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Study on wire electrochemical machining assisted with large-amplitude vibrations of ribbed wire electrodes

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ABSTRACT

A large-amplitude vibration of wire electrode tool is introduced to enhance electrolyte renewal and bubble removal in wire electrochemical machining. It is verified via simulation and high-speed video that hydrogen bubbles generated in electrochemical reactions can be expelled effectively from the machining gap by means of large-amplitude vibrations and a better effect was obtained in the upward duration. A ribbed wire electrode is employed to intensify electrolyte renewal process due to its specific structure. The experimental results demonstrated that the proposed large-amplitude vibration and ribbed electrode significantly accelerate electrolyte renewal, thereby hastening material removal rate and improving machining efficiency.

1. Introduction

Electrochemical machining (ECM) removes metallic material regardless of its mechanical properties via controlled electrochemical reactions. Wire electrochemical machining (WECM) applies a metallic wire as the cathode and produces anodic structures when a specified tool trajectory are carried out [1,2]. As it yields products without tool wear and heat affected zone [3], WECM has been expected for fabrication of aero-engine parts which have strict requirements on surface integrity.

In ECM, bubbles and by-products such as metal hydroxide sludge generated in the machining gap greatly influence electrolyte conductivity and thereby affect material removal rate. Especially for WECM, material dissolution takes place in a slit of high aspect ratio with a width of tens of microns, which makes products removal and electrolyte renewal difficult.

Vibration has been well employed in electrochemical machining processes to accelerate products removal. Natsu et al. [4] utilized complex ultrasonic vibrations of the tool electrode to clean the machining gap by means of cavitation and stirring the electrolyte. The replicating accuracy was improved by simultaneous longitudinal and lateral vibrations of amplitudes 10 μm and 4 μm, respectively. Bhattacharyya et al. [5] verified experimentally that tool vibrations in the Hz to kHz range could improve the performances of electrochemical micromachining. The lower frequencies were recommended for increasing material removal rate and decreasing overcut. Zeng et al. [6] enhanced the mass transport in WECM of a 100-μm-thick nickel plate by micro-vibrating the wire electrode at a frequency of 10 Hz and an amplitude of 8 μm.

Nevertheless, when the workpiece thickness increases to the size of millimetres, electrolyte renewal becomes more difficult in WECM. Thus, a large-amplitude vibration of wire electrode was expected to enhance electrolyte renewal and bring out products from the deep slit in WECM of thick workpieces. Moreover, the specific structure of a ribbed wire electrode is employed to intensify the process. Bubble behaviours in the frontal machining gap and current waveforms in experiments are observed to demonstrate the utility of large-amplitude vibrations. The results indicate that the proposed vibration and ribbed electrode significantly accelerate the electrolyte renewal process and improve material removal rate.

2. Principle of wire electrochemical machining assisted with large-amplitude vibrations

Fig. 1 illustrates the schematic diagram of WECM assisted with large-amplitude vibrations. The wire electrode is moved along the programmed tool path and simultaneously vibrated vertically with amplitude A ($2A$ peak to peak). In order to expel bubbles and by-products from the gap, the electrode vibration amplitude is assumed to be larger than the workpiece thickness D. A dimensionless ratio, α, is defined as vibration amplitude A divided by workpiece thickness D.

In ECM, bubbles and by-products distributed in the machining gap have a significant influence on the distribution of electrolyte conductivity, and consequently on the consistency of material removal rate. Shimasaki and Kunieda [7] reported that bubbles generated on the electrode surface is slowly diffused to the electrolyte and affect the process stability without rapid convection. Fujisawa et al. [8] demonstrated that the effect of by-products (in the form of metal hydroxide sludge) on electrolyte conductivity is negligible because of its extremely small volume fraction compared to that of hydrogen bubbles. Therefore, more attention in this paper is paid on removal of bubbles instead of metal hydroxide sludge. The computational fluid dynamics (CFD) model shown in Fig. 2 was established to investigate the effects of large-amplitude vibrations on the distribution of gas fraction in the machining gap. This model is based on the WECM of a 5-mm-thick

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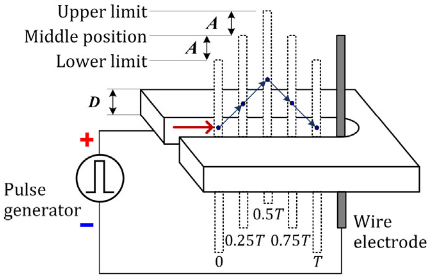

Fig. 1. Schematic diagram of WECM assisted with large-amplitude vibrations.

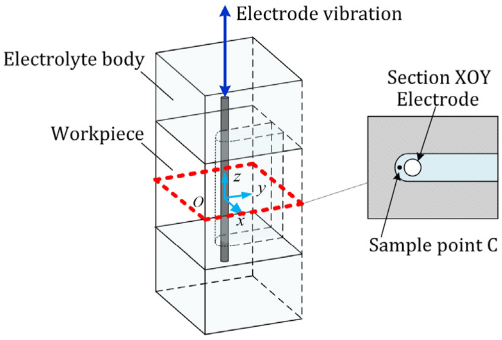

Fig. 2. CFD model of WECM assisted with large-amplitude vibrations.

plate of stainless steel 304. The diameter of the smooth wire electrode is 0.5 mm.

