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Short Communication

Effects of a Magnetic Field on the Machining Accuracy for the Electrochemical Drilling of Micro Holes

Changfu Zhang[1, 2,*], *Pixian Zheng*[1, 2], *Ruoyun Liang*[1, 2], *Kang Yun*[1, 2], *Xinguang Jiang*[1, 2], *Zhenghu Yan*[1, 2]

[1] School of Mechatronics Engineering, Xi'an Technological University, Xi'an 710021, China
[2] Shaanxi Key Laboratory of Non-Traditional Machining, Xi'an 710021, China
[*]E-mail: cfzhang@xatu.edu.cn

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Micro electrochemical machining (micro-ECM) is a promising machining technology for microparts of difficult-to-cut metallic materials and has been used in the industries of aeronautics and astronautics, ordnance, precision devices, and so on. The machining accuracy of micro-ECM is difficult to improve, so a magnetic field is employed to assist with the electrochemical drilling of micro holes. First, micro electrochemical drilling experiments with and without a magnetic field and with different magnetic flux densities were carried out. Then, the effects of the magnetic field on the machining accuracy of micro electrochemical drilling were analyzed and discussed based on the experimental results. The results showed that an external magnetic field whose direction was perpendicular to the feed direction improved the machining accuracy of micro electrochemical drilling, and the machining accuracy was the best when the magnetic flux density was approximately 0.1 T. This study can help to improve the machining accuracy of micro electrochemical drilling and accelerate further research on magnetic-field-assisted micro-ECM technology.

Keywords: Difficult-to-cut metallic material; Micro electrochemical machining; Magnetic field; Magnetic flux density; Machining accuracy

1. INTRODUCTION

As the demand for miniaturized products rapidly increases, the need to machine microparts of difficult-to-cut metallic materials has become urgent [1-3]. Thus, micromachining technologies play significant roles in microparts and have been applied in the industries of aeronautics and astronautics, ordnance, nuclear, precision devices, etc. However, it is very challenging to machine microparts of difficult-to-cut metallic materials with conventional cutting technologies and some nonconventional machining technologies.

To date, mechanical microcutting, silicon-based micromachining, micro electrical discharge machining (micro-EDM), laser micromachining and other machining technologies have been applied to machine microparts. However, most of them have defects and are not ideal machining technologies. For example, when mechanical microcutting technologies are used to machine microparts, cutting difficult-to-cut metallic materials is challenging, tool reachability is poor during the machining of complicated structures, and residual stress is generated at machining areas. Silicon-based micromachining technologies for micro-electro-mechanical systems (MEMS) are usually used to machine nonmetallic materials but not metallic materials. The application of micro electrical discharge machining (micro-EDM) is limited because of its low machining efficiency, high electrode wear and generation of surface metamorphic layers. Laser micromachining is also limited because of its poor 3D fabrication ability and the generation of deterioration layers and superficial microcracks.

Compared with the abovementioned machining technologies, micro electrochemical machining (micro-ECM) is an ideal machining technology for the microparts of difficult-to-cut metallic materials because of its special mechanism of material removal. Bhattacharyya [4] regarded micro-ECM as a promising future micromachining technique since it had many advantages in many areas of applications. Datta [5] thought electrochemical micromachining was an environmentally friendly, high-speed processing technology. Schuster [6] regarded micro-ECM as an ideal machining technology for the microparts of difficult-to-cut metallic materials. Spieser [7] considered micro-ECM an attractive research area. With this technology, the extra material of microparts is dissolved in the form of an ionic state based on electrochemical principles. Because the size of metal ions is 0.l nm or even smaller, micro-ECM has great potential in the fields of micro- and nano-manufacturing. Moreover, micro-ECM has many other advantages, such as no tool wear, no stress and a great ability to machine any metallic materials irrespective of their hardness. Therefore, micro-ECM has been increasingly applied in the field of micromanufacturing.

