Simulation and experimental study on improving electrochemical machining stability of high convex structure on casing surface by using backwater pressure

Zhenghui Ge¹, Wangwang Chen¹, Yongwei Zhu¹*¹

¹ College of Mechanical Engineering, Yangzhou University, Yangzhou225000, China
*Corresponding author: ywzhu@yzu.edu.cn
Full list of author information is available at the end of the article

Abstract

Casing parts are regarded as one of the key components in aero-engine components. Most casing parts are attached with different shapes of convex structures, and their heights range from hundreds of microns to tens of millimeters. The use of profiling blocky electrodes for electrochemical machining of casing parts is a widely used method, especially in the processing of high convex structures. However, with the increase of convex structure height, the flow field of machining areas will become more complex, and short circuits may occur at any time. In this study, a method to improve the flow field characteristics of machining area by adjusting the backwater pressure is proposed, the simulation and experiment are carried out respectively. The simulation results showed that the back-pressure method can significantly improve the uniformity of the flow field around the convex structure compared with the extraction outlet mode and the open outlet mode, and then the optimized back-pressure of 0.5 MPa was obtained according to simulation results. The experimental results showed that under condition of the optimized back-pressure parameters, the cathode feed-rate increased from 0.6 mm/min to 0.8 mm/min, and the convex structure with a height of 18 mm was successfully machined. This indicated that the back-pressure method is suitable and effective for the electrochemical machining of high convex structure with blocky electrode.

Keywords Casing parts · Electrochemical machining · Convex structures · Back-pressure method · Blocky electrode

1Introduction

Casing parts are regarded as one of the key components in aero-engine components, which play an important role in connection, load-bearing and support [1-3]. To meet the extreme working conditions of aero-engines, casing parts are usually made of hard-to-cut materials with excellent high temperature performance such as nickel base alloys, etc. Moreover, most of casing parts are thin-walled revolving parts with complex convex structures on the outer surface, and the height of the convex structures varies from several millimeters to tens of millimeters [4,5]. Therefore,
manufacturing these parts is a significant challenge for traditional machining methods due to serious tool wear, high machining cost, and long machining periods [6-9].

Electrochemical machining (ECM) is a non-contact machining that based on electrochemical dissolution of anode materials without limitations to the mechanical properties of the alloys [10,11]. Due to the advantages of high material removal rate, no tool wear, etc., ECM has recently become an important processing method for casing parts[12-14]. Zhu et al. proposed counter-rotating electrochemical machining (CRECM) technology [15-17]. Through the counter rotating movement of the rotary tool electrode and the work-piece, the one-time forming of convex structure on the casing surface can be realized, which effectively improves the machining efficiency and machining quality of the casing parts. Zhang et al. carried out the research on the technology of mask electrochemical machining (M-ECM) of casing parts, broke through the key technologies such as the preparation of the protective film of the rotary surface, and the uniformity control of the flow field, and realized the engineering application for a certain type of casing part [18,19]. However, up to now, the above methods are mainly used for machining of some casing parts with relatively low convexity height.

The use of profiling blocky electrodes for ECM of convex structures on the casing parts is a widely used method, especially in the processing of high convex structure on larger-sized casing parts, due to its high machining efficiency. Li et al. carefully designed a series of working stations and blocky cathode tools. By matching the position of the working stations and the cathode tools, the complex concave-convex structure of the casing parts surface was gradually formed [20]. Sheng et al. carried out the experimental research of ECM of convex structure on the casing surface by using blocky electrode. Based on the experimental results, the optimized flow field and process parameters were obtained, and the machining quality of the casing parts was improved [21,22].

However, it is well known that the flow field is an important factor affecting the machining performance of ECM [23,24]. Compared with other ECM methods such as CRECM and M-ECM, the machining area of blocky electrode method is larger, and the uniformity of flow field within the machining gap is more difficult to control. With the increase of the feed depth of the blocky electrode, the flow field of machining gap will become more complex, and short circuits may occur at any time. Therefore, ensuring the uniformity and stability of the flow field in the machining gap and avoiding the
occurrence of "dead water area" has become the most important factor in the process of ECM of high convex structure with a blocky electrode.

In this paper, the flow field characteristics during ECM of high convex structure with blocky electrode are emphasized, and the back-pressure method is proposed to improve the flow field of machining area. Three modes of extraction, open and back-pressure on the backwater outlet were studied in detail through the CFD software, and the optimized flow field state was obtained. Afterwards, experiments were conducted and the results indicated that the back-pressure method is suitable and effective for ECM of high convex structure with a blocky electrode.

