Journal of Materials Processing Technology 227 (2016) 129–137

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Enhancement of performance of wire electrochemical micromachining using a rotary helical electrode

Fang Xiaolong[a,b], Zhang Pengfei[a], Zeng Yongbin[a,b,*], Qu Ningsong[a,b], Zhu Di[a,b]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 8 August 2015
Accepted 13 August 2015
Available online 18 August 2015

Keywords:
Wire electrochemical micromachining
Electrolyte renewal
Helical electrode
Micro structures

ABSTRACT

The inherent characteristics of wire electrochemical micromachining (WECMM) enable it to be a feasible alternative to machining micro structures with good surface integrity in difficult-to-machine materials. Efficient electrolyte renewal has been proven to be important to the process stability and material removal rate in the machining of high aspect ratio micro structures. This paper proposes a method of WECMM using a rotary helical electrode to enhance electrolyte refreshment in the machining depth direction gap. Simulations of the flow field indicate that when a helical electrode revolves at a high speed, the electrolyte in the machining gap is stirred drastically, and the helical groove on the electrode surface is conducive to electrolytic flow in the axial direction. In addition, a series of experiments verifies that the maximum electrode feedrate and the slit width uniformity in the depth direction are enhanced by using a rotary helical electrode. Finally, two complex micro structures are successfully produced using a rotary helical electrode at a spindle speed of 20000 rpm.

1. Introduction

Miniaturization of products is in great demand for micro structures, which are increasingly being manufactured from stainless steel, super alloys and titanium alloys (Shin et al., 2011). These difficult-to-machine materials have created many challenges in micro machining technologies such as mechanical micromachining, laser micromachining, and electrical discharge micromachining (Rajurkar et al., 2013). Electrochemical micromachining (ECMM) removes material at the atomic format by anodic dissolution reactions in an electrolysis cell. As a noncontact micromachining method that is independent of material hardness and melting point, ECMM proceeds with no residual stress, no tool wear, and no metallurgical defects (Klocke et al., 2014). These inherent characteristics enable ECMM to be a feasible alternative for machining micro structures with good surface integrity in difficult-to-machine materials.

Wire electrochemical micromachining (WECMM) is an important component of ECMM, and inherits its positive features. The difference from normal ECMM is that WECMM has a metallic wire as the cathode rather than a shaped cathode, which would cost intensive tool developing processes (Klocke et al., 2013). With programmed relative movement between the wire electrode and the workpiece controlled by a computer numerical control system, micro metallic structures such as grooves (Kim et al., 2005), gears (Shin et al., 2008), and fans (Zhu et al., 2007) have been produced in acid aqueous solutions.

In WECMM, efficient electrolyte refreshment has been proven to be important to the process stability and material removal rate in WECMM of high aspect ratio structures (Zeng et al., 2012). Flowing electrolyte, which flushes the electrolysis products out from the machining gap, is the obvious method to use. Maeda et al. (1984) found that the maximum feedrate of the wire electrode was obtained at a critical pressure, which was related to the nozzle diameter and the length of the wire span. Béjar and Eterovich (1995) experimentally verified that a passivating electrolyte of $NaNO_3$ was beneficial for improving the feedrate and the accuracy of an NaCl electrolyte. Qu et al. (2013a,b) demonstrated that axial electrolyte flushing was effective for machining titanium alloys and feasible for multiple wire machining. Wang et al. (2012) developed a mathematical model of WECMM and optimized the parameters of the electrolyte flow on process stability and machining efficiency. Wang et al. (2011) introduced low-frequency vibrations of the wire electrode and the workpiece into WECMM. When the electrode vibrated up and down in the axial direction, the electrolyte was dragged into and out of the machining gap due to its viscosity. Xu

* Corresponding author at: P.O. Box 1005, 29 Yudao St Nanjing 210016, China.
E-mail address: binyz@nuaa.edu.cn (Z. Yongbin).

http://dx.doi.org/10.1016/j.jmatprotec.2015.08.014
0924-0136/

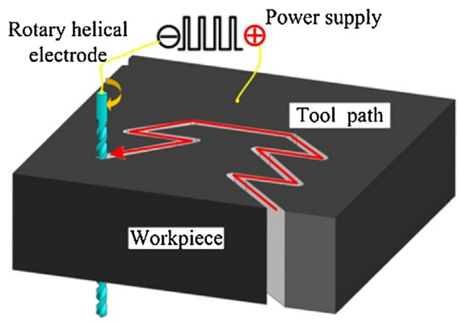

Fig. 1. Schematic diagram of WECMM using a rotary helical electrode.

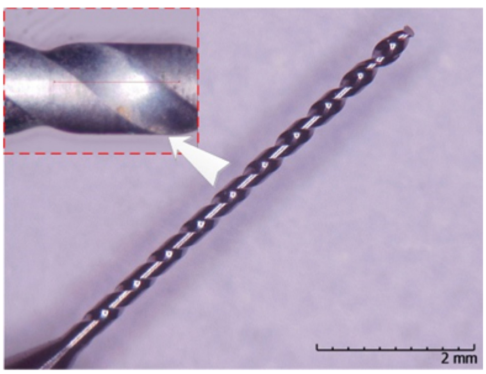

Fig. 2. Photographic view of a helical electrode with a diameter of 0.3 mm.

et al. (2015) found that cathode movement and anode vibration were helpful for improving the surface roughness in WECMM. Qu et al. (2014) applied a reciprocated traveling wire as the cathode to enhance product elimination, and the electrode feedrate reached 1 μm/s. Zeng et al. (2015) employed a closed wire ring as the cathode, which traveled in one direction to avoid the effects of frequent reversing in vibration and reciprocated traveling.