However, the machining accuracy of micro-ECM is not easily improved, which limits its application. In recent years, studies on improving machining accuracy of micro-ECM have mainly been conducted in the following aspects. First, ultrashort voltage pulses are often used to improve the machining accuracy of micro-ECM. Schuster [6] applied ultrashort voltage pulses between the tool electrode and the workpiece in ECM and achieved three-dimensional machining with submicrometer precision. Zemann [8] found that the highest manufacturing precision of micro-ECM depended highly on small working gaps through ultrashort voltage pulses in nanosecond durations. Skoczypiec [9] applied ultrashort (nanosecond range) voltage pulses to achieve high localization of the electrochemical dissolution process during the machining of microparts. Maurer [10] used electrochemical micromachining with ultrashort voltage pulses to machine microstructures to depths of 3 μm and 10 μm on a corrosion-resistant nickel-based superalloy (Hastelloy B-2). Second, special shape electrodes are used to improve the machining accuracy of micro-ECM. Wang [11] found that microhelix electrodes could improve ECM accuracy and stability by microhelix pump effects. Pa [12] presented a new approach using a graded modular tool in a precision μ-ECM process for the removal of defective ITO solid-state nanostructures from the surface of color filters on optoelectronic flat panel displays. Li [13] used side-insulated microelectrodes and a controlled micro gap strategy to improve machining accuracy. Third, hybrid micro-ECM technologies have been invented to enhance machining accuracy. Yang [14] applied ultrasonic vibrations to improve the electrolyte diffusion of micro-ECM. Zeng [15] found that the machining accuracy with a combination of micro-EDM and micro-ECM milling methods was much better than that of micro-ECM milling alone. Opran [16] studied the influence of a magnetic field on the electric field and hydrodynamic parameters, as well as the influence on productivity and machining accuracy. Ma [17] analyzed the influence of the magnetic field distribution on the ECM process and found that a proper magnetic field distribution can improve the machining accuracy and efficiency of ECM. Enache [18] found that a magnetic field exerted a strong positive influence on the entire ECM process, resulting in enhanced efficiency and machining accuracy. Moreover, the influence of the magnetic field on the electrochemical polishing quality has been increasingly studied [19, 20].

From the abovementioned studies, we can conclude that magnetic-field-assisted ECM has been an important aspect of ECM technologies and that a magnetic field can exert a strong positive influence on the machining accuracy of ECM. However, most of these studies focus on the ECM process of macrosized workpieces. This paper investigates whether the magnetic field can improve the machining accuracy of micro-ECM. The effects of a magnetic field on the machining accuracy of the electrochemical drilling of micro holes are mainly studied. This study can help to improve the machining accuracy of micro electrochemical drilling and accelerate further research on magnetic-field-assisted micro-ECM technology.

2. EXPERIMENTAL

2.1 Setup

Electrochemical drilling experiments for micro holes were carried out with an electromagnetic-field-assisted micro-ECM setup shown in Fig. 1. The setup includes the body of the machine (an X-Y-Z multiaxis platform, a motorized spindle, an air flotation supporting platform, etc.), a control system, a measuring system, two ECM power supply systems (a DC-regulated power supply and a nanosecond-pulsed power supply), an electrolyte circulating system, and so on.

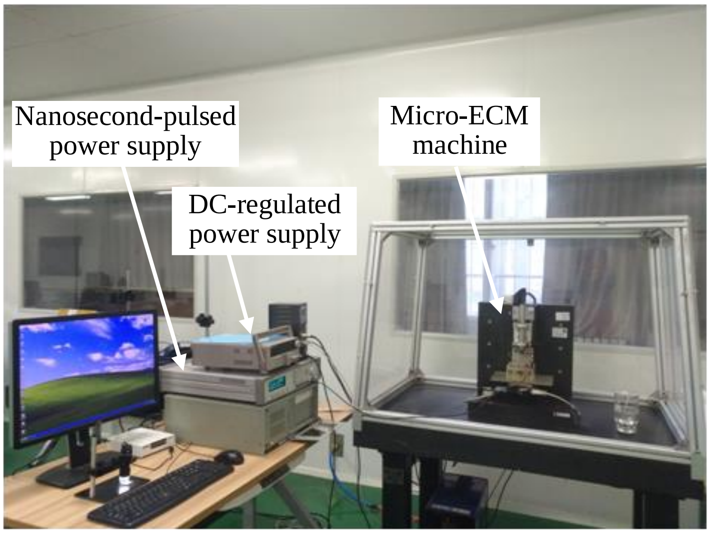

Figure 1. Magnetic-field-assisted micro-ECM experimental system.

