Experimental Investigation on Complex Structures Machining by Electrochemical Micromachining Technology

Liu Yong, Zhu Di*, Zeng Yongbin, Huang Shaofu, Yu Hongbing

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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Abstract

Electrochemical micromachining (EMM) technology for fabricating micro structures is presented in this article. By applying ultra short pulses, dissolution of a workpiece can be restricted to the region very close to the electrode. First, an EMM system for meeting the requirements of the EMM process is established. Second, sets of experiments is carried out to investigate the influence of some of the predominant electrochemical process parameters such as electrical parameters, feed rate, electrode geometry features and electrolyte composition on machining quality, especially the influences of pulse on time on shape precision and working end shape of electrode on machined surface quality. Finally, after the preliminary experiments, a complex microstructure with good shape precision and surface quality is successfully obtained.

Keywords: electrochemical; micromachining; ultra short pulse; working end shape; surface quality; complex structure

1. Introduction

With the development of micro-electro-mechanical system (MEMS), micromachining techniques have become a hot issue in modern industry. Micro-scale metal complex structures have a wide range of application in many fields, including biomedicine and aviation. For example, there are many micro metal parts or components in the impeller unit, transmission unit and manipulation unit of micro air vehicle. So far, micromachining techniques include lithography, electro discharge machining (EDM), ultrasonic machining, electrochemical micromachining (EMM) and so on. EMM is an electrochemical dissolution process that has many advantages such as no tool wear, stress-free, with smooth surfaces and the ability to machine complex structures in metallic materials, regardless of their hardness and high strength, high tension, or whether they are heat-resistant metals.

For nearly a decade, many research attempts at EMM have been done. Recent researches focus on EMM with the ultra high frequency pulse current. It has been reported that material removal is strongly localized when ultra high frequency pulse current is used instead of conventional DC or low frequency pulse current. Some simple shapes have been machined in recent years, but complex structures are needed in the actual production. In this article, the dominant characteristics of EMM are researched through sets of experiments according to various parameters, such as machining voltage, pulse on time, pulse frequency, feed rate, electrode diameter, working end shape of electrode and so on. After the preliminary experiments, a complex shape with good shape precision and surface quality is successfully obtained.

2. Principle of EMM

EMM is similar to common electrochemical machining (ECM) which is an electrochemical anodic dissolution process. During the machining process, an ultra short pulse direct current with low voltage is passed between workpiece and cathode. On the anodic workpiece surface, metal is dissolved into metallic ions by the electrochemical reaction. The micron scale cylindrical tungsten electrode is used as the cathode tool. Following the scheduled tool path, the required shapes or structures can be obtained as shown in Fig.1(a). Dilute acid electrolyte, in which the sludge can be dissolved, is used to improve the processing conditions. Beyond that, the hydrogen bubbles gener-
ated during the reaction can take heat away from the gap and promote the electrolyte supplement.

There are many factors which affect the machining quality in EMM such as electrolyte conductivity, the current density, the inter-electrode gap and so on. Electrolyte conductivity, acting as a variable resistance, has been recognized as one of the most important parameters in EMM\cite{10}. In this article, the reaction cell contains both resistance of the mechanical system $R_m$ and electrolyte $R_e$, as shown in Fig.1(b).

While the cathode feeding is down (see Fig.1(b)), $R_e_{\text{bottom}}$ is the electrolyte resistance of the shorter path between the tool and the workpiece, and $R_e_{\text{side}}$ is that of the longer path. Because of the small bottom gap, $R_e_{\text{bottom}}$ is also very small; therefore, the dissolved area is restricted to a localized region under the rear part of tool. When the nano-second voltage pulse on time is applied between the double layers, the electric current flows through the shorter path with the electrolyte resistance $R_e_{\text{bottom}}$. Then, EMM occurs strongly in the localized area under the end of tool. Likewise, while the cathode feeding in $X'Y'$ is flat (see Fig.1(c)), $R_e_{\text{side}}$ is the electrolyte resistance of the shorter path between tool and workpiece. The electric current flows through the shorter path with the electrolyte resistance $R_e_{\text{side}}$, and EMM occurs strongly in the localized area around the tool sidewall.

3. Experimental System of EMM

The developed EMM set-up consists of various sub-components such as electrodes unit, controlled electrolyte flow system, servo-control feed unit, data acquisition system, etc. Fig.2 presents a schematic view of the various system components of the developed EMM set-up. The electrode unit consists of tungsten cylinder cathode, workpiece, tool holder and electricity-conductive device. The controlled electrolyte flow system consists of machining chamber, micrometeor pump, filter, electrolyte tank and so on. All these elements have been designed so as to fulfill the design requirements of EMM system. The developed EMM experimental set-up along with all the control system components is exhibited in Fig.3.