2 Machining principle and flow field characteristics

Fig. 1 shows the schematic diagram of electrochemical machining of high convex structure on the surface of casing parts with a blocky electrode. The blank of casing part is fixed on the working table of the machine tool through a clamp, and is in a proper relative position with the cathode tool through a rotating disk before machining. The electrolyte is pumped into the electrode inlet, and then directly delivered to the machining gap through the internal flow channel. When a stable voltage difference is applied between the cathode tool and the anode work-piece, electrochemical dissolution occurs on the anode surface. The blocky cathode tool is continuously fed along the normal direction of the casing surface with a constant feed rate until the set machining depth is reached.

Fig. 1 Schematic diagram of electrochemical machining of high convex structure.

To realize the back-pressure machining method proposed in this paper, a special block electrode is carefully designed, as shown in Fig. 2. The red area is the main machining area and the rhombic window is the non-machining area to ensure that the anode work-piece surface forms a convex structure. The upper end of the blocky electrode is provided with inlet and back-water outlet. The inlet is responsible for delivering high-speed electrolyte to the entire machining area. The back-water outlet is connected with the window area to adjust the flow field state of the window area. The
rhombic window is an important area to ensure the formation of convex structure, and the flow field state is also more complicated. Therefore, the pressure mode of backwater outlet has an important influence on the flow field state of machining gap and the formation of the convex structure.

3 Theoretical model of flow field

The complex computational fluid dynamics (CFD) model of flow field was established as shown in Fig. 3, the light blue area is the inlet, the orange red area is the backwater outlet and the dark gray area is the outlet. To simplify the simulation process, some assumptions are made as follows [25]: (1) The electrolyte is assumed to be continuous and incompressible. (2) The shearing stress between adjacent layers of fluid of infinitesimally small thickness is taken to be proportional to the rate of shear in the direction perpendicular to the motion.

Fluid flow follows the physics conservation law of momentum conservation and mass conservation equations, which can be described as follows:
\[
\frac{\partial u_i}{\partial x_i} = 0 \tag{1}
\]

\[
\frac{\partial u_i}{\partial x_j} + u_j \frac{\partial u_i}{\partial x_j} = v \left( \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial p}{\partial x_i} - \frac{\tau_{ij}}{\partial x_j} \right) \tag{2}
\]

where \( u_i \) is the \( i \)th component of the mean electrolyte, \( x_j \) is the \( j \)th cartesian coordinate, \( x_i \) is the \( i \)th cartesian coordinate, \( \tau_{ij} \) is the \( ij \)th component of the stress tensor, \( p \) and \( v \) are the mean pressure and kinematic viscosity of electrolyte, respectively.

In the simulation model, the electrolyte flow path is complex and the size changes greatly, the flow field is in a complex turbulent state. In this paper, the renormalization group (RNG) \( k-\epsilon \) turbulence model, which is very suitable for flows that have high streamline curvatures and strain rates, is adopted.

The turbulence kinetic energy equation and dissipation rate equation for the RNG \( k-\epsilon \) turbulence model can be described as follows:

\[
\frac{\partial k}{\partial t} + \frac{\partial u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G - \epsilon \tag{3}
\]

\[
\frac{\partial \epsilon}{\partial t} + \frac{\partial u_j}{\partial x_j} \frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{\epsilon 1} \frac{\epsilon}{k} G - C_{\epsilon 2} \frac{\epsilon^2}{k} - C_\mu \eta^3 \frac{1 - \eta/\eta_0}{1 + \beta \eta^3} \frac{\epsilon^2}{k} \tag{4}
\]

Where \( t \) is the time, \( \eta = \left( k/\epsilon \right) \left( G/v_i \right)^{0.5} \) and \( G = \nu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \).

The values of the constants are \( \sigma_k = 0.7149, \ \sigma_\epsilon = 0.7149, \ C_{\epsilon 1} = 1.42, \ C_{\epsilon 2} = 1.68, \ C_\mu = 0.085, \ \beta = 0.012, \) and \( \eta_0 = 4.38. \)

**4 Simulation and results**

In this paper, the adopted CFD model is shown in Fig. 3. The light blue area is the inlet of electrolyte, which provides the necessary pressure for the machining process. In order to reduce the electrolyte velocity in the convex structure area where does not require machining, the backwater outlet is set to release the electrolyte pressure.

