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Effects of pulsating electrolyte flow in electrochemical machining

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ABSTRACT

Electrochemical machining (ECM) is a promising and low-cost process for yielding various components of difficult-to-machine materials, and has been well established in diverse applications. Distributions of gas and temperature affect the electrolyte electrical conductivity and determine the machining accuracy in ECM. Attempts have been made to generate the pulsating flow via a servo-valve in the electrolytic supply pipe, which is introduced to improve the heat transfer, material removal rate and surface profile in ECM. A multi-physics model coupling of electric, heat, transport of diluted species and fluid flow is presented. Simulation results indicate that pulsating flow has a significant impact on the distributions of velocity, gas fraction, and temperature near the workpiece surface along the flow direction. Experiments are conducted to verify the feasibility of the proposed process and study the effects of pulsating flow on material removal rate. The experimental results agree well with the simulations. Using optimal pulsating parameters, the material removal rate and surface profile are enhanced.

1. Introduction

Electrochemical machining (ECM) removes metal material by controlled anodic dissolution in an electrolytic cell. Compared to other typical machining technologies, ECM has superiority by having a high material removal rate, a good surface integrity, is stress free, and has no tool wear or metallurgical defects. ECM is a promising and low-cost process for yielding various components of difficult-to-machine materials, and has been well established in diverse applications, such as turbine blades, airfoils, and surgical implants (Rajurkar et al., 1999).

In ECM, the electrolyte with a velocity of 10–30 m/s is pumped into the inter-electrode gap to remove waste products (gases and metallic hydroxides) and Joule heat. The distributions of gases and Joule heat affect the electrolyte electrical conductivity and determine the machining accuracy. Therefore, many studies have focused on the disposal of metal hydroxide sludge and an efficient process simulation. Various approaches have been developed to modify the electrolyte flow regime and enhance the electrolyte refreshment in the inter-electrode gap. Rajurkar and Zhu (1999) found that orbital electrode movement reduces the flow disrupting phenomena and improves the machining accuracy and machining stability. Hewidy et al. (2001) proposed that orbital electrode movement eliminates the presence of the spikes and enhanced the ECM accuracy. Ruszaj et al. (2003) demonstrated that electrode ultrasonic vibration causes heterogeneous cavitation of electrolyte flow in the gap, and significantly improves the removal of heat and products out of the machining gap. Hewidy et al. (2007) shown that low frequency tool vibration provides a positive effect by changing the physical conditions in the inter-electrode gap, and enhances electrolytic renewal and the removal of sludge products. Wang et al. (2010) proposed that reverse electrolyte flow pattern with vacuum-extraction could prevent the occurrence of cavitations and diminishes sparking and formation of striations.

Furthermore, abundant computational methods have been used to analyse the characteristics of electrolyte flow, the distributions of gas and temperature, and acknowledge the anodic shaping rules. Analytical solutions (Hopenfeld and Cole, 1969) were obtained to describe the one-dimensional equilibrium-cutting gap along the flow direction. Fujisawa et al. (2008) established a multi-physics model, including multiphase flow, thermal fields and electric fields, to predict the final shape of a three-dimensional compressor blade. Van Tijum and Pajak (2008) used a multi-physics approach to support the design of the ECM process for machining the electric shaver. Lee et al. (2009) applied a multi-physics model, consisting of electric, convection and diffusion, to predict the parametric effects on machining accuracy. Deconinck et al. (2011) proposed the multi-ion transport and reaction model to describe the effects of water depletion, and temperature on the anodic process in ECM.

Havemann and Rao (1954) shown that periodic fluctuations of fluid flow create different hydrodynamic characteristics and alter

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Nomenclature

Notations

A	pulsating amplitude of electrolyte pressure (MPa)
bp	Bruggeman's coefficient
C_i	concentration of diluted species (mol m^{-3})
C_p	electrolyte specific heat capacity (J K^{-1} kg^{-1})
D_i	diffusion coefficient of diluted species (m^2 s^{-1})
E	electric field (V m^{-1})
f	pulsating frequency of electrolyte pressure (Hz)
F	Faraday constant (C mol)
i	current density (A cm^{-2})
k	electrolyte thermal conductivity
m	mass removed in machining (g)
M	molar mass of anodic material (g mol^{-1})
N	gas flux (mol m^{-2} s^{-1})
p	electrolyte pressure (MPa)
p_a	absolute pressure of electrolyte (MPa)
p_{av}	average electrolyte pressure (MPa)
P_{bulk}	Joule heating in the bulk of electrolyte
R	ideal gas constant (J mol^{-1} K^{-1})
$ReMRR$	relative material removal rate
t	machining time (s)
T	electrolyte temperature (K)
u	electrolyte velocity magnitude (m s^{-1})
U	applied voltage for ECM (V)
α	degree of temperature dependence
β_{gas}	gas void fraction in electrolyte
η	electric current efficiency
κ	electrolyte electrical conductivity (S m^{-1})
ρ	electrolyte density (g mm^{-3})
υ_n	material removal rate (μm s^{-1})
φ	electrical potential (V)
ω	volumetric electrochemical equivalent (mm^3 A^{-1} s^{-1})

Subscripts

0	property at the flow inlet
i	property of diluted species i
n	property in normal direction
constant	property at a constant electrolyte pressure

the thickness of the boundary layer; therefore, the pulsating flow of optimised pulsating parameters is beneficial to the transfer process. Pulsating flow has been applied to heat exchange, ramjet combustion, solid fermentation, drip irrigation emitter (Benavides, 2009).