Fig.2 Sketch of experimental system.

The high frequency pulse voltage is applied between the electrodes. 0.2 mol/L $\text{H}_2\text{SO}_4$ is preferred because the acid electrolyte usually produces much less by-product than common salt electrolytes do, which is important for a steady machining process in such a small machining gap.

The motion control system consists of a precise $XYZ$ stage and servo-control feed unit. The motion parts of $X$, $Y$ and $Z$ axes are driven by direct current servo motors with the resolution of 0.1 $\mu$m. Therefore, this machining control system meets the requirement of machining micron-sized structures. An appropriate inter-
polation procedure is required to process the scheduled graphics and structures.

Stability is the most important for this micro-machining with the gap of several micrometers. If the tool feed rate is too high, the tool would come in contact with the workpiece and cause short circuit. By-product in the electrolyte may also cause short-circuit due to the spark discharge. Since short circuiting seriously damages both the micro tool and the workpiece, a safety system is necessarily built in the EMM set-up. If the abnormal current signals are detected, the control system will rapidly change the velocity and direction of the tool movement. For example, when a short circuit is detected, the servo motor will stop and move backward along the preceding path immediately until the danger is clear.

4. Parametric Comparative Experiments and Discussion

Experiments were carried out on the developed platform of EMM system to illustrate the influence of the predominant process parameters, such as machining voltage, pulse on time, pulse frequency, feed rate, electrode diameter, etc. on machining accuracy and surface quality. Experimental results are plotted by graphs to exhibit the influence of different process parameters on machining accuracy and surface quality.

Experiments of EMM on a nickel plate with the thickness of 100 μm were carried out to demonstrate the effects of machining parameters on the groove width. As mentioned above, the groove width is considered as evaluation of machining accuracy in this article.

The groove width is dependent on the feed rate of electrode, pulse voltage, pulse on-time pulse frequency and electrode diameter. The machined surface quality is dependent on the working end shape of electrode and micro-spark times.

4.1. Effect of electrical parameters on machining accuracy

(1) Effect of machining voltage on machining accuracy

Machining conditions of this set of experiments were as follows: electrode diameter of 8 μm, 0.2 mol/L H₂SO₄ electrolyte, pulse frequency of 1 MHz and pulse on time of 45 ns, feed rate of 0.2 μm/s and machining voltage varying from 3.5 V to 5.0 V.

Fig.4 shows that the groove width is in direct proportion to voltage, which proves that the machining accuracy reduces with increasing voltage. Due to the increase in voltage, machining current also increases. Faraday’s law states that the material removal rate (MRR) is proportional to the machining current. But the graph clearly indicates that MRR does not vary linearly. As shown in Fig.4, the groove width from 3.5 V to 4.5 V varies almost linearly and increases less rapidly than in the range of 4.5-5.0 V. So, it can be concluded that the best machining voltage range is between 4.0 V and 4.5 V.

(2) Effect of pulse on time on machining accuracy

Machining conditions of this set of experiments were as follows: electrode diameter of 8 μm, 0.2 mol/L H₂SO₄ electrolyte, pulse frequency of 1 MHz and machining voltage of 4.5 V, feed rate of 0.2 μm/s and pulse on time varying from 40 ns to 90 ns.

Fig.5 shows that with the increase of pulse on time, the groove width also increases. That is to say, the machining accuracy becomes poor as the pulse on time increases. Increase in pulse on time implies that more time has been allowed to machine the workpiece for a fixed duration, because only during pulse on time material removal takes place. In other words, with the increase of pulse on time, average current density increases which leads to the increase of dissolution efficiency. As shown in Fig.5, dissolution efficiency increases rapidly in the range of pulse on time 40-50 ns, causing a rapid increment of MRR in this zone. With further increase of pulse on time in the range of 50-90 ns, MRR increases less rapidly than in the range of 40-50 ns.
Fig. 5  Variation of groove width with pulse on time.

For illustrating the influence of pulse on time on shape precision, a non-uniform rational B-spline (NURBS) curve, whose model is shown in Fig. 6, was machined at pulse on time of 90 ns and 45 ns respectively as shown in Fig. 7. Because of the maximum MRR at 90 ns, the sharp corners marked in two circles in Fig. 7(a) are caused by overcut at the position of smaller curvature radius. It is clear that the result in Fig. 7(b) is much smoother than that in Fig. 7(a). Good machining localization is the key factor to keep high shape precision. Therefore, in order to keep a good shape precision, it is very import to select a relatively smaller pulse on time to improve the machining location during the machining process. The suggested range of pulse on time in this article is between 40 ns and 50 ns.

