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Simulation and Prediction of Small Holes Machined by RCUECM

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Keywords: Rotary combined electrochemical machining (RCUECM); small holes; forming law; simulation machining;

ABSTRACT

One of the ways to improve technological factors in electrochemical machining is by introduction of the ultrasonic vibration of cathode. In order to study the forming law and the course of hole machined by the rotary combined ultrasonic and electrochemical machining (RCUECM), the small holes were processed by the RCUECM with hollow cathode with different machining time, then three-dimensional simulation machining are carried out based on ANSYS CFX using the hollow cathode. Simulation outcomes and experimental outcomes were carried out using the same machining time, the entrance diameter; bottom diameter and machining depth were measured and analyzed afterwards. The comparison results show that as the vibration of the cathode is applied in the simulation, the flow field is similar to the actual one in experiments, when the voltage was applied in the simulation, the couple filed of electric and flow was formed, so based on what was mentioned above, the simulation machining is suitable for describing the course of holes machined by RCUECM in actual. The three-dimensional profiles of holes were obtained by the three-dimensional simulation and were similar to these holes in experiments. Therefore the simulation can be used to predict the profile of parts machined by RCUECM, and it is a reliable method to describe the machining course in RCUECM for the three-dimensional simulation machining, which is helpful for the studying the forming law of the RCUECM.

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INTRODUCTIONS

The material removal principle of electrochemical machining (ECM) is based on the anode electrochemical dissolution. Because ECM is independent of the material hardness and toughness, it is often used to cut materials which are difficult to process with other methods. With the advantages of good surface quality and high material removal rate, ECM is applied to many industries such as automotive, forging dies, electronic equipment, medical devices and so on (Datta, M. et al., 1998; Zhu, D. 1999). However, because of the complex flow field in the inter-electrode gap (IEG), the controllability of the processing precision and stability is poor and there is always irregular dissolution, even produces sparks in the electrochemical machining. For improving the electrolyte circulation and processing quality, the pulse power or the vibration of the cathode are applied in ECM. The electrolyte is updated while there is no machining (Rajurkar, K. P., et al., 1993; Bhattacharyya, B., et al., 2007). The cavitation causing mechanical, thermal, chemical, and biological effects mostly occur on the electrode surface by the ultrasonic waves (Fu X. L., 2005; Gan X. P., et al., 2001; Chen, J. Q., et al., 2005). It is helpful for the high-frequency vibration to update the electrolyte and discharge the processing products, which affected the processing rate and accuracy (Ruszaj A.et al., 2003; Hewidy M. S. et al., 2007; Sebastian S.,2010), there has been some research in the field of micro-fabrication (Zhu Y.W., et al., 2008).

There is electrolyte with high flow rate between the anode and the cathode in the rotary combined ultrasonic and electrochemical machining (RCUECM) and the current is produced along the path of the electrolyte as the voltage is added to the anode and cathode, which allows the electric field to form in order to affect the dissolution rate of anode and the shaping precision (Xu J.W., 2008). In the conventional electrochemical forming machining, the shaping law was mostly studied to design the cathode or predict the shape of anode profile with a specific cathode to amend the cathode (XU J.W., et al., 2008).

Recently, the two-dimensional simulation machining of ECM was reported (Kozak J., et al., 1998; Zhao J.S., et al., 2007; Wang L., et al., 2010; Liu Z.X., et al., 2012) and the computer aided simulation system of electrochemical forming machining with the function of machining simulation, cathode design, machining parameter optimization and so on was developed and it was widely applied on electrochemical machining, electrochemical milling, electrochemical polishing and more fields (Kozak J.,et al., 2000;Kozak J., 2001).

The passivation which affected the dissolution is formed in the ECM. The main style of depassivation contain addition of chemical elements or abrasives, applying pulse power or high pressure electrolyte circulation system and compound machining, etc. The RCUECM is one of the compound machining, the characteristics of the vibration of cathode are:

1) The vibration is helpful for the depassivation on the anode surface;

2) The inter-electrode gap (IEG) is cyclically changed, which improves the local dissolution;

3) The updating of the electrolyte and the discharging of products in the ECM is strengthened, which weakens the effect of temperature and the bubble in the IEG.

