

Research Progress on Electrochemical Machining Technology

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Abstract

Electrochemical machining (ECM) is an excellent technique of processing for metallic materials, widely used in the shaping and preparation of metal structural components. According to the size requirements of the processed structures, in this paper, the current status of ECM development is introduced from the aspects of macro-electrochemical machining and micro-electrochemical machining; and its advantages and disadvantages are summarized, which provides significant reference for the further development of ECM.

Keywords

Electrochemical Machining; Electrochemical Milling; Macro-electrochemical Machining; Micro-electrochemical Machining.

1. Introduction

Electrochemical machining (ECM) is a specialized processing method that removes material from metal workpieces using the principle of electrochemical anodic dissolution [1]. It is not affected by the material's strength, hardness, toughness, or other mechanical properties [2]. ECM has advantages such as no tool cathode wear, high surface quality of the processed surface, no machining stress on the workpiece surface, and no heat-affected zone. It is particularly suitable for shaping hard-to-machine metal materials and is widely applicable in some fields such as aerospace and medical devices [3].

With the advancements in these related fields, there is a need to continuously improve ECM technology to meet requirements of processing quality. The challenges in forming large structural components lie in the optimization of the tool cathode and the flow field. For the forming of micro-structural components, the requirements for processing precision and quality are extremely high, necessitating the specific implementation plans based on particular processing requirements.

This paper will introduce the development status of ECM from the perspectives of macro-electrochemical machining (macro-ECM) and micro-electrochemical machining (micro-ECM) and will provide the outlook on the possible future trends in ECM development.

2. Research Progress on Macro-Electrochemical Machining Technology

Based on the movement mode of the tool cathode and its processing implementation method, macro-ECM can be mainly divided into traditional electrochemical machining (TECM), counter-rotating electrochemical machining (CRECM), and macro-electrochemical jet milling (macro-EJM).

2.1. Traditional Electrochemical Machining Technology

In TECM, the tool cathode moves relative to the workpiece anode during the machining process, see [Figure 1](#) [4]. It is mainly used for shaping large structural components.

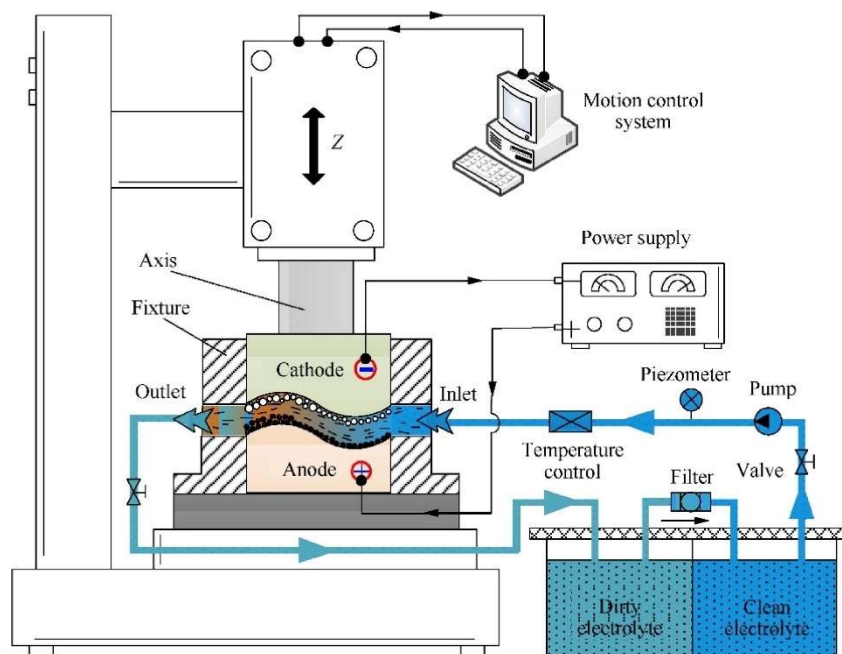


Figure 1. The processing principle of traditional electrochemical machining [4]

To ensure the precision of TECM, especially for complex surfaces, the geometric shape of the tool cathode must be accurately designed. Based on the contour characteristics and geometric dimensions of the desired final workpiece, the dissolution state of the workpiece anode surface and the current density distribution in a balanced state are analyzed. By solving the distribution of the inter-electrode gap and predicting the cathode surface morphology according to the numerical relationship between the inter-electrode gap and potential, the specific structure of the tool cathode is designed and optimized [5].