An Eulerian–Eulerian two-phase mixture model coupled with dynamic mesh is employed. The kinematic equation of the electrode vibration is

$$z = A\sin(2\pi f t - \pi/4) \quad (1)$$

where A is the vibration amplitude, f is the vibration frequency (fixed at 1.5 Hz), and t is the machining time.

From Faraday's law, the flux of hydrogen gas generated on the cathode surface can be expressed as

$$\frac{dN_{H_2}}{dt} = \frac{i}{2F} \quad (2)$$

where i is the machining current and F is the Faraday's constant. In the simulations, the flux of gas released from the electrode surface was fixed at 1.5×10^{-8} kg/s in order to calculate the distributions of gas fraction and electrolyte velocity in the machining gap.

Fig. 3 illustrates gas fraction distributions during a vibration cycle for two different electrode vibration amplitudes. For $\alpha = 0.1$ ($A = 0.5$ mm), the hydrogen gas remains in the machining gap regardless of the electrode movement. For $\alpha = 1$ ($A = 5$ mm), both gas and electrolyte are dragged up and down with the electrode. In

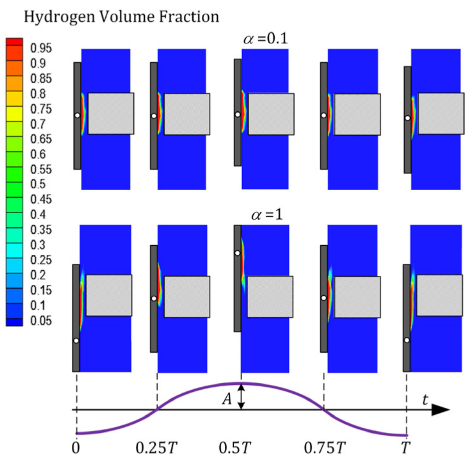

Fig. 3. Cross-sectional distributions of hydrogen (mainly red–green) in electrolyte (blue) during one vibration cycle for two different amplitudes.

the contour plots shown in Fig. 3, as the wire electrode reaches its upper limit for $\alpha = 1$, majority of the gas has been expelled from the machining gap. However, the gas displacement is smaller than the electrode movement because of wall slip. Hence, an amplitude larger than the workpiece thickness is required to expel all the gas.

In the downward duration, it was observed that only some of the hydrogen gas is expelled from the machining gap. Clearly, more gas is expelled for $\alpha = 1$ than for $\alpha = 0.1$. As the electrode moves downward, it is moving in the opposite direction to that of the buoyancy force, which weakens the drag action of the electrolyte on the gas in comparison to the case in the upward duration. These simulations with different vibration amplitudes show that a larger amplitude of electrode vibration helps the gas to escape, and that an upward movement is more effective than a downward one.

To understand the mass transport effects at the centre of the machining gap for different vibration amplitudes, point C ($x = 0$, $y = -0.29$ mm, $z = 0$; see Fig. 2) at the frontal machining gap in the central XOY section is selected as the sample point. Fig. 4 illustrates the variation of electrolyte velocity and gas fraction at point C for three different vibration amplitudes A. For $\alpha = 0.1$, the maximum electrolyte velocity is 1.3 mm/s and the gas fraction remains roughly constant at 35%. For $\alpha = 1$, the maximum electrolyte velocity is 23.5 mm/s and the gas fraction varies with time. In the upward duration ($t = 0$ to $0.5T$), the gas fraction decreases from roughly 30% to almost zero. In the downward duration ($t = 0.5T$ to T), the gas fraction increases back to a roughly constant value of 30%. For $\alpha = 1.5$, the maximum electrolyte velocity increases to 35.5 mm/s. The gas fraction drops more quickly than for $\alpha = 1$ in the upward duration. During the downward duration, it rises to about 20% and then drops abruptly to about 10%. These results show that a large-amplitude vibration is beneficial for gas products removal from the centre of the machining gap in WECM and that an upward motion is more effective than a downward one.

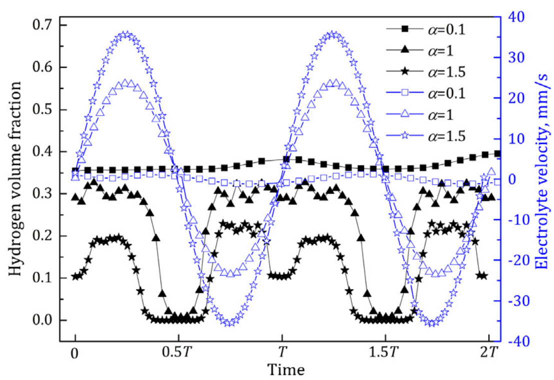

Fig. 4. Variations of gas fraction (black) and electrolyte velocity (blue) at point C for different vibration amplitudes.

3. Experimental apparatus

A specific experimental system was established to study the effects of large-amplitude vibration on WECM. Fig. 5 shows the constructed apparatus, which comprises of an X-Y-Z moving platform driven by linear motors, a pulse current generator, a

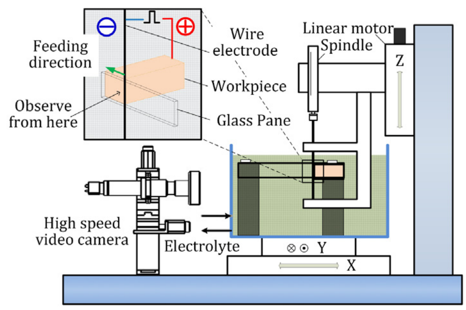

Fig. 5. Experimental apparatus for WECM assisted with large-amplitude vibrations.

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