The ultrasonic machining is not directly involved in the removal procedure of the anode material in the RCUECM. So the basic forming law of the ECM is suited for the RCUECM. As the ultrasonic action is applied in the ECM, the fluent field and the electric filed is changed. The electrolyte velocity is pulsed changed along the electrolyte channel in the machined area, which is helpful for the products of ECM to discharge. The Coupling simulation of fluent field and electric field has carried out, the velocity and the pressure of electrolyte in the IEG is pulsed changed (Liu Z. X., et al., 2016). The forming law of the small holes machined by RCUECM under the motion state of cathode was analyzed in this research. Based on these, the simulation machining by the three-dimensional was done and the experiments of small holes machined by RCUECM were carried out. The holes machined by the two machining styles respectively were analyzed, which will be the guidance for the research on the RCUECM.

BASIC DIFFERENTIAL EQUATIONS of ANODE in RCUECM

The IEG (Δ) in ECM is the function of time (t) and space(x, y, z), namely $\Delta(x, y, z, t)$. When the equilibrium state appears, the IEG (Δ) is not changed with time (t). The effect factors of the forming law are temperature, composition, concentration of electrolyte, electric field, flow field, electrode polarization, and work piece material and so on, in which the electric field is the decisive factor (Xu J.W., 2008). The essence of the forming law is to gain the dissolution rate of work piece at any point when the machining parameters are certain. According to the Faraday's law, the dissolution rate is proportional to the current density. The distribution of the current density is relative to the electric field. So the forming law is usually described as the spatial and temporal distribution of electric field intensity. Though the electric field is changed complexly in RCUECM, the process is idealized generally and the mathematical model of the forming law is established based on the electric field, then it can be corrected based on the actual processing. For the idealized processing, assumptions are（Xu J.W., 2008; Kang M.,2003）:

1) It is effective for the Ohm's law at the anode surface, cathode surface and electrolyte in IEG;

2) The surface of the anode and cathode are regarded as equipotential surface;

3) The current efficiency (η) is constant during the process;

4) The conductivity of the electrolyte in the IEG is constant;

The equations of the dissolution rate (v_a) and the IEG (Δ) are obtained by the Ohm's Law and Faraday's Law based on these assumptions about the ECM as follow (Xu J.W., 2008):

$$v_a = \eta w i \,, \tag{1}$$

$$\Delta = \eta w \kappa \frac{U - \delta E}{v_a} = \frac{A}{v_a} \,, \tag{2}$$

Where, v_a is the dissolution rate of the work piece (mm/min), Δ is the IEG (mm), U is the voltage between the anode and cathode (V), δE is the sum of the electrode potential of anode and cathode (V), i is the current density (A/mm^2), κ is the conductivity of the electrolyte(S/mm), w is the electrochemical equivalent of volume (mm^3/A·min), η is the current efficiency, A is hyperbolic constant, $A = \eta w \kappa (U - \delta E)$.

There are two kinds of states in the ECM. The state of equilibrium is the steady-state electric field that not relied on the time (t). The state of motion is the non-steady-state that dependent on the time (t), where the dissolution rate is the function of time (t). The basic equations of the forming law of small hole machined by RCUECM were analyzed under the motion state of in this research.

As shown in Figure 1, the solid lines represent the initial profile of the anode and the position of the cathode; the dotted lines represent the new profile of the anode and the new position after time (t) later. When the cathode feed with vibrating, equations can be gained as follow:

$$L = v_c \times t + a \sin(\omega t + \varphi) \,, \tag{3}$$

$$\Delta(t) = y(t) + \Delta_0 - v_c t - a \sin(\omega t + \varphi) \,, \tag{4}$$

$$\frac{d\Delta}{dt}=\frac{dy}{dt}-v_c-a\omega\cos(\omega t+\varphi)=\frac{A}{\Delta}-v_c-a\omega\cos(\omega t+\varphi), \quad (5)$$

$$p=\rho h\alpha=\rho h a\omega^2\sin(\omega t+\varphi), \quad (6)$$

Where, L is the feed distance of the cathode (mm), a is the amplitude of the ultrasonic vibration (mm); ω is the circumferential ultrasonic frequency (rad/s), $\omega=2\pi f$, f is the frequency of the vibration system (Hz); t is time parameter (s); φ is initial phase (rad).Δ_0 is the initial end face IEG (mm), $\Delta(t)$ is the current end face IEG (mm) after machining time t later, v_c is the feed rate of the cathode perpendicular to the work piece surface (mm/min), $y(t)$ is the dissolved length along the direction of the feeding of the cathode, the dissolution of the work piece is v_a and v_a=dy/dt, p is the produced pressure by vibration of cathode(Pa),h is the height of the cathode(m).