The machine can move in three feed directions (X-axis, Y-axis and Z-axis) with resolutions of 10 nm and positioning accuracies of 0.1 μm. The motorized spindle mounted on the Z-axis can rotate at a speed of 1000-60,000 RPMs. The DC-regulated power supply is used to prepare microelectrodes, and the nanosecond-pulsed power supply is used to machine microparts to achieve good machining accuracy. The electrolyte circulating system is employed to supply the electrolyte solution to the machining area and filter the electrolyte to keep it clean.

2.2 Micro-ECM comparative experiments with and without a magnetic field

To investigate the effects of the magnetic field on the machining accuracy of the electrochemical drilling of micro holes, comparative machining experiments with and without a magnetic field were carried out using a DC power supply (ITECH DC voltage supply).

Micro electrochemical drilling experiments with a 0.1 T magnetic field and without a magnetic field were carried out in static 6 wt% $NaNO_3$ electrolyte solution. A highly elastic 3J21 nickel iron alloy sheet plate with a thickness of 300 μm was machined by a cylindrical tungsten electrode with a diameter of 300 μm. The electrode was linked with the negative pole of the DC power supply and the workpiece (3J21 sheet plate) was linked with the positive pole. The main parameters of the experiments are shown in Table 1.

Table 1. Experimental conditions of the comparative experiments.

Working conditions	Descriptions
Power supply type	DC power supply
Voltage (V)	5.0
Spindle feed speed (μm/s)	2.0
Initial machining gap (μm)	30
Spindle feed depth (μm)	380
Electrolyte	6 wt% $NaNO_3$
Magnetic flux density (T)	0 / 0.1

In the experiments without a magnetic field, many bubbles were generated and remained around the machining area (see Fig. 2), and bubble breakups often occurred, which caused electrolyte splashing. During the micro electrochemical drilling experiments with a 0.1 T magnetic field, bubbles rotated with the electrolyte and diffused quickly. Only a few bubbles stayed around the machining area and nearly no electrolyte-splashing phenomena occurred, as shown in Fig. 3.

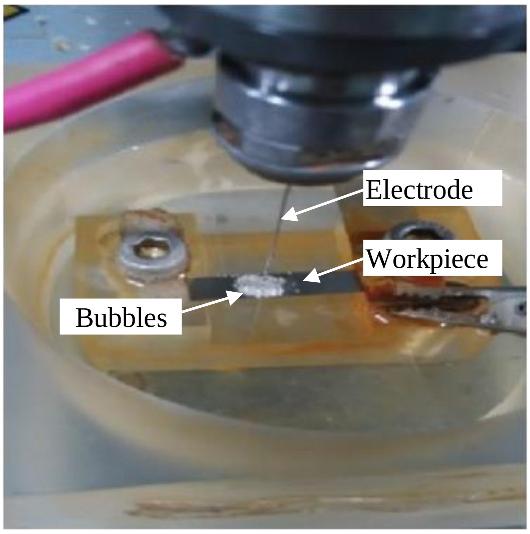

Figure 2. Micro electrochemical drilling without a magnetic field.

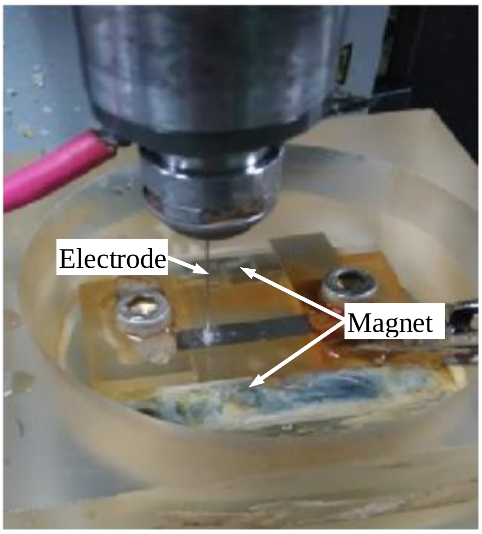

Figure 3. Micro electrochemical drilling with a magnetic field (0.1T).

