Analysis and test of conductive shaft of large horizontal NC ECM machine tool

Lin Tang · Yaze Zheng · Chengjin Shi · Lifeng Zhang · Zhao Wang

Received: 26 October 2021 / Accepted: 23 April 2022 / Published online: 5 May 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
In order to solve the problems of serious heating and easy ablation of conductive shaft in electrochemical machining of special-shaped deep hole with large aspect ratio, the two schemes of single-sided copper bar and symmetrical copper bar of conductive shaft are studied by ANSYS software. By establishing the thermoelectric coupling model of the conductive shaft, the distribution law of temperature field and thermal deformation of conductive shaft under different working conditions is analyzed. The conductive shaft structure based on symmetrical copper bar scheme is determined. Monitoring points are set at the key parts of the conductive shaft, and the temperature field distribution is verified by using the data acquisition card. The temperature acquisition results are consistent with the simulation results. Through the machining test of special-shaped inner spiral deep hole parts with large aspect ratio, the results show that under the conditions of working current of 15 000 A, feed rate of 5 mm/min, and continuous machining for 14 h, the forming accuracy of the workpiece is ±0.15 mm and the surface roughness is better than Ra0.8 μm. The performance of the conductive shaft is stable and meets the actual processing requirements. The heat dissipation performance of the conductive shaft is optimized by providing air flow on the upper surface and side at the same time.

Keywords ECM machine tool · Conductive shaft · Thermal-electrical coupling mode · Temperature field

1 Introduction
The special-shaped inner spiral deep hole parts with large aspect ratio are widely used in weapons and equipment, petroleum drilling and production, and other fields [1–3]. Due to high material hardness and complex inner spiral structure, traditional processing method cannot meet the actual needs. While electrochemical machining has the advantages of not limited by material mechanical properties, no cutting stress, and high machining efficiency, it has become an irreplaceable processing method for such parts [4–10]. As the core component of horizontal NC ECM machine tool, the rationality of its structure and performance has a great impact on the reliable processing of the machine tool. Especially under the processing conditions of small gap, large current, and high flow rate, the ECM machine tool can realize long-term stable, reliable, high-precision, and high-efficiency processing.

Many scholars have carried out a lot of research work on the existing conductive shaft with serious heating, large structural deformation, and even ablation and shaft holding. In terms of processing technology, some scholars put forward the compound machining technology of EDM and ECM-lapping, which improves the surface roughness of the hole [11]. Some scholars optimized the processing parameters, realized the stability of the machine tool in actual processing, and improved the efficiency of electrochemical machining [12–15]. Other scholars optimized the cathode movement path to improve the quality of electrochemical machining [16]. The special machining method combined with electrochemical machining and other machining methods had attracted the attention of relevant researchers and ensured the reliability of the machine tool [17]. In terms of machine tool design, literature [18] mainly studied the
performance of horizontal ECM machine tool and optimized the performance. Document [19] conducted research on machining parts with complex inner surface using ECM technology. Through in-depth research on ECM, researchers combined ECM machine tools with the computer field, and used computer-aided technology to complete the design of ECM cathode [20–24]. In view of the complex machining surface of parts, some scholars have realized the application of ECM rifling in practical production [25, 26]. Document [27] constructed a knowledge-based system to realize the intelligent selection of ECM parameters in combination with the characteristics of machine tools and machined workpieces. Some scholars had developed a desktop machine tool prototype called “the ion controlled desktop machine tool.” The machine tool could automatically change the resistance of machining fluid and carry out complex machining and continuous complex machining on the same machine tool at the same time. [28]. Professor Fan [29] developed a horizontal two-axis linkage NC ECM machine tool for the spiral machining of deep hole parts with large aspect ratio. The forming accuracy was ±0.07 mm with a surface roughness of Ra0.8 μm. Literature [30] designed a small magnetic drive ECM. The strength and deformation of ECM machine tool were analyzed. High-precision machining of holes, surfaces, and other shapes could be realized. Experiments show that the device meets the design requirements. ECM machine tools are developing towards large scale, intelligent, and high precision [31–34].