Based on the finite element method(FEM), the physical model was dispersed to a large number of element nodes and the processing time was divided to the small time △t. Therefore, the formula 1 was changed as follow:

$$v_{An}=\eta\cdot w\cdot i_{An}, \quad (7)$$

Where, v_{An} is the dissolution rate of the node A_n (X_{An}, Y_{An}, Z_{An}) and i_{An} is the current density of the node A_n. The coordination of the new node named B_n (X_{Bn}, Y_{Bn}, Z_{Bn}) can be gained as follow(Liu Z.X., 2012):

$$X_{Bn}=X_{An}-\Delta t\cdot v_{Anx}=X_{An}-\Delta t\cdot\eta\cdot\omega\cdot i_{Anx}, \quad (8)$$

$$Y_{Bn}=Y_{An}-\Delta t\cdot v_{Any}=Y_{An}-\Delta t\cdot\eta\cdot\omega\cdot i_{Any}, \quad (9)$$

$$Z_{Bn}=Z_{An}-\Delta t\cdot v_{Any}=Z_{An}-\Delta t\cdot\eta\cdot\omega\cdot i_{Any}, \quad (10)$$

Where, i_{Anx}, i_{Any} and i_{Anz} are the components of the current density respectively on the X-axis , Y-axis and Z-axis.

The end face IEG at any period is as follow:

$$\Delta(n)=\Delta_0+a\sin(\omega t+\varphi)-v_c\Delta t+\eta w\kappa\frac{U-\delta E}{\Delta(n-1)}\Delta t \quad (11)$$

The new boundary on the anode surface was established based on these new points B_n (X_{Bn}, Y_{Bn}, Z_{Bn}) connected by the spline curve for the next simulation and the machining curve can be obtained at last.

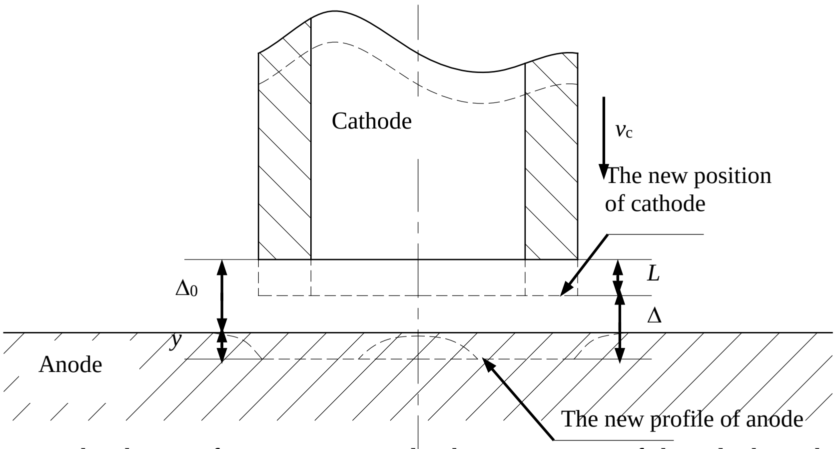


Fig.1 Sketch map of ECM process under the motion state of shaped tube cathode

THREE-DIMENSIONAL SIMULATIONS and MACHINING

Three-dimensional models

In ECM, work piece is dissolved and the gas is produced at the cathode, so the electrolyte is composed of pure electrolyte and insoluble gas. Hence gas-liquid two-phase flow model is applied to analyze the pressure, velocity and gas volume fraction distribution of electrolyte. In order to improve the quality of the grid and reduce the computation time, a quarter of three-dimensional geometrical model is applied as shown in Figure 2, a hollow cylindrical tool with the outer diameter 1.8mm and inside diameter 1.4mm was used. The mesh model was shown in Figure 3, the tetrahedral was used to mesh the grid and the skewness was used to evaluate the quality of the grid. As it is of the qualitative analysis, assumptions are done as follows (Liu Z.X., et al., 2016):