However, electrolyte refreshment in the above-mentioned methods was still slow and limited the machining efficiency. This paper firstly proposes a method for WECMM using a rotary helical electrode. Tsui et al. (2008) used a micro helical tool as the cathode in electrochemical drilling (ECMD). It verified that the renewal of the electrolyte and electrolysis products in the machining zone were facilitated as the micro helical tool rotated. WECMM is different from ECMD in electrode feeding format, the machining zone shape and so on. When the wire electrode in WECMM revolves at a high speed, the electrolyte in the machining gap is stirred drastically, and the helical groove on the electrode surface is supposed to be conducive to electrolytic flow in the axial direction. The effect of a rotary helical electrode on the flow field is then studied via simulation, and a series of experiments is conducted to verify the simulation. Ultimately, two complex structures are successfully produced using a rotary helical electrode at a spindle speed of 20000 rpm.

2. Principle of WECMM using a rotary helical electrode

Fig. 1 shows a schematic diagram of WECMM using a rotary helical electrode. A helical electrode is actually a high aspect ratio cylinder with spiral grooves on the surface. In this study, a micro drill made of tungsten carbide, as presented in Fig. 2, is employed as a helical wire electrode (cathode). The workpiece, as the anode, is immersed in the electrolyte cell. The helical wire electrode is attached to a high-speed spindle and fed along the programmed tool path to fabricate a structure.

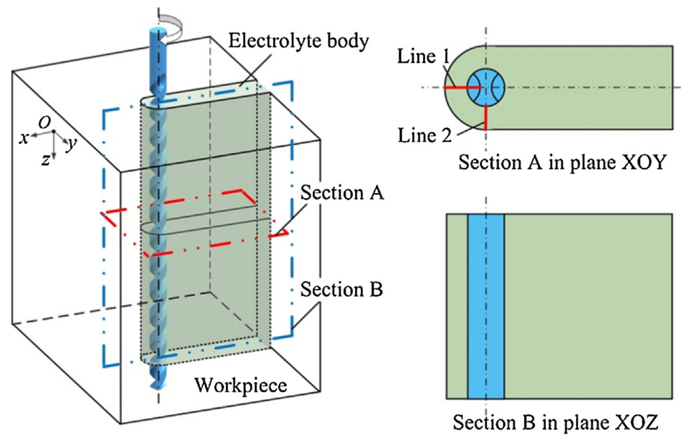

Fig. 3. Electrolyte body in the inter-electrode gap of WECMM.

Table 1
Parameters applied in flow field simulation.

Parameter	Value
Electrode diameter	0.3 mm
Spindle speed	5000, 10,000, 20,000, 50,000 rpm
Slit width	0.5 mm
Workpiece thickness	5 mm
Machined length	2 mm

With rotation, the fresh electrolyte is dragged into the machining gap from the bottom of the workpiece, while the dirty electrolyte containing the electrolysis products is extruded out to the upper surface. A flow field model of WECMM was established to analyze the effects of electrode rotation on the electrolyte refreshment process, as shown in Fig. 3. In this model, a cylindrical electrode and a helical electrode are used, respectively. Section A and section B are chosen to illustrate the different velocity distributions in WECMM using these two different electrodes. Line 1 and line 2 are referenced to describe the specific electrolyte velocity in the machining gap. Table 1 lists the parameters applied in the simulation. The calculation was carried out via ANSYS Fluent 14.5.

Fig. 4 presents electrolyte velocity contours in the machining gap of WECMM using a rotary cylindrical electrode. Here, the absolute velocity is three-dimensional and comprises of an X directional component, a Y directional component and a Z directional component parallel to the spindle axis namely axial velocity. Fig. 4a shows the absolute velocity distribution in section B, and Fig. 4b shows the axial velocity component distribution in section B. Fig. 4c shows the absolute velocity distribution in section A, and Fig. 4d shows the axial velocity component distribution in section A. The results indicate that the electrolyte in the machining gap moves with the electrode rotation. When the electrode was fed without rotation, the electrolyte in the machining gap was static. The electrolysis products are diffused from the workpiece surface under natural convection driven by concentration gradient. When the spindle speed was 10000 rpm, the maximum velocity reached 0.1 m/s, as shown in Fig. 4a and c. The electrolyte in the machining gap is stirred drastically and the electrolysis products are diffused under forced convention driven by flow. The electrolyte refreshment and mass transfer rate has been greatly enhanced. However, the axial velocity component was nearly zero, as shown in Fig. 4b and d. It has been proved that the axial velocity component is the main reason for electrolyte refreshment in the machining gap of WECMM.

Fig. 5 presents electrolyte velocity contours in the machining gap of WECMM using a rotary helical electrode. Fig. 5a shows the absolute velocity distribution in section B, and Fig. 5b shows the axial velocity component distribution in section B. Fig. 5c shows