2.3 Micro electrochemical drilling experiments with different magnetic-flux-density fields

To further explore the influences of different magnetic flux densities on the machining accuracy of micro electrochemical drilling, comparative experiments with different magnetic flux densities (0, 0.05 T, 0.1 T, 0.15 T and 0.2 T) were carried out with a nanosecond-pulsed power supply. The direction of the magnetic field was perpendicular to the machining feed direction.

A highly elastic 3J21 nickel iron alloy sheet plate with a thickness of 300 μm was machined by a cylindrical tungsten electrode with a diameter of 300 μm in static 6 wt% $NaNO_3$ electrolyte solution. The electrode was linked with the negative pole of the nanosecond-pulsed power supply and the workpiece (3J21 sheet plate) was linked with the positive pole. The main parameters of the experiments are shown in Table 2.

When the magnetic flux densities were 0, 0.05 T, 0.1 T, 0.15 T and 0.2 T, the machining procedure of the micro holes was very smooth. When the magnetic flux density was larger than 0.2 T, short-circuit phenomena between the workpiece and the electrode occasionally occurred.

Table 2. Experimental conditions of different magnetic flux densities.

Working conditions	Descriptions
Power supply type	Nanosecond-pulsed power supply
Voltage (V)	5.0
Pulse period (ns)	1000
Pulse width (ns)	500
Spindle feed speed (μm/s)	0.8
Initial machining gap (μm)	30
Spindle feed depth (μm)	380
Electrolyte	6 wt% $NaNO_3$
Magnetic flux density (T)	0, 0.05, 0.1, 0.15, 0.2

3. RESULTS AND DISCUSSION

To analyze the effects of the external magnetic field on the machining accuracy of micro electrochemical drilling, the hole-taper or the taper-angle of the machined micro holes is often calculated and analyzed [21-23]. In this paper, the hole-taper k is employed to analyze the machining accuracy of micro electrochemical drilling, which can be represented as:

$$k = \frac{d_1 - d_2}{h} \tag{1}$$

where d_1 is the diameter of the inlet, d_2 is the diameter of the outlet, and h is the height of the plate. The values of d_1, d_2 and h can be obtained by measuring the diameters of the inlet and outlet of the micro holes and the height of the plate.

3.1 The effect of the external magnetic field on the hole-tapers of the machined micro holes

One group of the machined micro holes in the comparative experiments with and without a magnetic field is shown in Fig. 4. One group of the machined micro holes in the comparative experiments with different magnetic flux densities (0, 0.05 T, 0.1 T, 0.15 T and 0.2 T) is shown in Fig. 5.

After being measured and calculated, the hole-tapers of the micro holes machined in the comparative experiments with and without a magnetic field are shown in Table 3. The hole-tapers of the micro holes machined with different magnetic flux densities are shown in Table 4. Similar results can be seen in [24].

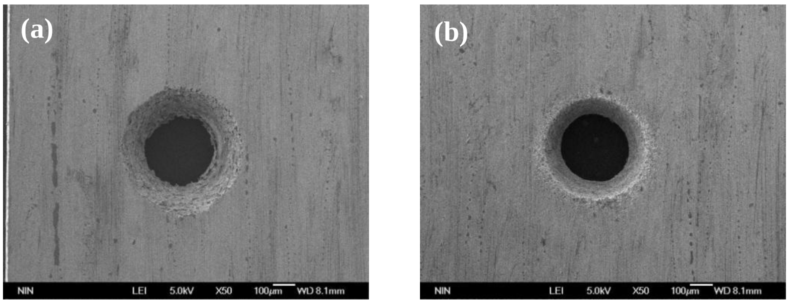

Figure 4. Micro holes machined in the comparative experiments: (a) without magnetic field and (b) with 0.1T magnetic field.