1) Bubbles are uniformly distributed and isotropic in the liquid phase, the gas and liquid phases are incompressible. There is no mass transition between the two phases, and the change of gas phase state obeys the ideal gas state equation. The flow velocity, temperature and pressure of gas phase and

liquid phase are equal on the same cross section. In the analysis process, the rate of hydrogen generation is not considered, and the gas which is insoluble in water is treated uniformly;

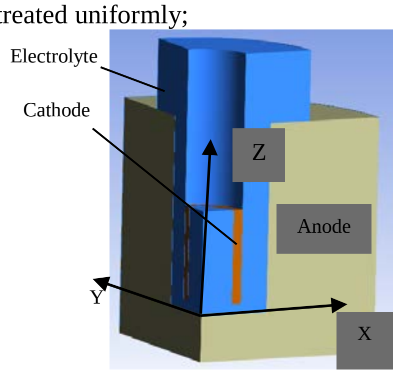


Fig.2 Three-dimensional geometrical modeling

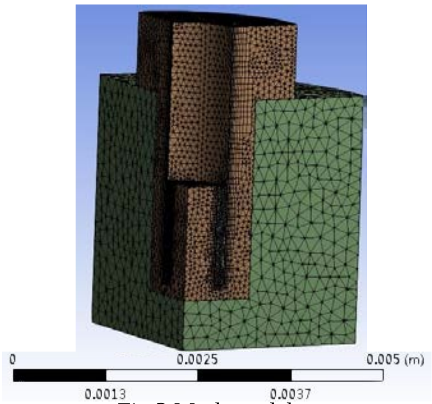


Fig.3 Mesh model

2) The heat exchange between the electrolyte and the cathode and anode is also in equilibrium. The influence of cathode motion on the thermal energy of electrolyte is neglected. The size of tool cathode and work piece anode is relatively small, and the heat transfer between electrolyte, cathode and work piece is neglected. The parameters are no longer a function of time but a function of positions;

3) The effects of gravity and buoyancy are not considered in the simulation. The mixture of electrolyte and water vapor satisfies the following equation:

$$\alpha_e + \alpha_g = 1;$$
$$\rho_m = \alpha_e \rho_e + \alpha_g \rho_g , \qquad (12)$$
$$\mu_m = \alpha_e \mu_e + \alpha_g \mu_g$$

Where, α_e is the volume fraction of pure electrolyte; α_g is the volume fraction of water vapor; ρ_m is density of mixed electrolyte(kg/m^3); ρ_e is the density of pure electrolyte(kg/m^3); ρ_g is the density of saturated vapor(kg/m^3); μ_m is the dynamic viscosity of mixed electrolyte(Pa • s); μ_e is the dynamic viscosity of pure electrolyte(Pa •s); μ_g is the dynamic viscosity of water vapor. Simulation machining is isothermal. It is considered that the dynamic viscosity of pure electrolyte and water vapor is a constant.

4) In the process of machining, the influence of electrolyte produces and bubbles on the conductivity of electrolyte was neglected, and the factors such as electrode polarization and double-layer are ignored. The cathode and anode are all equipotential surfaces. The voltage is set to U_1 and U_2 respectively, ignoring the boundary effect. It is considered that the electric field between electrodes is approximate stable, and the potential distribution in the model meets the requirement of three-dimensional Lap lace equation:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0 , \qquad (13)$$

Where, φ is the electric potential (V); x, y and z are the coordinate values in the model.

The Euler-Euler multiphase flow model is used to solve the flow field simulation. The mixed electrolyte is described by the following equations (Liu Z.X., et al., 2016).

1) Mixed model continuity equation:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla(\rho_m v_m) = \dot{m} , \qquad (14)$$

Where, v_m is the velocity of the electrolyte, $\dot{m}$ is the transformed quality between electrolyte and water vapor due to the cavitation.