Aiming at the problem of serious heating and even ablation of the existing conductive shaft, this paper proposes an overall design structure of the conductive shaft based on the symmetrical copper bar power transmission scheme, which is suitable for large horizontal NC ECM machine tools. By establishing the thermoelectric coupling model of the conductive shaft, the temperature field of the conductive shaft was simulated and analyzed, and the distribution law of the temperature field of the conductive shaft under different working conditions was studied. Finally, the designed conductive shaft was applied to the large horizontal NC ECM machine tool to verify the reliability of the structural design of the conductive shaft.

2 Structural design of conductive shaft

The conductive shaft structure of large horizontal NC ECM machine tool is mainly composed of power introduction part, support part, rotary sealing part, and other accessories. All parts cooperate with each other to complete the functions of conductive shaft, such as conduction, rotation, and sealing.

2.1 Overall structure of conductive shaft

The threaded hole is preset on the base plate, and the support assembly is fixed on the floor through the connection between the bolt and the threaded hole. During installation, the base plate passes through the conductive shaft body and adjusts the position to ensure that the support assembly can support the conductive shaft. The support assembly is fixed on the floor through bolts to complete the overall installation of the conductive shaft. Finally, the elastic force of the carbon brush holder is debugged so that the shaft can be rotated while the carbon brush is pressing the axis of the conductive shaft. The overall scheme of the conductive shaft is shown in Fig. 1.

2.2 The supporting structure

In the conductive shaft device, the support part is mainly used to support the conductive shaft and ensure that the conductive shaft can complete the predetermined rotation function. The support assembly is used to support and rotate the conductive shaft body. The support assembly is composed of main shaft support, bearing, upper support cross bar, and support pull rods on both sides, and is fixed with nut main shaft support. The structure can realize the accurate positioning of the conductive shaft body, adjust the position of the conductive shaft body by relying on the bolts on the support, and facilitate maintenance and disassembly while
completing the support and rotation function of the conductive shaft.

2.3 The rotary seal structure

The sealing structure of the conductive shaft adopted the combination of mechanical seal and packing seal to ensure the reliable sealing of the conductive shaft in the working process. The sealing structure is shown in Fig. 2. The primary seal of the sealing device is mechanical seal, which adopts the combination of moving ring and static ring. The moving ring is pressed on the bushing according to the elastic force and rotates with the conductive shaft. The static ring is in close contact with the outer cavity shell of the rotary sealing structure by means of tension, and remains relatively stationary. The contact surface of the two will have a layer of dense liquid film, which reduces the friction between the dynamic ring and the static ring. Realize the sealing and complete the preset rotation function at the same time. The secondary packing seal of the sealing device is the packing seal, and the filler is organic synthetic fiber and carbon fiber, which is conducive to the stable operation of the rotary sealing device.

2.4 The power transmission structure

The circuit designed in this paper is to control the rotation of one end and the static stable and reliable power supply at the other end. The carbon brush conduction is to press the carbon brush on the circumferential surface of the conductive shaft by using the elastic force. And the carbon brush is fixed on the base plate to realize the power supply between the fixed part and the relative rotating part. The schematic diagram of the carbon brush power supply scheme is shown in Fig. 3.

Changing the number of carbon brushes or base plates can provide different sizes of current with high flexibility. When installing the carbon brush holder, the angle of the

![Fig. 2 The seal structure diagram](image-url)
carbon brush holder can be adjusted to make it at a certain angle with the normal direction of the conductive shaft body, so that the force on the carbon brush is more uniform in the process of rotation and the whole rotation process is more stable. The specific way of using carbon brush to lead electricity is to draw the current from the negative pole of the power supply, enter the power leading device through the cable, and connect the carbon brush and conductive shaft with the current by relying on the base plate. Finally, the current on the conductive shaft is guided to the cathode by the pull rod. Set the parameters of conductive shaft, substrate, and carbon brush structure, as shown in Table 1.