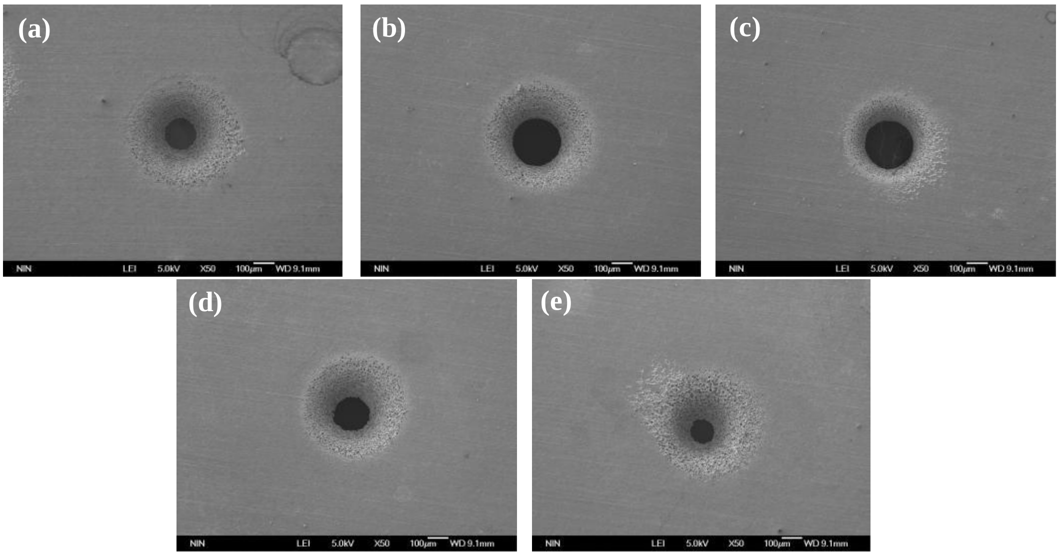

Figure 5. Micro holes machined with different magnetic flux densities: (a) 0T, (b) 0.05T, (c) 0.1T, (d) 0.15T and (e) 0.2T.

Table 3. Tapers of the machined micro holes in the comparative experiments.

Working conditions	Description
Without magnetic field	0.79
With 0.1T magnetic field	0.55

Table 4. Tapers of the machined micro holes with different magnetic flux densities.

Magnetic flux density (T)	Hole-taper
0	0.84
0.05	0.67
0.10	0.58
0.15	0.83
0.20	1.16

From Fig. 4 and Table 3, we can conclude that the external magnetic field made the hole-taper of the machined micro hole smaller and the roundness better, which means that the magnetic field improved the machining accuracy of micro electrochemical drilling.

From Fig. 5 and Table 4, when the magnetic flux density increased from 0 to 0.1 T, the hole-tapers of the micro holes gradually decreased, and the machining accuracy of the micro holes improved. When the magnetic flux density increased from 0.1 T to 0.2 T, the hole-tapers gradually increased, and the machining quality became worse. From this, we can conclude that the external magnetic field has a positive effect on the machining accuracy of micro electrochemical drilling and the improvement of the 0.1 T magnetic field on machining accuracy was the best.

Why can the magnetic field improve the machining accuracy of the micro electrochemical drilling? The influences of the magnetic field on the electric field, hydrodynamic parameters, productivity and machining accuracy in electrochemical machining (ECM) for macrosized workpieces have been previously reported [16-18]. Fan [25-27] studied the improvement of the permanent magnets on the machining accuracy of macrosized workpieces in ECM. Li [28] analyzed the coupled effect of magnetic field, electric field, and electrolyte motion on the material removal amount in ECM. In micro-ECM, Lin [29] studied the machining properties of magnetic field assisted with micro electrochemical drilling and decreased the diameter-values of micro holes from 407 μm to 106 μm with a magnetic assistance. Tsui [30] applied a helical tool and the Lorentz force of a magnetic field to enhance the renewal of the electrolyte and machining efficiency in electrochemical milling.

In contrast with these studies, this study mainly focused on the effects of a magnetic field on the machining accuracy of micro-ECM from two aspects: the effect of a changing motion trajectory of charged ions and the “stirring” effect of the electrolyte with magnetic assistance.