2) The momentum equation of the mixed model:

$$\frac{\partial}{\partial t}(\rho_m v_m) + \nabla \times (\rho_m v_m v_m) = -\nabla p + \nabla \times [\mu_m (\nabla v_m) + \nabla v_m^T] + F . \qquad (15)$$

3) Volume fraction equation of gas phase:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \times (\alpha_g \rho_g v_m) = 0 . \qquad (16)$$

Boundary Conditions Setting

There is fluid domain and two solid domains in the finite element model. The boundary conditions such as inlet and outlet are applied in the fluid field, while the tool model and work piece model are solid models, which are mainly used to apply the boundary conditions such as cathode rotation, vibration and processing voltage. Electromagnetic Model models are added to fluid and solid domains, and voltage boundary conditions are set. There are overlapping surfaces among the models, which need to be set up by domain interface. In order to simplify the model, the phase angle is set to zero, and other material parameters and boundary conditions are shown in Table 1.

Tab.1 Boundary conditions

Inlet pressure (MPa)	Outlet pressure （MPa）	Dynamic Viscosity of Electrolyte （Pa•s）	Dynamic Viscosity of Water Vapor （Pa•s）	Conductivity of electrolyte （S/m）	Conductivity of 45 steel （S/m）	Conductivity of water vapor （S/m）	Voltage of cathode （V）	Voltage of anode （V）
0.5	0	0.001	1.84e-5	4.45	1.0e+7	0	0	10

Holes gained by three-Dimension Simulation Machining

The Three-dimension simulation machining was carried out based on the coupled simulation of three-dimensional fluid field and electric field by ANSYS CFX. The electric parameters were applied on the model as the same as these used in the experiments in latter.

The contour of current density on work piece surface after simulation of the initial model was gained as showed in Figure 4 and it is the interface between the upper surface of the work piece model and the bottom of the electrolyte model. As the resistance of the work piece is negligible, it was considered as the machining current density on the interface. The current density below the cathode end face is relatively large and the current density decreases as the distance from the cathode increases. The distribution contours of gas volume fraction at the section of hole was shown in Figure 5, as the vibration of the tool with the amplitude of 30μm was used in the simulation, the gas was formed in the hole and gathered together, that is to say the function of the vibration to the electrolyte was displayed, so there is no need to divide the interval time $\triangle t$ into the integer times of the vibration period and considering the actual machining in the experiments, the interval time $\triangle$t is 15s.

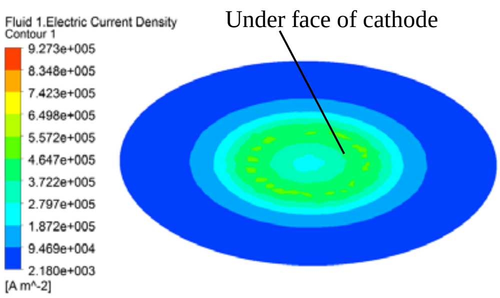


Fig.4 Contour of current density on work piece surface

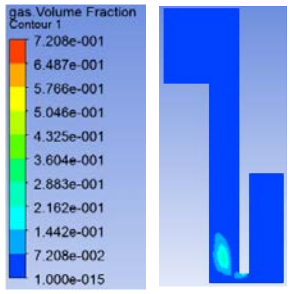


Fig.5 Distribution contours of gas volume fraction at the section of hole

ANSYS CFX has a powerful post-processing function. In the post-processing, the profile curve of the hole was established, and the current density of the hole profile curve was obtained. The three-dimensional coordinate value of corresponding nodes were obtained and exported, then with the interval time $\triangle t$, the new three-dimensional coordinate value of the nodes were calculated according to the equation (8), (9) and (10). The calculated results were imported to the software, and the new surfaces of the hole were formed by the computed data, which was shown in Figure 6, and the two-dimensional profile curve of the hole machined by the three-dimensional simulation machining was shown in the Figure 7. As the hollow cathode was used in the machining, there was small bump at the bottom of the hole in the practical machining and so is in the three-dimensional simulation machining.