Two placement schemes of single-sided copper bar and symmetrical copper bar are proposed. The carbon brush holder is simplified into a carbon brush. The parameters in Table 1 are used for modeling. The number of substrates is six. And the simplified three-dimensional model is shown in Fig. 4.

**Table 1** Main parameters of conductive shaft

| Structure | Conductive shaft | Substrate | Carbon brush holder |
|-----------|------------------|-----------|---------------------|
| Name      | Internal diameter | External diameter | Length | Length | Height | Width | Length | Width | Thickness |
| Size (mm) | 65               | 150       | 500     | 360    | 380    | 10    | 10     | 5     | 8         |
The placement scheme of single-sided copper bar is shown in Fig. 4a. It has relatively simple structure and convenient assembly with base plate and carbon brush. Since the overall structure of conductive shaft will change with the feed device, the connection between single-sided copper bar and external power supply is convenient and has obvious advantages in economy and practicability. On the contrary, the symmetrical copper bar placement scheme shown in Fig. 4b has complex structure and assembly. Besides, the connection with the cathode of the power supply is cumbersome. Now, the temperature field is simulated by two power introduction schemes under different working conditions. And the structure of the conductive shaft is determined.

3 The temperature field simulation of conductive shaft

3.1 Establish the temperature field model

When analyzing the temperature field of conductive shaft structure, in order to reduce the amount of calculation and improve the calculation accuracy, it is necessary to simplify or delete the structure independent of temperature field. The temperature field simulation is carried out according to the physical three-dimensional model established in Fig. 4. Only the parts with current passing through during the processing are considered. The model mainly includes conductive shaft, substrate, carbon brush, and copper bar.

The temperature field of conductive shaft is simulated and analyzed by ANSYS software. And the thermoelectric coupling model of conductive shaft is established. The conductive shaft and carbon brush materials are set as red copper and graphite respectively, and their parameters are shown in Table 2.

Mesh the geometric model and set the surface contact coefficient to simulate the conductive efficiency between the carbon brush holder and the substrate and between the carbon brush holder and the conductive shaft body in the actual conductive process. The positions where the conductive shaft often fails are in the contact area between the carbon brush and the conductive shaft body. In order to accurately analyze the current situation of these positions during operation, these positions are divided in detail. Conventional free tetrahedral mesh is selected for other areas, and the division results are shown in Fig. 5.

3.2 Effect of processing time on temperature of conductive shaft

The transient temperature field of the conductive shaft is analyzed. The duration of electrochemical machining, a complete workpiece, is 8 h, which is divided into three stages: stage I, the time step is set as 10 s for the duration

| Materials   | Density (g/m³) | Specific heat capacity (J/ (Kg·K)) | Thermal conductivity (W/(m·K)) | Elastic modulus (GPa) | Poisson ratio | Coefficient of linear expansion (10⁻⁶/K) |
|-------------|----------------|-----------------------------------|--------------------------------|-----------------------|--------------|---------------------------------------|
| Red copper  | 8300           | 385                               | 401                            | 110                   | 0.34         | 18                                    |
| Graphite    | 2250           | 960                               | 173                            | 71                    | 0.308        | 23.6                                  |
of 600 s; stage II, the time step is set to 30 s for the duration of 3 000 s; stage III, the time step of 180 s for the duration of 25 200 s. The temperature field simulation and thermal deformation of the conductive shaft are carried out under the conditions of working current 20 000 A and the ambient temperature of 23 °C. Taking the conductive axis structure of the symmetrical power transmission scheme as an example, the boundary conditions shown in Fig. 6 are set.

The section transient temperature field is shown in Fig. 7. The temperature at the front end of the conductive shaft is greater than that at the rear end of the conductive shaft, and there will be an obvious temperature rise at the positions connected with the conductive shaft body, which may be due to the collection of current at these positions. The temperature of the conductive shaft increases with time. After 2 400 s, the distribution of the overall temperature field of the conductive shaft does not change and reaches a stable state.