The parameters used in the simulation were set as follows: the inter-electrode gap was 0.5 mm, the pressures of inlet and outlet were 1 and 0 MPa respectively, the extraction outlet pressure was 0.4 MPa, the open outlet pressure was 0 MPa, the
backwater pressure were 0~1 MPa.

4.1 Influence of flow mode on the flow field

In this paper, three modes of extraction outlet, open outlet and back-pressure outlet are designed to obtain a better flow field state. Fig.4 shows the flow field in the machining gap with an outlet pressure of 0 MPa, extraction pressure of 0.4 MPa, and back-pressure of 0.4 MPa. It can be seen that there is an obvious low-speed area around the convex structure (especially the upper edge area) under the extraction outlet mode and the open outlet mode, which will cause uneven corrosion in the machining area. In contrast, the flow field of the convex edge region is significantly improved when the back-pressure mode is applied. Therefore, it can be concluded that the back-pressure outlet mode is beneficial to improve the flow field state of the machining gap and enhance the uniformity and stability of the machining process compared with the extraction outlet mode and the open outlet mode.

![Fig. 4 Electrolyte velocity distribution of machining gap with different flow mode.](image)

4.2 Influence of backwater pressure on the flow field

In this section, the flow field of machining gap under different back-pressures are studied in detail. Fig. 5 shows the electrolyte velocity distribution of the machining gap at back-pressures of 0.2, 0.6 and 1 MPa, respectively. It can be seen that with the increase of back-pressure, the flow field around the convex structure is also improved.

![Fig. 5 Electrolyte velocity distribution of machining gap with different backwater pressure.](image)
Fig. 5 Electrolyte velocity distribution of machining gap with different back-pressures.

To better explain the above phenomena, this paper establishes the spline curves of the top area and the surrounding area of the convex structure (as shown in Fig. 3), and extracts the electrolyte velocity parameters. Fig. 6 (a) displays the electrolyte velocity distribution of the spline curve 1 around the convex structure under different back-pressure. It can be seen that when the back-pressure is less than 0.4 MPa, the electrolyte velocity around the convex structure is less than 4 m/s, which can be considered as a dangerous area that may cause short circuit. With the increase of back-pressure, the electrolyte velocity of dangerous area is improved, and the overall velocity of curve 1 is also increased accordingly. Fig. 6 (b) shows the electrolyte velocity distribution of the spline curve 2 on the top of convex structure with different back-pressure. It is obviously that, when the back-pressure is greater than 0.6 MPa, the electrolyte velocity on the top area of the convex structure is already greater than 5 m/s, which indicates that there may be large stray corrosion on the top of convex structure. In summary, the back-pressure method can improve the flow field state of the machining gap, but too high back-pressure will cause excessive stray corrosion in the top area of convex structure that is undesirable during processing. Therefore, the back-pressure of 0.5MPa will be applied preferentially in the following experiments.

Fig. 6 Electrolyte velocity distribution contours in convex structure area of machining gap.

5 Experimental verification

To further verify the effectiveness of the proposed method in this paper, experiments of ECM of high convex structure on a certain casing part surface were also carried out. The experimental set-up consists of tool motion control system, electrolyte circulation system, power supply system, and current direction system, as shown in Fig. 7(a). The cathode fixture is made of fiber-reinforced plastic material, the work-piece
Fixture is made of stainless steel material, and the assembly site for machining process is shown in Fig. 7(b). In the machining process, the outlet is an open outlet with a constant pressure of 0 MPa, the backwater pressure outlet is an adjustable outlet. The conditions and parameters of the experiments are given in Table 1.

![Diagram of experimental set-up and assembly site for ECM process.](image)

**Fig. 7** (a) schematic diagram of experimental set-up; (b) assembly site for ECM process.

| Parameter                  | Value       |
|----------------------------|-------------|
| Workpiece material         | Nickel-based superalloy |
| Cathode material           | Stainless steel |
| Applied voltage (V)        | 30          |
| Electrolyte inlet pressure (MPa) | 1          |
| Electrolyte outlet pressure (MPa) | 0          |
| Backwater outlet pressure (MPa) | 0.5        |
| Electrolyte conductivity (mS/cm) | 150        |
| Electrolyte temperature (°C) | 30          |