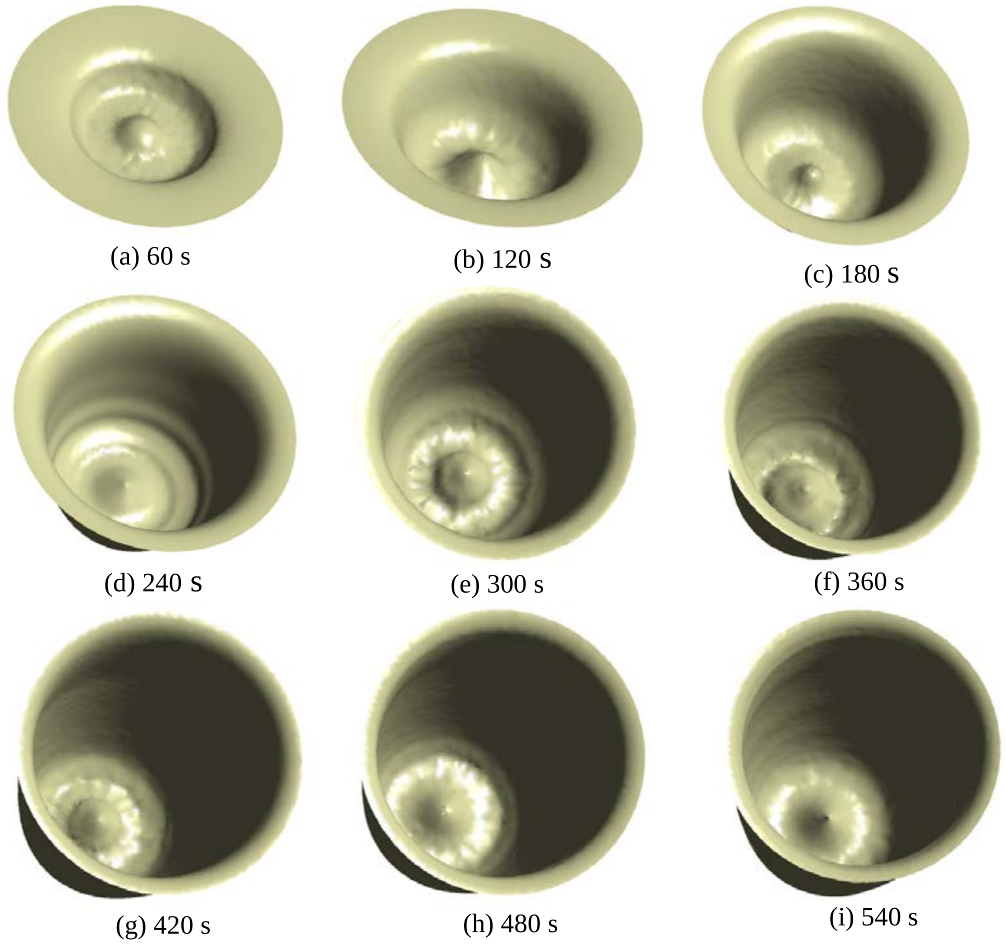


Fig.6 Results of 3D simulation machining

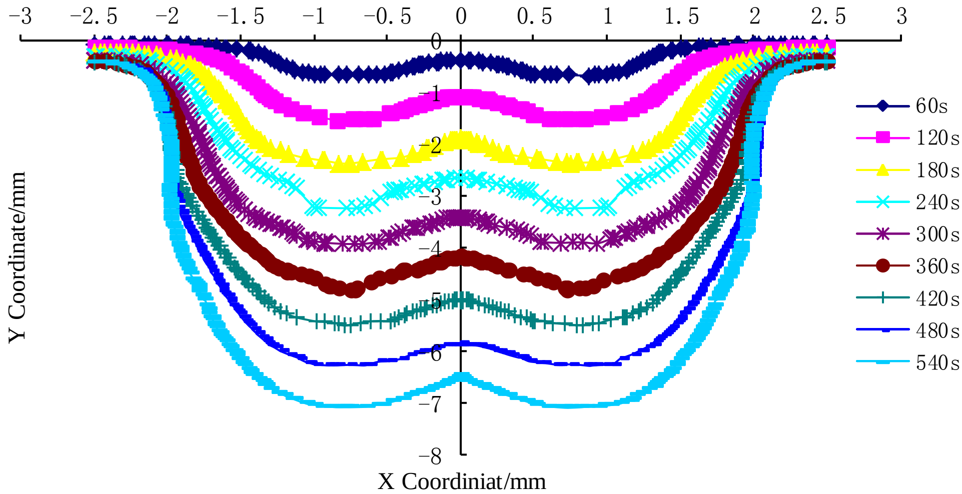


Fig.7 Calculation results of anode surface under η=60% condition by 3D simulation machining

SMALL HOLES PROCESSING EXPERIMENTS

The experiments were carried out using the RCUECM with the same parameters used in three-dimensional simulation; the parameters are shown in Tab.2. The machining time was 60 s, 120 s, 180 s, 240 s, 300 s, 360 s, 420 s, 480 s and 540 s respectively. The actual machined holes were showed in Figure 8.