### 3.3 Effect of processing current on temperature field of conductive shaft

The electric conduction of the conductive shaft is mainly realized by installing the conductive copper bar at the base plate of the conductive shaft. When setting the boundary conditions, as shown in Fig. 8, the application of 20 000 A current is taken as an example and the ambient initial temperature is set to 23 °C. The side of the conductive copper bar is the position where the current is applied. The current flows from the copper bar to the base plate, and then it flows into the shaft body of the conductive shaft with the carbon brush. It is necessary to set the front end face of the conductive shaft to zero voltage, so as to ensure the flow direction of current.

The electric field distribution of two different power transmission schemes under stable state is shown in Fig. 9. The electric field of the single-sided power transmission scheme is shown in Fig. 9a, and the area with the largest...
current density is generated at the position of the connecting substrate of the power transmission copper bar. It can be seen in Fig. 9b that the area with the maximum current density of bilateral power transmission also occurs at the position where the current flows from the power transmission copper bar to the substrate. Different from...
single-sided power transmission, the scheme of symmetrical power transmission copper bar can make the electric field evenly distributed on both sides of the substrate and greatly reduce the maximum current density.

Set the working conditions with the processing current of 12,000 A, 15,000 A, and 20,000 A, respectively, and analyze the temperature field of the conductive shaft structure. After reaching the stable state, the variation law of the conductive shaft temperature field of the two power transmission schemes on the processing current is shown in Figs. 10 and 11 respectively. It can be seen from Fig. 10 that with the increase of the processing current of the conductive shaft, the temperature of the overall structure shows an upward trend. And under different processing current conditions, the temperature at the front end of the conductive shaft is much greater than that at the rear end of the conductive shaft. Besides, the maximum temperature appears on the substrate connected to the front end of the conductive shaft.

It can be seen from Fig. 11 that the temperature of the overall structure of the conductive shaft increases with the increase of the working current. Under the same conditions, the current confluence will occur at the front end of the conductive shaft, resulting in the high temperature of the carbon brush structure and the substrate connected to the front end of the conductive shaft. And the temperature at the front end of the conductive shaft is greater than that at the rear end of the conductive shaft. The rear end of the conductive shaft is connected with the electrolyte, which may lead to low temperature.

According to the simulation and experimental results of the temperature field of the conductive shaft, it is not difficult to find that the current density and temperature field peak value of the unilateral power transmission scheme are significantly greater than that of the symmetrical power transmission scheme under the same conditions. Although the structure and assembly relationship of the unilateral power transmission scheme are relatively simple, the maximum temperature...
of single-sided power transmission scheme is almost three times higher than that of symmetrical power transmission scheme. The increase of temperature is easy to cause thermal deformation of the conductive shaft, which will reduce the positioning accuracy of the conductive shaft and make the conductive shaft unable to work in serious cases. Therefore, the overall structure of the conductive shaft is designed based on the symmetrical copper bar power introduction scheme.

3.4 The effect of ambient temperature on temperature field of conductive shaft

The ambient temperature also has an important influence on the temperature field of the conductive shaft. The variation law of the temperature field of the conductive shaft structure under different ambient temperatures is analyzed. The processing current was set to 12 000 A and the ambient temperature was 5 ℃, 15 ℃, 25 ℃, and 35 ℃. The temperature field of the conductive shaft is analyzed. The variation law of the temperature field of the conductive shaft with the ambient temperature is shown in Fig. 12. With the increase of the ambient temperature, the temperature of the overall structure of the conductive shaft shows an upward trend. At different ambient temperatures, the highest temperature appears in the front end of the conductive shaft.