Fig. 8 shows the machined samples under different conditions. For the machined sample under the condition of open outlet mode with the feed rate of 0.6 mm / min, short circuit occurs when the feed amount is deep, as shown in Fig. 8 (a). The blocky electrode tool is also damaged as shown in Fig. 9. Fig. 10 shows the current signal collected during machining. It can be seen that the machining time is about 14 minutes, and the corresponding convex structure height is about 8.4 mm, which is significantly higher than that obtained by other electrochemical machining methods such as CRECM and M-ECM etc [10,11]. This illustrates that the blocky electrode method has a significant advantage in the machining of the high convex structure on the surface of casing parts.
Fig. 8 The machined samples: (a) open outlet mode with feed rate of 0.6 mm/min; (b) back-pressure outlet mode with feed rate of 0.8 mm/min and back-pressure of 0.5 MPa.

Fig. 9 Short circuit region of cathode under open outlet mode with feed rate of 0.6 mm/min.

Fig. 8 (b) shows the machined sample under the condition of back-pressure mode with the back-pressure of 0.5 MPa. The feed rate is increased to 0.8 mm/min and the machining time is extended to 23 minutes. The forming height of the convex structure is about 18 mm, which is more than twice the forming height of the open outlet mode, and the forming contour is very sharp. The results fully indicate that the back-pressure method can significantly improve the stability during the electrochemical machining high convex structure with blocky electrode, and greatly increase the forming height of convex structure. This conclusion is in good agreement with the simulation results in section 4, which further proves that the back-pressure method is feasible and reliable in the ECM of high convex structure by using blocky electrode.
6 Conclusions

This paper focuses on the flow field characteristics during the electrochemical machining of high convex structure on the surface of casing parts. According to the simulation and experiment results, some conclusions can be drawn as follows:

1) The simulation experiments of three modes were carried out respectively. The results show that the back-pressure mode can significantly improve the uniformity of the flow field around the convex structure and eliminate potential dangerous areas compared with the extraction outlet mode and the open outlet mode.

2) The back-pressure mode was specially studied, and the results show that with the increase of the back-pressure, the flow field around the convex is significantly improved, but the velocity at the top of the convex is also significantly increased, which may aggravate the unnecessary stray corrosion. Then, the optimized back-pressure of 0.5 MPa is obtained according to simulation results, which can realize uniform and stable distribution of flow field in machining area.

3) Experiments were conducted to verify the effectiveness of the simulation results. The experimental results show that under condition of the optimized back-pressure parameters, the cathode feed-rate increased from 0.6 mm/min to 0.8 mm/min, and the convex structure with a height of 20 mm was successfully machined. The results indicated that the back-pressure method is suitable and effective for the electrochemical machining of high convex structure with blocky electrode.

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Authors’ Contributions

ZG was in charge of the whole trial; WC and YZ wrote the manuscript; YZ provided guidance and discussion in theory. All authors read and approved the final manuscript.
Authors’ Information

Zhenghui Ge, born in 1980, a lecturer and a master tutor at College of Mechanical Engineering, Yangzhou University. He received his PhD degree from Nanjing University of Aeronautics and Astronautics. His main research interest is electrochemical machining. E-mail: zhge@yzu.edu.cn

Wangwang Chen, born in 1997, is currently a master candidate at College of Mechanical Engineering, Yangzhou University. E-mail: 488316662@qq.com

Yongwei Zhu, born in 1966, a professor and a PhD supervisor at College of Mechanical Engineering, Yangzhou University. He received his PhD degree from Nanjing University of Aeronautics and Astronautics. His main research interest is non-traditional machining. E-mail: ywzhu@yzu.edu.cn

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Competing Interests

The authors declare that they have no competing interests.