3.2.2 Effect of the changing motion trajectory of charged ions on the machining accuracy

The motion of ions (anions and cations) in magnetic-field-assisted micro-ECM machining will be affected by the electric field force and the Lorentz force. The force of anions can be expressed as

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{2}$$

where $\vec{F}$ is the total force of the electric-field force and the Lorentz force exerted on anions, q is the quantity of electric charge, $\vec{E}$ is the magnetic flux density, $\vec{v}$ is the speed vector and $\vec{B}$ is the magnetic flux density. Under these forces, the trajectory equation [31] of charged ions can be expressed as

$$\begin{cases} x = \dfrac{C_1}{\omega}\sin(\omega t + \alpha) + \dfrac{E}{B}t + x_0 \\ y = \dfrac{C_1}{\omega}\cos(\omega t + \alpha) + y_0 \\ z = C_2 t + z_0 \end{cases} \tag{3}$$

$$\omega = qB/m \tag{4}$$

where C_1, C_2, α, x_0, y_0 *and* z_0 are constants. From equation (3), we can see that the motion trajectory of charged ions will change under the Lorentz force. That is, charged ions will move along spiral lines, and their trajectories will become longer [32]. This kind of motion is inclined to make more ions reach the peak area or middle area of the protruding microstructures of the workpiece surface, as shown in Fig. 6. Thus, more electrochemical reactions in these areas will occur, and more materials can be removed than without an external magnetic field. From this aspect, the external magnetic field can help to enhance the effect of a “removing peak”, which improves the machining accuracy of the workpiece.

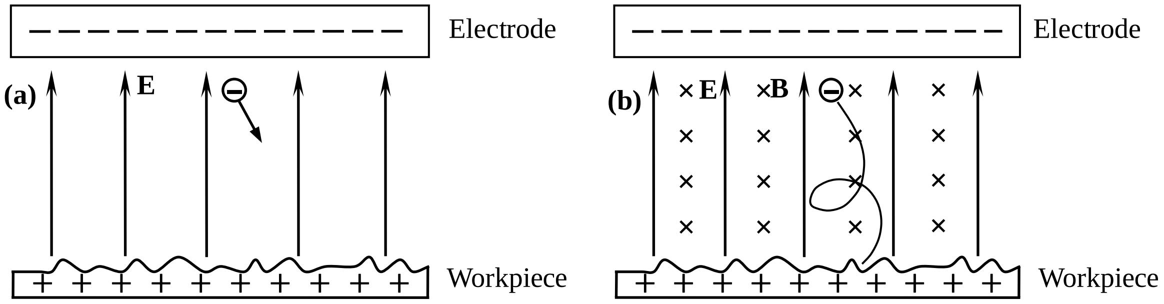

Figure 6. Effect of the magnetic field on material removal areas: (a) without magnetic field and (b) with a 0.1 T magnetic field.

The “removing peak” effect is related to the magnetic flux densities, which can be classified into the following types. (a) When the magnetic flux density is less than 0.05 T, the effects of the Lorentz force on the micro-ECM are weak, and the motion trajectories of the charged ions are minimally affected. Thus, a magnetic field of less than 0.05 T can only affect the taper and the machining accuracy of the machined micro holes within a small range. In other words, a very weak magnetic field can improve the machining accuracy very little. (b) When the magnetic flux density equals 0.05 T ~ 0.1 T, the Lorentz force exerted on the ions becomes stronger, which makes the radii of helical motions for the charged ions larger and the trajectories of the charged ions longer. Thus, collisions between the ions and unionized molecules will increase, which can help to stir the electrolyte near the machining area. This will affect the mass transfer process and help to improve the machining accuracy of the micro-ECM. (c) If the magnetic flux density equals 0.1 T ~ 0.2 T, the Lorentz force will increase, which makes the radii of helical motions larger and the motion trajectories longer. As a result, some ions will move out of the reaction area and will not participate in the electrochemical reaction. Thus, the improvement of the magnetic field ranging from 0.1 T to 0.2 T on the machining accuracy decreases. (d) If the magnetic flux density is larger than 0.2 T, the Lorentz forces exerted on charged ions will be relatively large, which makes most of the charged ions pass by the surface of the workpiece and get out of the machining area of the workpiece. In this case, the machining accuracy of micro-ECM cannot be improved.

3.2.3 “Stirring” effect of the magnetic field on the electrolyte near the machining area

In ECM, it is significant that the clean and fresh electrolyte is constantly supplied to the machining gap to realize ECM precisely [33]. The external magnetic field affects the mass transfer process of the electrolyte [34]. Mori [35] and Li [36] found that the mass transfer rate was increased by applying a magnetic field. Gorobets [37] and Shinohara [38] found the effect of multivortex electrolyte stirring in the vicinity of a solitary electrode in a magnetic field. From these studies, we can conclude that the magnetic field has a "stirring" effect on the electrolyte, which is helpful to keep the electrolyte near the machining area fresh.