4 Optimize the heat dissipation performance of conductive shaft

The temperature field of the conductive shaft is improved by improving the flow field in the conductive axle box. The cuboid $ABCD-EFGH$ represents the conductive shaft box. The simulation model established by fluent fluid analysis software is shown in Fig. 13. The steady-state temperature of the conductive shaft was taken as the initial temperature of the conductive shaft, and the improvement effect of different heat dissipation methods on the conductive shaft temperature field was analyzed. There are three heat dissipation schemes: scheme I, an air source is set at the plane $ABCD$ of the box; scheme II, set the air source at the plane $CDEF$ of the box; scheme III, the air source was set at the plane $ABCD$ and plane $CDEF$ of the box at the same time.

When the processing current is 20 000 A and the ambient temperature is 23 ℃, the flow field distribution of different schemes is shown in Fig. 14. Figure 14a shows the flow field distribution around the conductive shaft in scheme I. After the cold air flows through the conductive shaft, the original uniform flow field changes. On the side away from the plane $ABCD$, a large number of areas cannot contact the cold air flow, and the temperature in this area is significantly higher than that in other areas. The flow field distribution around the conductive shaft in scheme II is shown in Fig. 14b. There are still a large number of areas at the bottom of the conductive shaft that cannot contact the cold air flow. The flow field distribution around the conductive shaft in scheme III is shown in Fig. 14c. Compared with scheme I and scheme II, most structures of the conductive shaft can be fully contacted with the cold air flow. The temperature difference increases the convective heat transfer coefficient on the surface of the conductive shaft and significantly reduces the temperature in the axle box. It can be seen that scheme III can significantly improve and optimize the heat dissipation performance of the conductive shaft.

The air flow at the inlet was set at different temperatures to study the improvement of the thermal characteristics of the conductive shaft after using the refrigeration equipment. The average surface temperature of the conductive shaft varies with the temperature at the inlet. As shown in Fig. 15, the average temperature of the axle box has a linear positive
correlation with the inlet temperature. The lower the temperature at the inlet, the lower the average temperature of the conductive shaft. When the air source is set to make the inlet temperature at 15 °C, the maximum average surface temperature of the conductive shaft is about 70 °C.

Add refrigeration equipment on the original conductive axle box, and install the conductive shaft on the machine bed. Set an insulating block between the bottom plate of the conductive shaft and the machine bed. And insulate the conductive shaft device from the machine bed to ensure the overall insulation of the machine bed.

5 The process test

In order to analyze the correctness of the simulation results of the temperature field of the conductive shaft, it is necessary to measure the real-time temperature of the key position of the conductive shaft with the help of the data acquisition card. According to the location and analysis of the field fault, monitoring points are set at several key positions of the conductive shaft. The temperature data acquisition card is shown in Fig. 16.

And the specific location of the monitoring points is shown in Fig. 17. Nos. 1 ~ 6 are the monitoring points near the installation position of the carbon brush on the upper
surface of the conductive shaft body, which are used to monitor the change law of the contact position between the carbon brush and the upper half of the conductive shaft body. Nos. 7 ~ 12 are the monitoring points near the installation position of the carbon brush on the lower surface of the conductive shaft body, which are used to monitor the change law of the contact position between the carbon brush and the lower half of the conductive shaft body.

The rationality and stability of the conductive shaft structure are verified by machining the special-shaped inner spiral deep hole parts with large length-diameter ratio on a large horizontal NC ECM machine tool. The length of the machine body is about 16 m long, and the machining gap is only 0.5 ~ 1 mm. Through the process test, the rationality and stability of the conductive shaft structure are verified. The processing parameters used in the test are shown in Table 3.

The assembly relationship between the conductive shaft and the workpiece during processing is shown in Fig. 18. The workpiece and the spindle box are connected and sealed by threads. The spindle box changes in the axis direction with the feed device to realize the movement of the tool cathode, and finally achieve the process of workpiece processing. The tooling fixture on the machine bed plays an auxiliary supporting role for the workpiece. The power supply system provides energy for the whole processing process.

