $\kappa_m$, can be expressed as:

$$\kappa_m = \kappa_0(1 + \alpha \cdot \Delta T)(1 - \beta)^n \qquad (2)$$

where $\kappa_0$ is the initial electrolyte conductivity, $\alpha$ is the temperature coefficient of the electrolyte conductivity, $\Delta T$ is the electrolyte temperature rise, $\beta$ is the volume fraction of hydrogen and hydroxide sludge, and $n$ is a constant ranging from 1 to 2.

By combining Eq. (1) with Eq. (2), $\kappa$ in the Eq. (1) is replaced by $\kappa_m$ in the Eq. (2), the following equation about the actual machining balance gap, $\Delta_{bm}$, can be attained:

$$\Delta_{bm} = \eta\omega\kappa_0(1 + \alpha \cdot \Delta T)(1 - \beta)^n\frac{U_R}{\upsilon_c} \qquad (3)$$

In EMM, the effect of temperature on the electrolyte conductivity can be ignored as the electrolyte temperature rise is very small. So, $\Delta_{bm}$ varies with the volume fraction of

---

* Corresponding author.

0007-8506/$ – see front matter © 2012 CIRP.
http://dx.doi.org/10.1016/j.cirp.2012.03.082

electrolysis product as indicated in Eq. (3). If the mass transport, namely removing the electrolysis products and renewing electrolyte, is limited in the gap, the volume variation of electrolysis product is big, and thus the variation of $\Delta_{\mathrm{bm}}$ is big. A great $\Delta_{\mathrm{bm}}$ fluctuation, which may produce short circuits in the worst of cases, results in an unstable machining and produces irregular shapes. However, if the mass transport rate is fast enough, there would be little change of the actual machining balance gap and the machining would become stable.

## 3. Electrolyte flushing

### 3.1. Principle of electrolyte flushing

With respect to flushing, the most efficient method of electrolyte delivery is to provide a stream of electrolyte coaxial with the wire as shown in Fig. 1. The function of electrolyte flushing is to continuously deliver fresh electrolyte under constant flowrate to the work area. As the stream of electrolyte envelopes the wire penetrating the workpiece, the electrolysis product will be carried away from the machining gap.

### 3.2. Optimization of electrolyte flow entrance angle

During the experiments, machining was stopped as soon as electric short circuit was observed. The experimental parameters are: 10 V applied DC voltage, tungsten cathode wire of 20 μm in diameter, 10 g/L $NaNO_3$ solution. The workpiece is stainless steel 304 with thickness of 5 mm. Fig. 2 shows that the processing stability decreased as the electrolyte flow entrance angle increased. In the case of electrolyte flow entrance angle was more than 0°, the wire could be deformed due to the impact force of the electrolyte flow, and hence the processing stability became worse. The electrolyte flow with 0° entrance angle is used in this paper.

### 3.3. Influence of electrolyte flowrate on machining productivity and stability

The influence of electrolyte flowrate on machining productivity and stability is shown in Fig. 3. The number of electric short circuits was recorded during a set of 10 repeated 800 μm straight slit cutting experiments. Fig. 3a exhibits the influence of electrolyte flowrate on the maximum wire feedrate with electric short circuit less than 5 times. When the electrolyte flowrate is less than 0.75 m/s, the maximum wire feedrate increased as electrolyte flowrate increased. High flowrate provides adequate flushing to carry away the electrolysis products from the gap, and uniform flow field in the processing zone, which in turn boots the productivity. However, when the flowrate is more than 0.75 m/s, the maximum wire feedrate will no longer increased as the electrolyte flowrate increased. This is because the machining gap is reduced as the wire feedrate increased. When the machining gap is too small for electrolyte stream to penetrate the workpiece, electric short circuits occur. Fig. 3b shows that the machining stability increased as the electrolyte flowrate increased for the same wire federate. However, when the flowrate was higher than 1.0 m/s, the number of short circuits tends to increase with increasing flowrate due to the distortion and unpredictable radial swing of the micro wire.

Therefore, the optimal electrolyte flowrate and wire feedrate was determined to be 0.75 m/s and 0.5 μm/s, respectively.

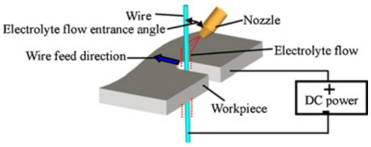

**Fig. 1.** Schematic diagram of micro wire electrochemical machining with electrolyte flushing.

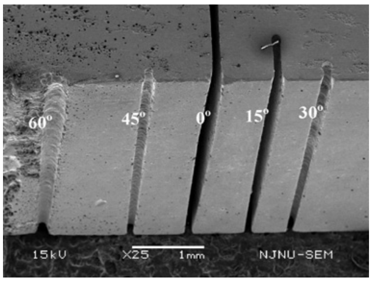

**Fig. 2.** Slits machined with different electrolyte flow entrance angle.

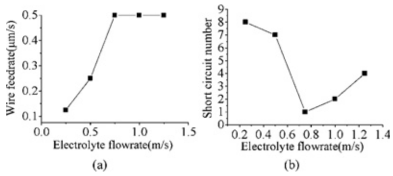

**Fig. 3.** Variation in stability and productivity with flowrate. (a) Variation in productivity with flowrate and (b) variation in stability with flowrate under constant wire feedrate of 0.5 μm/s.

### 3.4. Fabrication of microstructures with electrolyte flushing

With the electrolyte flushing along the wire, microstructures on stainless steel 304 with thickness of 5 mm were machined. Fig. 4a shows a micro spline structure with slit width of 160 μm. Fig. 4b shows a micro beam with slit width of 160 μm. The width of the slits is uniform and the aspect ratio is 31.

## 4. Wire traveling in one direction

### 4.1. Principle and flow field model of wire traveling in one direction

For fabricating microstructures with high aspect ratio, traveling ring wire as the cathode tool is introduced to ensure good flow conditions in the extremely narrow and long machining gap as shown in Fig. 5. In the machining region, the wire traveling direction is arranged to be always in coincident with the direction of gravity. This is very helpful to removal the hydroxide. For keeping the wire traveling in one direction, a ring wire is used as shown in Fig. 6, and a special apparatus is developed to drive and control the wire tension during the machining process. As shown in Fig. 7, the electrolyte in the machining gap is forced to flow and the velocity of the electrolyte can be described as Eq. (4) [6].

$$u_x = -\frac{h^2}{2\mu}\frac{dp}{dx}\left[1-\left(\frac{y}{h}\right)^2\right]+\frac{U}{2}\left(\frac{y}{h}\right)+\frac{U}{2} \tag{4}$$

where $\mu$ is the electrolyte viscosity, $p$ is the electrolyte pressure, and $U$ is the wire traveling speed.

### 4.2. Wire traveling speed

Slit cutting experiments were used to examine the influence of wire traveling speed on machining stability. During the experiments, machining was stopped as soon as electric short circuit was observed. The experimental parameters are: 10 V applied voltage, copper ring wire of 200 μm in wire diameter, and 10 g/L $NaNO_3$ solution. The workpiece is stainless steel 304.

Fig. 8 indicates that the machining is unstable when the wire traveling speed is either too slow or too fast. The reason is that the

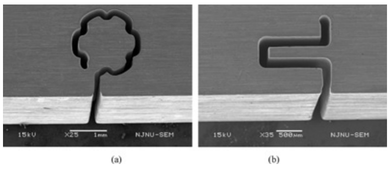

**Fig. 4.** Microstructures on stainless steel fabricated with 0.75 m/s electrolyte flowrate and 0.5 μm/s wire feedrate. (a) Micro spline and (b) micro beam.