To study the "stirring" effect of the external magnetic field on the electrolyte, bromocresol purple $C_{21}H_6Br_2O_5S$ (an acid-base indicator with a discoloration ranging from pH 5.2 (yellow) to pH 6.8 (purple)) was mixed into the electrolyte and the reaction procedure was analyzed according to the color changing of electrolyte. Similar method can be seen in [39]. During the electrochemical reaction, the color of the electrolyte mixed with $C_{21}H6Br_2O_5S$ gradually changed from yellow into purple. With time, the pH value of the electrolyte solution near the machining area became larger than 6.8 at first, and a purple color began to appear. Then, the purple solution became increasingly darker and gradually became a spiral flow that rotated counterclockwise and spread outward, as shown in Fig. 7.

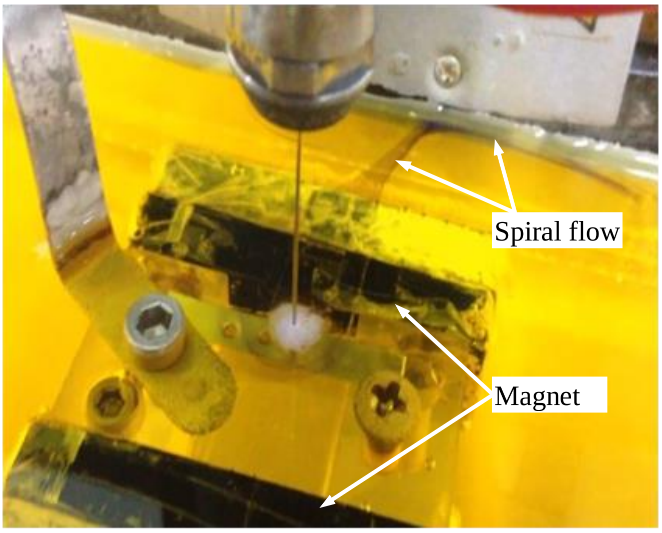

Figure 7. Rotation of the electrolyte under the magnetic field.

As shown in Fig. 7, the purple spiral flow rotated counterclockwise and spread outward during micro electrochemical drilling under a magnetic field, which implies that the magnetic field can help to promote the movement of the electrolyte. As discussed above, the motion status and trajectory of charged ions will change under the Lorentz force caused by magnetic field and electric field, which increases their collision probability with other molecules. This also enhances the mass transfer rate of the electrolyte. Thus, the magnetic field has a "stirring" effect and helps to keep the electrolyte near the machining area fresh. This effect can decrease the short-circuit phenomena between the workpiece and the electrode, and make electrochemical reaction more smooth and stable. Moreover, the "stirring" effect can make the temperature of the electrolyte more stable. All these improve the machining accuracy and stability of micro-ECM.

4. CONCLUSION

The effects of a magnetic field on the machining accuracy of electrochemical drilling for micro holes were studied with verification experiments and theoretical analysis. The magnetic field improved the machining accuracy of micro electrochemical drilling. The magnetic field enhanced the "removing peak" effect and the "stirring electrolyte" effect during the mass transfer process in micro electrochemical drilling. These effects help to remove the material of the peak and middle areas of the protruding microstructures of the workpiece surface and to stir the electrolyte near the machining area. These effects are helpful in achieving better machining accuracy of micro-ECM. The results of comparative experiments with different magnetic flux densities ranging from 0 to 0.2 T showed that the machining accuracy of micro electrochemical drilling became better with an increasing of magnetic flux density from 0 to 0.1 T, while it became worse when the magnetic flux density increases from 0.1 T to 0.2 T. The machining accuracy of micro electrochemical drilling was the best when the magnetic flux density was approximately 0.1 T. This study can help to improve the machining accuracy of micro electrochemical drilling and accelerate further research on magnetic-field-assisted micro-ECM technology along with industrial applications of micro-ECM for manufacturing microstructures of hard-to-cut metallic materials.

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