For the conductive shaft structure with single-sided copper bar power introduction scheme, during the electrochemical experiment, the conductive shaft was ablated, as shown in Fig. 19, resulting in the forced interruption of electrochemical processing. In the actual processing process, the current convergence causes the temperature at the connection between the substrate and the conductive shaft to rise sharply. At the same time, the electrolyte in the conductive shaft and the device to optimize the heat dissipation performance of the conductive shaft cannot reduce the increased temperature in time, so the ablation of the conductive shaft may occur.

When conducting the electrochemical experiment with the conductive shaft structure of the symmetrical copper bar power transmission scheme, the whole processing process is stable. And the results of real-time temperature collection at each monitoring point are shown in Fig. 20. The simulation results of temperature field simulation are generally consistent with the measured temperature value change trend of...
Fig. 17 Setting of conductive shaft monitoring points

Table 3 The test processing parameters

| Parameters         | Working current (A) | Processing voltage (V) | Ambient temperature (°C) | Feed rate (mm/min) | Electrolytic pressure (MPa) | Electrolyte temperature (°C) |
|--------------------|---------------------|------------------------|--------------------------|--------------------|-----------------------------|-----------------------------|
| Value              | 15 000              | 10 – 15                | 23                       | 5                  | 1.5                         | 30                          |

Fig. 18 Assembly relationship between conductive shaft and workpiece. a Processing and assembly. b Headstock structure

Fig. 19 Ablated conductive shaft
Fig. 20 Instantaneous temperature at monitoring point. **a** Simulation temperature of nos. 1–6. **b** Simulation temperature of nos. 7–12. **c** Measured temperature of nos. 1–6. **d** Measured temperature of nos. 7–12

Fig. 21 The processed workpiece. **a** The complete workpiece. **b** The workpiece slice

(a) The complete workpiece  (b) The workpiece slice
data acquisition card, and the correctness of the simulation results is verified within the allowable error range. As can be seen from Fig. 20, with the increase of time, the temperature of each detection point gradually increases, and after 2400 s, the temperature of the monitoring point basically does not change significantly. The time for each detection point to reach the steady-state temperature is basically close, which means that the different positions of the whole conductive axis basically reach the steady-state temperature field at the same time. The upper surface temperature of the conductive shaft is higher than the lower surface temperature, which is likely to cause the deformation of the upper surface of the conductive shaft body to be greater than that of the lower surface.

The real object of the workpiece after electrochemical processing using the conductive shaft structure of the symmetrical copper bar power transmission scheme is shown in Fig. 21a, and the real object of the workpiece after slicing is shown in Fig. 21b.

Number the sliced workpieces according to the processing sequence. Measure and record the size of the processed workpieces. Some data of the sliced size error and surface roughness measured after processing are shown in Table 4. The data analysis shows that the forming accuracy of the workpieces reaches ±0.15 mm and the surface roughness reaches Ra0.8 μm. It can well meet the actual processing requirements.

Through the electrochemical experiments on the conductive axis structure of the single-sided copper bar and symmetrical copper bar, the correctness of the structure selection based on the simulation results is verified. The service performance of the symmetrical copper bar is better than that of the single-sided copper bar, and the single-sided copper bar cannot ensure the stability of the electrochemical machining process. Therefore, the symmetrical copper bar scheme is selected as the power transmission mode of the conductive axis, which provides a theoretical basis for practical engineering application.

### 6 Conclusion

In this paper, the structure, temperature field, and heat dissipation performance of the conductive shaft of large horizontal NC ECM machine tool are analyzed. The main conclusions are as follows:

1. By establishing the finite element model of the conductive shaft of large horizontal NC ECM machine tool, two new conductive shaft structures with different power transmission modes are proposed, and the temperature field of the conductive shaft structures with different power transmission schemes is analyzed.

2. The thermoelectric coupling model of the conductive shaft is established, and the temperature of the conductive shaft under different working conditions is analyzed. The results show that the maximum thermal deformation is at the substrate, and the current has a significant effect on the temperature rise of the conductive shaft. The heat dissipation performance of the conductive shaft can be significantly improved by providing air flow on the upper surface and side at the same time.