Recently, the low-frequency tool vibration has been introduced to ECM, and high precision was obtained. When the electrode vibrates, the gap dimension oscillates in the same amplitude, and an electrolytic fluctuation is observed. However, this pulsating flow generated in an oscillating gap is different from those in a constant gap, which have been well applied in heat and mass transfer. Research shows limited studies on this pulsating flow in electrochemical machining.

In this study, attempts have been made to generate the pulsating flow via a servo-valve in the electrolytic supply pipe. This work focuses on the improvement of the heat transfer and material removal rate in ECM. A multi-physics model coupling of electric, heat, transport of diluted species, and fluid flow is presented to study the variations of electrolytic velocity, electrolytic temperature, and ion concentration along the flow direction near the workpiece surface. Moreover, experiments have been conducted to verify the feasibility of the proposed process.

2. Theoretical models

ECM is a field-synergy electrolysis process, which consists of mass transfer, energy transfer, momentum transfer and chemical reactions (McGeough, 1974). When a voltage is applied across the cathode tool and the anodic workpiece, the metallic ions of the anodic dissolution migrate from the anode surface to the electrolyte by an electrical force and are formed to insoluble hydroxides in neutral solutions. At the same time, hydrogen and oxygen is generated on the cathode and anode surface, respectively. Heat generated by the passage of current and electrochemical reactions will heat the electrolyte in the inter-electrode gap. All these occurrences interactively influence the electrolyte electrical conductivity, which would affect the current density distribution and the local material removal rate. The relation between the electrical conductivity κ, the electrolyte temperature T, and the gas void fraction β_{gas} is given as follows (Van Tijum and Pajak, 2008):

$$\kappa = \kappa_0(1-\beta_{gas})^{bp}(1+\alpha(T-T_0)) \quad (1)$$

where bp is the Bruggeman's coefficient.

Fig. 1 illustrates the schematic diagram of a typical ECM process with pulsating electrolyte flow. With a pulsating electrolyte, periodic fluctuations of flow create different characteristics of flow and heat transfer along the flow direction. The electrochemical cell consists of a cathode tool (Boundaries 9–11) and an anode workpiece (Boundaries 3–5), with electrolyte pumped through the electrode gap from the left inlet (Boundary 1) to the right outlet (Boundary 7). To simplify the proposed model, several assumptions are made as follows:

(1) The electrolyte flow is impressible single-phase flow. The scale of bubbles in the electrolyte is small enough to neglect its impact on fluid flow (Brebbia and Mammoli, 2011).
(2) The diffusion coefficient of bubbles is temperature independent and at a constant value of 3.0×10^{-6} m^2/s (Fujisawa et al., 2008).
(3) The electrolyte dynamic viscosity is assumed to be a constant value of 1.003×10^{-3} Pa s (Van Tijum and Pajak, 2008).
(4) The heat generated in the electrolyte is only Joule heat.

2.1. Impressible fluid model

The entire flow channel has dimensions of 1 mm in height, 112 mm in length and 12 mm in width; the distance from the inlet to the workpiece is 60 mm; the workpiece and cathode have a cross section of 12 mm × 12 mm with an initial machining gap of 0.15 mm. The governing equations, which usually describe the turbulent flow in ECM (Fujisawa et al., 2008), are given as follows:

$$\begin{aligned} -\mu\nabla^2 u + \rho(u\cdot\nabla)u + \nabla p &= 0 \\ \nabla\cdot u &= 0 \end{aligned} \quad (2)$$

The electrolyte pressure at the inlet is given as follows:

$$p_0(t) = A\ \sin(2\pi ft) + p_{av} \quad (3)$$

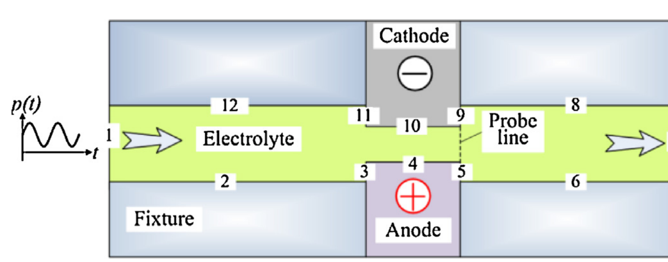

Fig. 1. Schematic diagram of ECM with pulsating electrolyte flow.