(3) Effect of pulse frequency on machining accuracy

Machining conditions of this set of experiments were as follows: electrode diameter of 8 μm, 0.2 mol/L H₂SO₄ electrolyte, pulse on time of 45 ns, machining voltage of 4.5 V, feed rate of 0.2 μm/s and pulse frequency varying from 0.5-2.0 MHz.

Fig. 8 shows that with the increase of pulse frequency, the general trend of groove width rises. Therefore, the machining accuracy becomes poor as the pulse frequency increases. Although the pulse on time keeps unchanged, pulse interval time decreases during a pulse period. It is implied that more time has been allowed to machine the workpiece for a fixed duration with increase in pulse frequency. Dissolution efficiency increases rapidly in the range of pulse frequency 1.0-2.0 MHz, causing a rapid increment of MRR in this zone. During pulse frequency in the range of 0.5-1.0 MHz, MRR increases less rapidly than in the range of 1.0-2.0 MHz. So, the suggested range of pulse frequency in this article is between 0.5 MHz and 1.0 MHz.

4.2. Effect of feed rate on machining accuracy

Machining conditions of this set of experiments were as follows: electrode diameter of 8 μm, 0.2 mol/L H₂SO₄ electrolyte, pulse frequency of 1.0 MHz and machining voltage of 4.5 V, and feed rate varying from 0.1 μm/s to 0.6 μm/s.

It is clear from Fig. 9 that with the increase of feed rate, the groove width decreases. That is to say, the machining accuracy becomes higher as the feed rate increases. Increase of feed rate implies that the smaller inter-electrodes front gap can be achieved. In other words, with the increase of feed rate, average current density around the tool increases which leads to the increase of dissolution efficiency. So, the side gap could be much smaller. As shown in Fig. 9, the groove width decreases rapidly in the range of 0.1-0.2 μm/s, and with the further increase of feed rate in the range of 0.2-0.6 μm/s, the groove width decreases less rapidly than in the range of 0.1-0.2 μm/s. Therefore, the feed rate as high as possible under a steady machining process is proposed for the improvement of the ma-
chining accuracy. In this article, the suggested feed rate is 0.2 μm/s.

4.3. Effect of electrode geometry features on machining quality

As a tool of EMM, the fabrication of tungsten micro electrode is very important. The micro electrodes used in this article are fabricated by electrochemical etching. According to theory of diffusion layer, high current density forms a thicker diffusion layer surrounding the tungsten electrode, which slows down the dissolved speed of the metal. Then, the tungsten electrode would become a reverse conical shape gradually. Otherwise, lower current density can produce micro electrodes with conical shape. There is a relationship between the electrode diameter and electric charge\(^{[11-12]}\). The electrode diameter and working end shape can be controlled by voltage and immersion depth.

(1) Effect of electrode diameter on machining accuracy

Machining conditions of this set of experiments were as follows: 0.2 mol/L H\(_2\)SO\(_4\) electrolyte, pulse frequency of 1 MHz and machining voltage of 4.5 V, feed rate of 0.2 μm/s, and electrode diameter varying from 3 μm to 20 μm.

Fig.10 shows that with the increase of electrode diameter, the groove width increases rapidly. That is to say, the machining accuracy will become much higher if the electrode diameter is very small. As shown in Fig.10, the groove width increases slowly in the range of 3-5 μm, and with further increase of electrode diameter in the range of 5-20 μm, the groove width increases rapidly than in the range of 3-5 μm and varies almost linearly. Therefore, the electrode diameter as small as possible is suggested for the improvement of the machining accuracy. Fig.11 is a scanning electron microscope (SEM) micrograph of a polygonal line with groove width of about 10 μm and electrode diameter of 4 μm.

(2) Effect of working end shape of electrode on machined surface quality

The micro electrodes developed by electrochemical etching are shown in Fig.12. Fig.12(a) shows an electrode with sharp working end, and Fig.12(b) shows an electrode with arch working end. The processing conditions for Fig.12(a) were as follows: initial diameter of 300 μm, machining voltage of 4.0 V, immersion depth of 3 mm, 2 mol/L NaOH solution. The processing conditions for Fig.12(b) were almost the same as those for Fig.12(a) except for machining voltage of 5.0 V.