3. The temperature acquisition card is used to measure the key detection points set on the conductive shaft to verify the correctness of the simulation results. Under the conditions of current 15 000 A, feed speed 5 mm/min, and continuous processing for 14 h, the stable and reliable processing of special-shaped internal spiral deep hole parts with large aspect ratio could be realized, the forming accuracy of processed workpiece could reach ±0.15 mm, and the surface roughness could reach Ra0.8 μm.

### Author contribution

Lin Tang was the main contributor and corresponding author of the manuscript. Professor Lin Tang designed the research process, and led Yaze Zheng and Zhao Wang to finish the structure design of conductive shaft and the simulation of temperature field. Lifeng Zhang and Chengjin Shi completed the structural performance verification experiment of conductive shaft and guided the manuscript writing.

### Funding

This work was financially supported by Shaanxi Province Key Research and Development projects (grant no. 2020GY-153), Scientific Research Program for Youth Innovation Team Construction of Shaanxi Provincial Department of Education (no. 21JP054), and Shaanxi University Youth Innovation Team Project (grant no. 20201020).

### Availability of data and materials

All data generated or analyzed during this study are included in this published article.

### Declarations

#### Ethics approval

Not applicable.
References

1. Wang GQ, Li HS, Zhang C, Zhu D (2019) Improvement of machining consistency during through-mask electrochemical large-area machining. Chin J Aeronaut 32(04):1051–1058
2. El-Hofy H (2019) Vibration-assisted electrochemical machining: a review. Int J Adv Manuf Technol 105(1–4):579–593
3. Liu J, Wang H, Zhu D (2018) Electrochemical machining of γ-TiAl intermetallic blades by using the stainless steel anti-coated tool electrodes. Procedia CIRP 68:757–761
4. Burger M, Koll L, Werner EA, Platz A (2012) Electrochemical machining characteristics and resulting surface quality of the nickel-base single-crystalline material LEK94. J Manuf Process 14(1):62–70
5. Holstein N, Krauss W, Konys J (2011) Development of novel tungsten processing technologies for electrochemical machining (ECM) of plasma facing components. Fusion Eng Des 86(9–11):1611–1615
6. Dhobe SD, Doloi B, Bhattacharyya B (2011) Surface characteristics of ECMed titanium work samples for biomedical applications. Int J Adv Manuf Technol 55(1–4):177–188
7. Tang L, Li B, Yang S, Duan QL, Kang BY (2014) The effect of electrolyte current density on the electrochemical machining of stainless steel on electrochemical machining of electrolyte composition. Mater Manuf Processes 28(4):457–462
8. Zhu ZW, Wang DY, Bao J, Wang NF, Zhu D (2015) Cathode design and experimental study on the rotate-print electrochemical machining of revolving parts. Int J Adv Manuf Technol 80(9–12):1825–1833
9. Tang L, Guo YF (2013) Experimental study of special purpose stainless steel on electrochemical machining of electrolyte composition. Mater Manuf Processes 28(4):457–462
10. Jia J, Liu JH, Wang X (2015) Experimental investigation on the inner cavity of gun barrel chamber in electrochemical machining. Int J Control Aut 8(4):169–180
11. Kuriya T, Hattori M (2006) A study of EDM and ECM/ECM-lapping complex machining technology. Int J Mach Tools Manuf 46:1804–1810
12. Asokan P, Kumar RR, Jayapaul R, Santhi M (2008) Development of multi-objective optimization models for electrochemical machining process. Int J Adv Manuf Technol 39(1–2):55–63
13. Mukherjee R, Chakraborty S (2013) Selection of the optimal electrochemical machining process parameters using biogeography-based optimization algorithm. Int J Adv Manuf Technol 64(5–8):781–791
