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Simulation of Electrochemical Maching of Non-cylindrical Pin Hole

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Abstract: Based on the principle of electrochemical machining, a new method for electrochemical machining of non-cylindrical pin hole using multi-segment cathodes is proposed. According to the theory, the parameters needed required on each electrode were calculated. By changing the voltage or current applied to each electrode, the processing shape can be controlled. The simulation experiment was carried out with COMSOL multi-physics coupling software, and the optimal electrolytic gap was obtained. In view of the fact that a straight line appears at both ends of the target machining curve, an electrode is added at both side to achieve the shape requirements. After parameter adjustment, the results of simulation are highly consistent with the target curve, which proves the practicability of the method and provides theoretical support and new ideas for the processing of non-cylindrical pin hole.

1. Introduction

With the improvement of engine power and emission requirements, the piston is subjected to more severe mechanical and thermal loads. Aluminum-silicon alloy materials are difficult to meet requirements [1]. Forged steel pistons have become the new choice of heavy-duty engines. However, the increase of the material strength cause problems with machine tool. For example, the shape of the pin hole machined was far from the requirements [2-3].

For workpieces with complex surfaces and difficulty processing materials, there are two common machining methods. One is traditional machining methods, and the other is nontraditional machining method, including electrochemical machining, EDM, laser machining, and electron beam machining[4]. The processing technology has been quite mature, it can meet most of the work requirements. However, it is difficulty to manufacture some workpieces with poor cutting performance and complicated shapes. Nontraditional machining method is produced in this case. It is not limited by the processing materials, and it does not produce cutting stress. It has been rapidly developed, and it has a great potential to replace traditional machining methods in the field of micro-machining. Now it has been widely used in biomedical and aviation, precision instruments and military fields [5].

As we all known, electrochemical machining method has the advantages of no tool wear, no cutting stress, high productivity, and good surface quality. However, one-electrode machining is inefficient with stray current corrosion, which affects the shape accuracy of the workpiece[6]. This paper proposes multi-segment electrode processing method. The voltage applied to each electrode can be controlled individually. The shape is controlled to machine the desired non-cylindrical shaped holes. The method has the advantages of high processing efficiency. It can also improve the shape accuracy of the processed pin hole.

Through the theoretical analysis, the paper accurately calculates the required variables, and verifies the feasibility by using simulation experiments. By extending the length of the cathode, the requirements of the contours of the two sides of the shaped hole are guaranteed. The simulation results show that the theoretical data is in good agreement with the target curve, which can meet the accuracy requirements of profiled hole machining contours.

2. Principle of Multi-Segment Cathodes Process

Electrochemical machining is a process in which anode materials are dissolved in an external electric field to obtain the desired shape [7]. The cathode tool is connected with the negative electrode of the power source, and the workpiece is connected with the positive electrode of the power source. Between the anode and the cathode is suitable electrolytic gap [8]. In conventional electrochemical machining, the cathode tool is a whole part, and its shape is designed according to the target contour of the workpiece. Due to the interaction of various factors such as electric field and flow field, it is very difficult to design the cathode [9-10]. In this study, an multi-segment cathodes device is adopted, in which the cathode is composed of a plurality of segment electrodes. Each electrode controlled by a separate closed loop is independent of each other, which can be separately stimulated or simultaneously supplied with different voltages by computer control. Each electrode forms a static matrix, and different excitations are also used to machine different shapes.

The schematic diagram of the working principle is shown in Figure 1. The picture shows the traditional electrochemical processing, the cathode is a whole part electrode, and its shape must be designed according to the required processing contour, and the electrode fabrication is difficult. The figure 2 is a new type of electrode used in this study. The cathode is composed of several ring electrodes of the same shape and size. During the process, different magnitudes of voltage excitation are used. The shape can be formed by different amounts of corrosion in the same time. The controller processes the desired profile by switching the sequence and duration of the voltage pulses applied to the multiple electrodes. Each electrode includes a flexible wire and the barrier includes a flexible insulating sheath surrounding each wire.