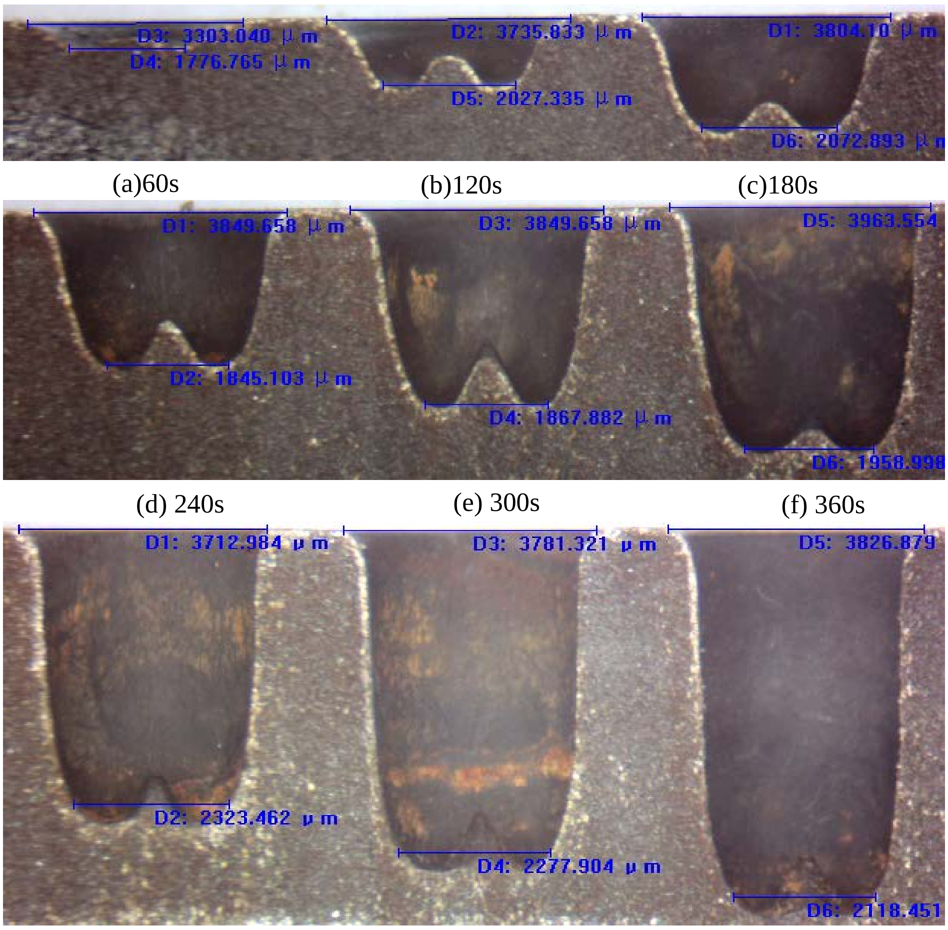
In order to compare with the holes machined in the simulation, the entrance diameter (E.D.), bottom diameter (B.D.) and machining depth (M.D.) was obtained by the software Image-Pro Plus 6.0 which is shown in Tab.3. Based on the actual data, the relative errors were calculated.