14. Damme SV, Nelissen G, Bossche BVD, Deconinck J (2006) Numerical model for predicting the efficiency behavior during pulsed electrochemical machining of steel in NaNO₃. J Appl Electrochem 36(1):1–10
15. Tang L, Yang S (2013) Experimental investigation on the electrochemical machining of 00Cr12Ni9Mo4Cu2 material and multi-objective parameters optimization. Int J Adv Manuf Technol 67(9–12):2900–2916
16. Qu NS, Xu ZY (2013) Improving machining accuracy of electrochemical machining blade by optimization of cathode feeding directions. Int J Adv Manuf Technol 68(5–8):1565–1572
17. Zhang ZY, Peng QY, Cai MX, Huang L, Jiang YJ (2015) Research on stress-etching complex microstructure of aluminum alloy in laser electrochemical machining. Int J Adv Manuf Technol 81(9–12):2157–2165
18. Liu GX, Zhang YJ, Luo HP, Zhou C, Wang YN, Zhang CY (2016) Large lead ball nut raceway ECM machine tool. Electrical Machining and Die 1:59–61 (in Chinese)
19. Wang MH, Peng W, Yao CY, Zhang QF (2010) Electrochemical machining of the spiral internal turbulator. Int J Adv Manuf Technol 49(8–12):969–973
20. Mahdavinejad R, Mehraban M, Mahdavinejad D (2006) The behaviour of REFEL SiC under electrode discharge machining. Proc Inst Mech Eng B J Eng Manuf 220(10):1635–1646
21. Xu ZY, Liu J, Xu Q, Gong T, Zhu D, Qu NS (2015) The tool design and experiments on electrochemical machining of a blisk using multiple tube electrodes. Int J Adv Manuf Technol 79(1–4):531–539
22. Kozak J, Chuchro M, Ruszaj A, Karbowski K (2000) The computer aided simulation of electrochemical process with universal spherical electrodes when machining sculptured surfaces. J Mater Process Technol 107(1–3):283–287
23. Purcar M, Doroienko A, Bortels L, Deconinck J, Van den B.B, (2007) Advanced CAD integrated approach for 3D electrochemical machining simulations. J Mater Process Technol 203(1–3):58–71
24. Pattavainitch J, Hinduja S, Atkinson J (2010) Modelling of the electrochemical machining process by the boundary element method. CIRP Ann Manuf Technol 59(1):243–246
25. Tang L, Gan WM (2014) Utilization of flow field simulations for cathode design in electrochemical machining of aerospace engine blisk channels. Int J Adv Manuf Technol 72(9–12):1759–1766
26. Mahdavinejad R, Hatami M (2008) On the application of electrochemical machining for inner surface polishing of gun barrel chamber. J Mater Process Technol 202(1–3):307–315
27. Amalnik M, McGough J (1996) Intelligent concurrent manufacturability evaluation of design for electrochemical machining. J Mater Process Technol 61(1):130–139
28. Tsuone K, Chiaki E, Yashiro M, Hiroshi M, Kazuhiro T, Fumiak T, Hiromichi I, Keigo O, Kouji K (2008) Mechanical/electrochemical complex machining method for efficient, accurate, and environmentally benign process. Int J Mach Tools Manuf 48:1599–1604
29. Tang L, Fan ZJ, Zhao GG, Yang F, Yang S (2016) High aspect ratio deep spiral tube electrochemical machining technology. Procedia CIRP 42:407–411
30. Zhang CF, Wang FG, Xu SY (2012) A small magnetic driving ECM machine. Adv Mat Res 411(000):72–76
31. Jeon DH, Kim BH, Chu CN (1966) Micro machining by EDM and ECM. J Korean Soc Precis Eng 23(10):52–59
32. Alexandre S, Atanas I (2015) Design of an electrochemical micromachining machine. Int J Adv Manuf Technol 78(5–8):737–752
33. Zhong H, Tong H, Wang ZQ, Li Y, Pu YB (2020) Scanning micro-electrochemical machining process for V-shaped grooves. J Micro Nano-Manuf 8(1)
34. Sindhi O, Akbari H, Ramier J (2021) Fabrication of high aspect ratio tungsten microtools through controlled electrochemical etching. Mater Manuf Processes 36(11):1236–1247

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.