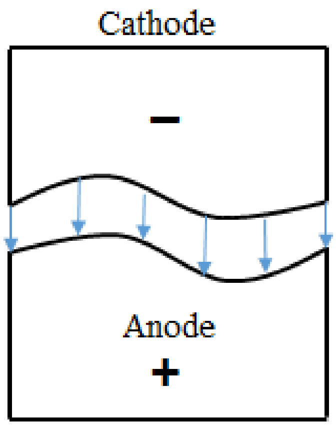


Figure 1: Schematic diagram of traditional ECM

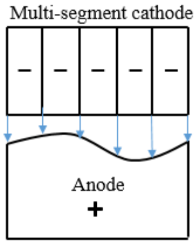


Figure 2: Schematic diagram of multi-segment cathodes ECM

3. Modeling Approach

3.1 Basic rules of ECM

The electric field distribution in the gap of electrochemical machining obeys Faraday's law[11]. At the beginning electrochemical machining process is unstable. After a period of time, it enters the equilibrium state, the parameters in the electric field are independent of time, but only a function of position. The corrosion rate of the anode workpiece in the normal direction is as follows:

$$v_a = \eta\omega i \tag{1}$$

The fixed cathode machining gap theory means that the cathode is not subjected to the feed motion. The cathode has no feed motion, as the processing time becomes longer, the machining gap is larger[12]. The current density is correspondingly reduced, and the anode workpiece is eroded. By balancing the machining gap theory from the upper side, the formula for the relationship between machining time and machining gap during fixed cathode electrochemical machining can be obtained.

$$\Delta = \sqrt{2\eta\omega\sigma U_R t + \Delta_0^2} \tag{2}$$

Where η is current efficiency; U_R is the anode surface potential; Δ0 is the initial machining gap. Because of the different applied voltage, the amount of erosion is different in the same time, and because of the interaction of electric field between the electrodes, the processing contours of each segment can be smoothly connected, and finally the processed curve is formed.

3.2 Simulation Research Based on COMSOL

3.2.1 Target shape

The machining object studied in this paper is the non-cylindrical shaped pin hole. The machining process diagram is as follows. Figure 3 shows that the curve is divided into three sections. The leftmost curve equation is $y = 0.756 \times 10^{-4} x^2$, the middle section is a straight line, and the right end curve equation is $y = 1.020 \times 10^{-4} x^2$.

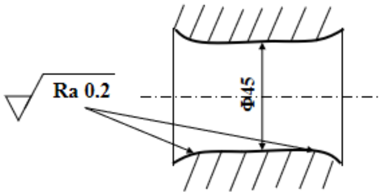


Figure 3: target curve shape

3.2.2 Accuracy Requirements for Special Pin Hole

Requirements of shape accuracy

(1) The control of the transverse waviness of the pin hole is shown in Figure 4 below. The transverse shape of the pin hole shall be smooth transition. Within any 30 ° range, the height difference (H1) between the crest and trough shall not be greater than 1 μm, and the local sudden change value (H2) shall not be greater than 1 μm.

(2) The control of the longitudinal waviness of pin hole, as shown in Figure 5, the longitudinal shape of pin hole shall be smooth transition, the height difference (H1) between adjacent wave crest and wave trough shall not be greater than 1 μm, and the local sudden change value (H2) shall not be greater than 1 μm.

Surface roughness: Ra ≤ 0.2μm.

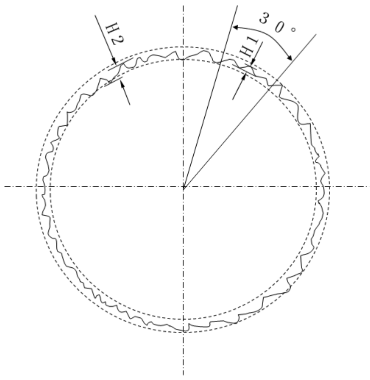


Figure 4: profile requirements of cross section

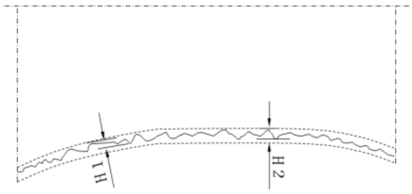


Figure 5: profile requirements of longitudinal section

3.2.3 Simulation Research Based on COMSOL

Considering that it is a rotary body, in order to simplify the calculation, the profile curve is first taken for two-dimensional simulation processing. Firstly, according to the target curve, the cathode is reasonably segmented. The middle segment is a straight segment and the two sides are curved segments. According to the above electrode segmentation, the simulation model shown in Figure 6 below can be obtained:

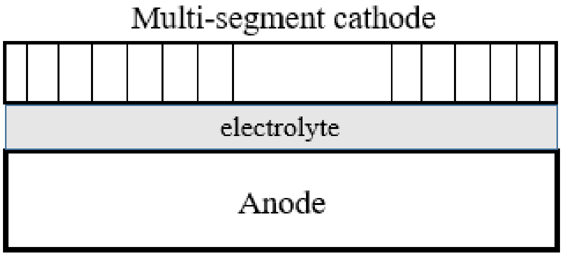


Figure 6: simulation model

Firstly, according to the target curve, the cathode is reasonably segmented. The segmentation is shown in Figure 7: (unit/mm)

Left Segment 11.5 (Total length)							Middle Segment 7 (Total length)	Right Segment 7 (Total length)					
1	2	3	4	5	6	7	8	9	10	11	12	13	14
0.4	1.0	0.9	2.3	2.3	2.3	2.3	7	1.75	1.75	1.75	0.75	0.7	0.3

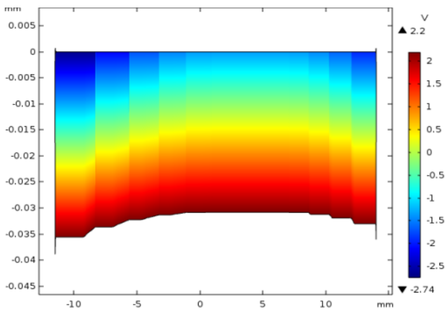
Figure 7: Cathode length of each segment

4. Simulation Result Analysis

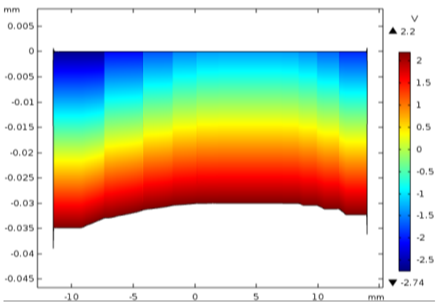
4.1 Influences of Initial Machining Gap on Shape Accuracy

Table 1: Values of simulation parameters

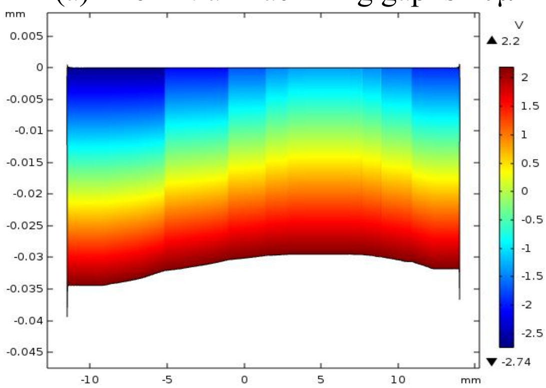
name	Numerical value
Workpiece material	Forged steel
Electrolyte	$NaNO_3$
Mass fraction	20%
Electrolyte conductivity	16.2(S/m)
Current efficiency	1
Mass electrochemical equivalent	1.042g/(A ħ)
Volume electrochemical equivalent	133mm^3/(A ħ)
density	7.85g/cm^3
Molar mass	56g/mol