Tab.2 Machining Parameters of Small Holes

Voltage (V)	Feed Rate (mm/min)	Speed (r/min)	Bared Length of Cathode (mm)	Initial Gap of end face (mm)	Mass Fraction of Electrolyte ($NaNO_3$%)	Amplitude of vibration (μm)	Temperature of Electrolyte (℃)
10	0.8	600	3.0	0.3	25		35

Tab.3 relative errors of holes

Time (s)	Simulation Machining Value			Experimental Value			Relative errors		
	E.D. (mm)	B.D. (mm)	M.D. (mm)	E.D. (mm)	B.D. (mm)	M.D. (mm)	E.D. (%)	B.D. (%)	M.D. (%)
60	3.220	2.000	0.657	3.303	1.777	0.555	2.5	12.5	18.4
120	3.480	2.160	1.500	3.736	2.027	1.273	6.9	6.6	17.8
180	3.780	2.120	2.350	3.804	2.073	2.083	0.6	2.3	12.8
240	3.960	2.020	3.230	3.850	1.845	2.731	2.9	9.5	18.3
300	4.060	2.040	3.910	3.850	1.868	3.517	5.5	9.2	11.2
360	4.120	1.814	4.760	3.964	1.959	4.350	3.9	7.4	9.4
420	4.140	2.240	5.490	3.713	2.323	5.068	11.5	3.6	8.3
480	4.160	2.220	6.280	3.781	2.278	5.785	10.0	2.5	8.6
540	4.180	2.260	7.080	3.827	2.118	6.503	9.2	6.7	8.9



(a)60s (b)120s (c)180s

(d) 240s (e) 300s (f) 360s

(g) 420s (h) 480s (i) 540s

Fig.8 Sketch map of work-piece

Data in Tab.3 shows the entrance diameter, the bottom diameter and the machined depth of the holes machined by simulation is greater than those holes machined by actual machining. For the entrance diameter of the holes machined by simulation machining, as the spray electric existed and is stronger than that in actual machining, the sizes of the entrance diameter of the holes machined by simulation gradually increase and so is the bottom diameter and machined depth. That is to say, the current efficiency is greater for the experiments. With the smaller current efficiency, the sizes of the holes machined by simulation are closer to the real size in experiments. Comparing Fig.6 and Fig.8, as the tube cathode was used in both processing, the small protruding existed at the bottom of the holes, which can be decreased or even eliminated by the auxiliary tool in the hollow tube (Liu Z.X., et al., 2015). That is to say the simulation machining really reflected the actual machining, and it can simulate the holes or other parts machined by RCUECM, which is helpful for the research and application of the RCUECM in future.

CONCLUSIONS

Based on the electrochemical machining, the cathode is vibrated and rotated, which improves the roundness of the holes, the surface quality and the machining velocity in the RCUECM. The main role of the vibration and rotation cathode was to improve the environment of ECM and destroy the passivation coating produced. The forming law of the holes machined by the RCUECM was analyzed in this research and the simulation machining of three-dimension was carried out. In the three-dimensional simulation, comparing with the experiments, as the vibration and the rotation of the cathode, the pressure, velocity of the electrolyte and the hollow electrode were considered, the holes machined by three-dimensional simulation are similar to the holes machined by the RCUCEM. Therefore three-dimensional simulation can be used to predict the profile of parts machined by RCUECM. Comparing with the values of experiments, the relative error is smaller when the machining time is longer. The profile of holes at different time was displayed, which is helpful for using the three-dimensional simulation to master the forming law and the course of the holes machined by the RCUECM.

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旋轉超聲電解複合加工小孔的模擬與預測

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摘要

陰極施加超聲振動是提高電解加工技術參數的方法之一。為研究旋轉超聲複合加工小孔成型規律和加工過程，採用空心管電極進行了不同加工時間的小孔旋轉超聲電解複合加工試驗，並基於ANSYS CFX 軟體，採用空心管電極，對不同加工時間的小孔分別進行了三維模擬加工。對比兩種方法加工的小孔，測量並分析入口直徑、出口直徑和加工深度。分析結果表明由於在模擬中考慮了陰極振動，電解液流場與實際加工流場更貼近，而在模擬加工中施加電壓，形成了實際加工中電場和流場的耦合場，基於以上分析，三維模擬加工方法是適合描述小孔旋轉超聲電解複合加工過程的，且三維模擬加工中顯示的小孔的三維輪廓與實際加工的小孔輪廓相似，因此該方法可以用來預測旋轉超聲電解複合加工的零件輪廓，是一種描述旋轉超聲電解複合加工過程的可靠方法，這有助於旋轉超聲電解複合加工成型規律的研究。