Author Details

1 College of Mechanical Engineering, Yangzhou University, Yangzhou225000, China.

Reference

[1] J Wang, M Luo, B H Wu, et al. A trochoidal path planning method of cycloid rough machining trajectory of aeroengine casing. Acta Aeronaut Astronaut Sinica, 2018, 39(6):216-227.
[2] D Y Wang, Z W Zhu, B He, et al. Counter-rotating electrochemical machining of a combustor casing part using a frustum cone-like cathode tool. Journal of Manufacturing Processes, 2018, 35:614-623.
[3] E Poursaeidi, A Kavandi, K Vaezi, et al. Fatigue crack growth prediction in gas turbine casing. Engineering Failure Analysis, 2014, 44: 371–381.
[4] CM Wang. Machining technology of casing. Beijing: Science Press, 2018, (in Chinese).
[5] B He, D Y Wang, Z W Zhu, et al. Research on counter-rotating electrochemical machining of convex structures with different heights. The International Journal of Advanced Manufacturing Technology, 2019 (10):3119-127.
[6] S Bolsunovskiy, V Vermel, G Gubanov, et al. Thin-walled part machining process parameters optimization based on finite-element modeling of workpiece vibrations. Procedia CIRP, 2013, 8:276-80.
[7] Y Y Gao, J W Ma, Z Y Jia, et al. Tool path planning and machining deformation compensation
in high-speed milling for difficult-to-machine material thin-walled parts with curved surface. The International Journal of Advanced Manufacturing Technology, 2016, 84:1757-67.

[8] J Kohler, T Grove, O Maib, et al. Residual stresses in milled titanium parts. Procedia CIRP, 2012, 2: 79–82.

[9] R M'saoubi, D Axinte, S L Soo, et al. High performance cutting of advanced aerospace alloys and composite materials. CIRP Annals, 2015, 64(2): 557–580.

[10] F Klocke, M Zeis, A Klink, et al. Experimental research on the electrochemical machining of modern titanium- and nickel-based alloys for aero engine components. Procedia CIRP, 2013, 368-72.

[11] J Sun, W Chen, J L Song, et al. Fabrication of Superhydrophobic Micro Post Array on Aluminum Substrates Using Mask Electrochemical Machining. Chinese Journal of Mechanical Engineering, 2018, 31(1):1-7.

[12] K P Rajurkar, D Zhu, J A Mcgeough, et al. New developments of electro-chemical machining. CIRP Annals, 1999, 48(2): 567–579.

[13] Y D Wang, Z W Zhu, N F Wang, et al. Effects of shielding coatings on the anode shaping process during counter-rotating electrochemical machining. Chinese Journal of Mechanical Engineering, 2016, 29(5):971-976.

[14] Y C Ge, Z W Zhu, Y W Zhu. Electrochemical Machining of Nickel-based Cast Casing using a Cylindrical Rotating Electrode. International journal of electrochemical science, 2019, 14(9): 8439-8449.

[15] Z W Zhu, D Y Wang, Bao J, et al. Cathode design and experimental study on the rotate-print electrochemical machining of revolving parts. The International Journal of Advanced Manufacturing Technology, 2015, 80:1957-63.

[16] D Y Wang, Z W Zhu, D Zhu, et al. Reduction of stray currents in counter-rotating electrochemical machining by using a flexible auxiliary electrode mechanism. Journal of materials processing technology, 2017, 239:66-74.

[17] D Y Wang, Z W Zhu, H R Wang, et al. Convex shaping process simulation during counter-rotating electrochemical machining by using the finite element method. Chinese Journal of Aeronautics, 2016, 29(2):534-541.

[18] H Y Li, M Q Zhang, J Feng, et al. Development and application of mask electrochemical machining technology. Aviation manufacturing technology, 2015, 58(23):57-60.

[19] Pan ZF, Zhang MQ, Cheng XY, Li HY (2012) Research on High Efficient Electrochemical Machining Technology of Gyroscopic Processing Complex Concavo-Convex and Large Moulding Surface. Aero Manuf Tech 000(001):108-11.

[20] N H Li, J Liu, H He. An electrochemical machining method for Aeroengine case profile. CN103624347A, (in Chinese).

[21] W J Sheng, B Xu. Technological test of electrochemical machining of aero-engine casing. Electromachining Mould, 2010, 2:52-9. (in Chinese)

[22] B Xu, W J Sheng. Experimental study on electrochemical machining of casing profile. Electromachining Mould, 2011, 04:40-2.

[23] JZ Li, D Y Wang, D Zhu, et al. Analysis of the flow field in counter-rotating electrochemical machining. Journal of Materials Processing Technology, 2019, 275:116323.

[24] L Tang, X Feng, K G Zhai, et al. Gap flow field simulation and experiment of electrochemical machining special-shaped inner spiral tube. Int J Adv Manuf Tech, 2019, 100:2485-93.

[25] D Zhu, D Zhu, Z Y Xu, et al. Investigation on the flow field of W-shape electrolyte flow mode in electrochemical machining. Journal of Applied Electrochemistry, 2010, 40(3):525-532.