Experiments proved that machined surface quality could be affected largely by the working end shape of electrode. In order to obtain a qualitative analysis of the machined surfaces, the appearances of the machined surfaces were measured in the cross-sectional profiles which were obtained by three-dimensional profilometer (MicroXAM, ADE, America). The square cavity in Fig.13(a) was machined by an electrode similar to that in Fig.12(a). Because of the excessive concentration of the electric field around the sharp working end, a lot of pits on the machined surface
could be formed. We can see that the bottom surface quality of square cavity in Fig.13(a) is very poor. The cross-sectional shape (A-A) of the poor machined surface is indicated in Fig.13(a). The figure shows the surface topography of the poor bottom has large fluctuation, and the maximum distance between the hills and valleys is more than 4 \( \mu m \). After measurement and calculation, the surface roughness \( R_a \) of A-A cross-section is 0.501 \( \mu m \). It is found that the type of electrode as shown in Fig.12(b) can help to improve the situation. A square cavity shown in Fig.13(b) is fabricated by the latter electrode. The cross-sectional shape (B-B) of the better machined surface is indicated in Fig.13(b). The figure shows the surface topography of the good bottom has little fluctuation, and the maximum distance between the hills and valleys is less than 1 \( \mu m \). The surface roughness \( R_a \) of B-B cross-section is 0.215 \( \mu m \) by measurement. It is clear that the surface quality of cavity in Fig.13(b) is much better.

4.4. Effect of electrolyte composition on machining process

During the above electrochemical processing of anodic dissolution, anodic passivation of nickel in the dilute sulfuric acid could hinder the normal dissolution and cause the process instability. The anodic passivation reaction can be summarized as follows:

\[
\text{Ni} + \text{H}_2\text{O} \rightarrow \text{NiO} + 2\text{H}^+ + 2e
\]

\[
3\text{NiO} + \text{H}_2\text{O} \rightarrow \text{NiO} \cdot \text{Ni}_2\text{O}_3 + 2\text{H}^+ + 2e
\]

The above reaction products of NiO and Ni_2O_3 are the major components of passive film, which is difficult to dissolve and cover on the Ni surface to hinder the reaction. Because of the passive film, the micro-spark occurs from time to time and seriously affects the processing quality.

The passive film can be decomposed by adsorptive action of chlorine ion, and the removal process is as follows:

\[
2\text{H}^+ + \text{NiO} + 2\text{Cl}^-_{\text{ad}} \rightarrow \text{NiCl}_2 + \text{H}_2\text{O}
\]

\[
\text{Ni}_2\text{O}_3 + 2\text{Cl}^-_{\text{ad}} + 6\text{H}^+ \rightarrow 2\text{Ni}^{2+} + \text{Cl}_2 \uparrow + 3\text{H}_2\text{O}
\]

Experiments proved that Chloride ions can largely improve the processing conditions, and reduce the times of micro-spark. So, the optimized electrolyte was chosen as 0.1 mol/L H_2SO_4 + 0.05 mol/L HCl mixed solution in this article.

5. Complex Structures

Fig.14 shows that a complex micro-structure composed of curve and sharp corners was successfully obtained under the following conditions: electrode diameter of 8 \( \mu m \), 0.1 mol/L H_2SO_4 + 0.05 mol/L HCl electrolyte, pulse frequency of 1 MHz, machining voltage of 4.5 V, pulse on time of 45 ns, and feed rate of 0.2 \( \mu m/s \). The cross-sectional shape (C-C) of the machined surface is indicated in Fig.14. Fig.14 shows the bottom surface topography has little fluctuation. After measurement and calculation, the surface roughness \( R_a \) of C-C cross-section is 0.219 \( \mu m \). It is proved that the electrochemical micromachining can achieve high machining location and good surface quality by controlling the machining parameters.
6. Conclusions

Through the experiments and what have been discussed above, some conclusions can be generalized.

(1) An EMM system for achieving micron-sized complex structures is developed in this article.

(2) In order to obtain good machining accuracy and machined surface quality, the following rules should be observed. First, lower machining voltage, smaller pulse on time and minor diameter electrode can be used in the process to improve the machining accuracy. Second, the feed rate as high as possible under a steady machining process is suggested. Third, electrode with arch working end can be used to improve the machined surface quality. Furthermore, acid electrolyte with chlorine ions can be applied in order to reduce times of micro-spark and improve the processing situation due to the activation effect of the chlorine ions.

(3) Successful fabrication of the complex micro-structure proves that electrochemical micromachining is a promising micromachining technique which can be used to process the complex MEMS parts.

References


Biographies:

Liu Yong  Born in 1982, he is a Ph.D. candidate from Nanjing University of Aeronautics and Astronautics. His main research interests are electrochemical micromachining and its automatic control technology.
E-mail: rzliuyong@163.com

Zhu Di  Born in 1954, he is a professor of Nanjing University of Aeronautics and Astronautics. His main research interest is non-traditional machining technology.
E-mail: dzhu@nuaa.edu.cn