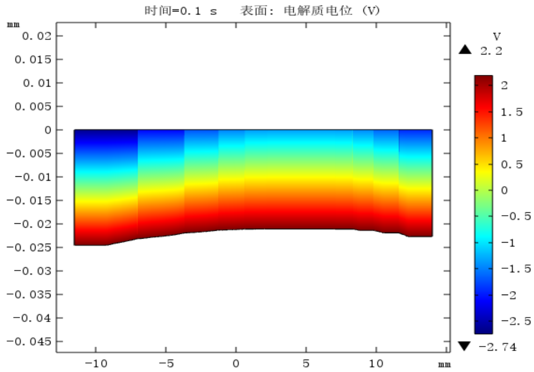
(a) The initial machining gap is 10μm



(b) The initial machining gap is 7μm



(c) The initial machining gap is 4.5μm



(d) The initial machining gap is 3μm

Figure 8: Results under different initial machining gaps

Computer simulation processing parameters are set as shown in Table 1. According to references, the machining gap has an important influence on the processing efficiency and accuracy. To explore the optimal initial machining gap, we make the cathode reasonably segmented and the other parameters consistent. The machining gap is set to 10μm,7 μm, 4.5μm, 3μm. After 0.2s, numerical calculation is performed to obtain the electrolyte potential cloud image of electrochemical machining. It can be seen from Figure 8(a)-Fig. 8(d) that when the machining gap is 10μm, the shape of the workpiece is more serious, especially the over-extension is more obvious at the junction of the electrodes at both ends. The forming precision is poor as well. As the machining gap decreases, the degree of anode step is reduced or even disappears within the error range; However, when it is reduced to 4 μm or less, a curved surface cannot be formed. The anode workpiece is etched at the same speed. The smaller the machining gap, the higher the requirements for the control system, so 4.5μm is the best gap in the actual machining.

4.2 Influence of Cross Electric Field on Forming Precision

Simulation was carried out under the optimal machining gap. By analyzing the results we can found that there is a certain error between the final shape of the anode and the target contour. Especially at the two ends of the anode, a straight line appears, and the left and right ends of the hole are close to the middle portion, and the error is small. The machining curve at both ends of the hole has a large deviation from the theoretical curve. There is a straight line appears near the two ends. The length of the straight segment is consistent with the length of the electrode. Solution: Add an additional electrode at both ends of the target processing curve to form a crossover electric field with the original outermost electrode. The portion of the straight line segment that is inevitable at the outermost end appears outside the target machining curve. This will get the target requirements we need.

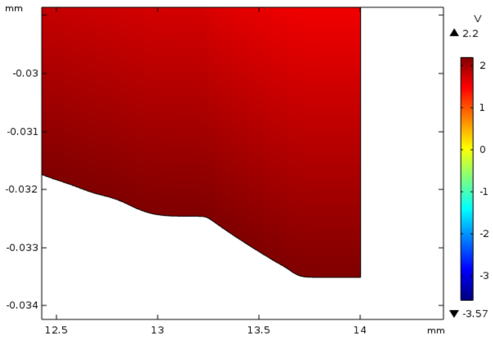


Figure 9: Simulation results before improvement

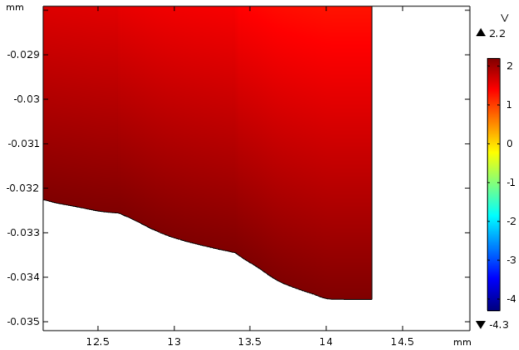


Figure 10: Improved simulation results

Figure 9 and Figure 10 are comparison of simulation results which shows the difference after improvement. The starting point of the modeling is the left end of the middle segment, so the coordinates of the right end of the target curve are 14mm. It can be clearly seen that the electrode is not increased. A straight line segment appears near the end of the right end. It is found that this phenomenon cannot be avoided. Therefore, we can move the straight line segment to the target curve by adding a segment of the electrode. Figure 9 shows that the straight line segment has been completely moved to the target after adding a segment of the electrode. Outside the curve, you can get the desired curve to achieve the best processing results.

After constantly adjusting the parameters, the final result is shown in Figure 11:

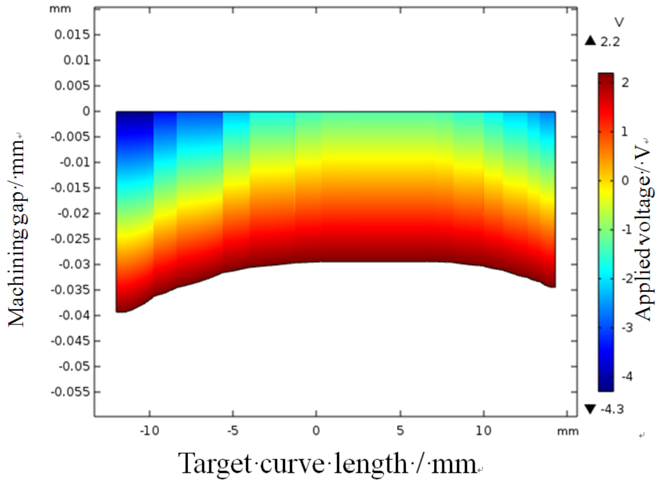


Figure 11: Final electrolyte potential distribution cloud map

In order to analyzing the error of simulated anode surface profile and the target curve, the anode surface curve coordinates are imported into the Matlab software and compared with the target curve in the same coordinate system, as shown in Figure 12:

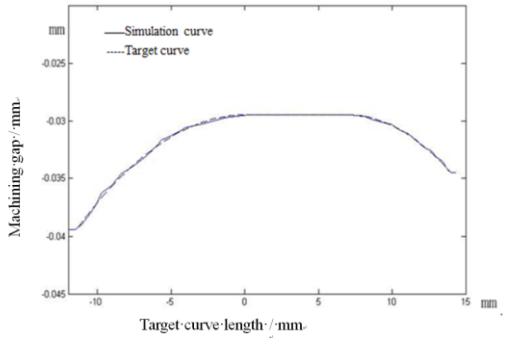


Figure 12: Comparison of simulation curve and target curve

It can be seen that after the electrode is improved by both ends, the final simulation result is highly consistent with the target curve, and the error is controlled within a small range, indicating that the new processing method proposed in this paper is feasible.

5. Conclusions

(1) The multi-segment cathodes ECM proposed in this paper is feasible for processing non-cylindrical pin hole. By calculating the voltage applied to each electrode accurately and adding a reasonable segmentation to the cathode, an arbitrary target curve can be obtained.

(2) The initial machining gap is an important factor affecting the accuracy of the contour of the hole. The larger the machining gap, the worse the contour accuracy. The machining gap is too small

to affect the erosion of the workpiece and to form the required contour. The simulation results show that the initial clearance of 0.0045 mm is better when the electrolyte and the material of the workpiece are fixed.

(3) The linear segment at the end of the electrode is due to the action of a single electric field. We can solve it by adding additional electrodes at the end point. The multi-segment electrode can generate a crossover electric field to process a rounded curve so that the straight line segment can be moved outside the target curve. We have proved the feasibility of this method through simulation.

References

[1] Zhai P, Zhang C Y, Et Al. Research on Machining Principle of Piston Special Pin Hole Based on GMM. Piezoelectricity and Acoustooptic, 2007 (01): 125-128.

[2] Zhou L, Li G. Research on a new type of special-shaped pinhole piston machining method[J]. Science and Technology Innovation Review,2010(28):126.

[3] Chen Y. Research status and prospects of electrolytic processing technology at home and abroad [A]. [C]. China Mechanical Engineering Society Special Processing Branch, Guangdong University of Technology:, 2017:1.

[4] Qin Y F. Multi-field coupling numerical simulation in high frequency microsecond pulse precision electrochemical machining [D]. Hefei University of Technology, 2014.

[5] Lu J, Riedl G , Kiniger B , Et al. Three-dimensional tool design for steady-state electrochemical machining by continuous adjoint-based shape optimization[J]. Chemical Engineering Science, 2014, 106:198-210.

[6] Zhou Y, Bai W, Cao Y,Et al. Design method of surface gear cathode based on standard cathode characteristics [J]. Precision Forming Engineering, 2018, 10 (04): 114-120.

[7] Li Z, Wei D, Di S. Research on Variable Cross-section Holes in Electromagnetic Pulse Processing. Journal of Ordnance Engineering, 2012(02): 197-202.

[8] Liu, Y. Experimental investigation of micro wire electrochemical discharge machining by using a rotating helical tool. Journal of Manufacturing Processes, 2017. 29: p. 265-271.

[9] Niu J, Guo C, Liu Y, Et al. Simulation and experimental study on micro-electrolytic drilling of high-speed spiral electrodes. Modern Manufacturing Engineering, 2017(04): 6-10.

[10] Mi D, Natsu W. Design Of Ecm tool electrode with controlled conductive area ratio for holes with complex internal features [J]. Precision Engineering, 2017, 47:54-61.

[11] Nomura H, Mi D, Natsu W. Fabrication and Experimental Verification of Electrochemical Machining Tool for Complex-shaped Hole [J]. Procedia Cirp, 2016, 42:117-120.

[12] Klocke F, Heidemanns L, Zeis M, Et Al. A Novel Modeling Approach for the Simulation of Precise Electrochemical Machining (PECM) with Pulsed Current and Oscillating Cathode [J]. Procedia Cirp, 2018, 68:499-504.