To explore the impact of the inter-electrode gap on electrochemical energy transfer, K.P. Rajurkar et al. [6] established a mathematical model of ECM based on Faraday's laws, analyzing the numerical relationship between the inter-electrode gap and potential distribution. To ensure the design accuracy of the tool cathode, it is essential to consider the coupled multi-physics fields in ECM, such as the electric field, flow field, electrochemical field, and thermal field. M. Zeis et al. [7] and T. Fujisawa et al. [8] developed multi-physics mathematical models for ECM of complex surfaces, performing numerical simulations based on the workpiece anode's contour to determine the tool cathode's geometric shape.

When the workpiece anode is too large or the structure is too complex, it is necessary to design the tool cathode structure in sections to optimize the machining process [9]. In sectional TECM, to avoid the mutual influence of the flow fields in different machining zones and prevent re-electrochemical corrosion in the processed areas, a certain connection gap must be left when splicing the tool cathode to form a "barrier" at the junctions of the machining zones [10]. Due to the fast material removal rate and small machining gap in TECM, the electrolysis products from the workpiece anode and gas bubbles from the tool cathode tend to accumulate in the machining area, disrupting the stability of the electric field within the inter-electrode gap and affecting machining accuracy. To mitigate the impact of electrolysis products on ECM, D. Zhu et al. [11] used a reciprocating feed tool cathode and a pulsed power source for physical field synchronous coupling, enabling intermittent electrochemical machining to reduce the accumulation of electrolysis products in the inter-electrode gap and improve machining accuracy.

Currently, the algorithms for inversely solving the tool cathode geometry in TECM are relatively mature, allowing precise design of the tool cathode's shape and size required for machining.

During the electrochemical machining process, the electrolysis products of the anode and cathode can significantly affect the dynamic distribution of the flow field, thermal field, and electric field within the inter-electrode gap, impacting machining accuracy. To further enhance TECM accuracy, research focuses on improving the machining environment, such as optimizing the tool cathode structure and using pulsed power sources, to promote the removal of electrolysis products or reduce their impact.

2.2. Counter-Rotating Electrochemical Machining Technology

In CRECM, both the tool cathode and the workpiece anode rotate around their own central axes at the same angular velocity, while the workpiece cathode feeds relative to the workpiece anode, see [Figure 2](#) [12-14]. This method is mainly used for machining rotational structural components.

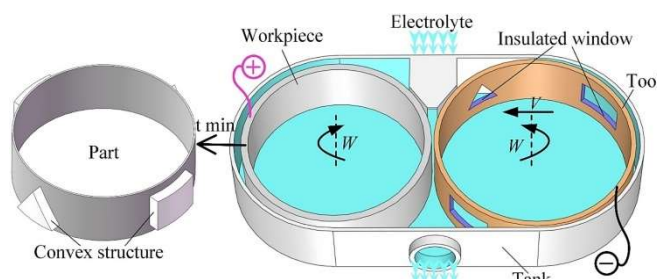


Figure 2. The processing principle of counter-rotating electrochemical machining [14]

For TECM of cylindrical or tubular blanks, the workpiece anode is necessarily divided into several sector-shaped machining zones, each corresponding to a segment of the tool cathode. During machining, maintaining consistent machining gaps across all zones is challenging, and "seam marks" often remain at the junctions between zones [10]. Therefore, the process of TECM for rotational workpieces needs improvement.

To address this issue, D. Zhu et al. [12,13] proposed CRECM, using an annular tool cathode with a hollow structure for machining complex curved surfaces. During the machining process, the workpiece anode and tool cathode rotate at the same angular velocity around their central axes, achieving a smooth and continuous machining surface. The tool cathode feeds with high precision, allowing accurate control of the machining thickness of the curved structure.

To further enhance the precision of this technique, the team conducted extensive research, establishing a mathematical model for CRECM and performing numerical simulation analysis to optimize the flow field [14,15]. And they successfully machined a boss structure with a contour deviation of less than 0.05 mm. However, due to the lack of insulation on the sidewalls of the hollow structure of the tool cathode and the relatively turbulent flow field in this area, stray corrosion occurred at the top of the boss structure. Therefore, localized insulation treatment of the tool cathode can improve the precision and surface quality of CRECM as needed [16].

Current research focuses primarily on optimizing the machining flow field to enhance the precision of CRECM.

2.3. Macro-Electrochemical Jet Milling Technology

The tool cathode in macro-EJM typically has a square pipe structure. During the machining process, it moves parallel and feeds relative to the workpiece anode, enabling precise machining of complex three-dimensional structures. The processing principle is illustrated in [Figure 3](#) [17].

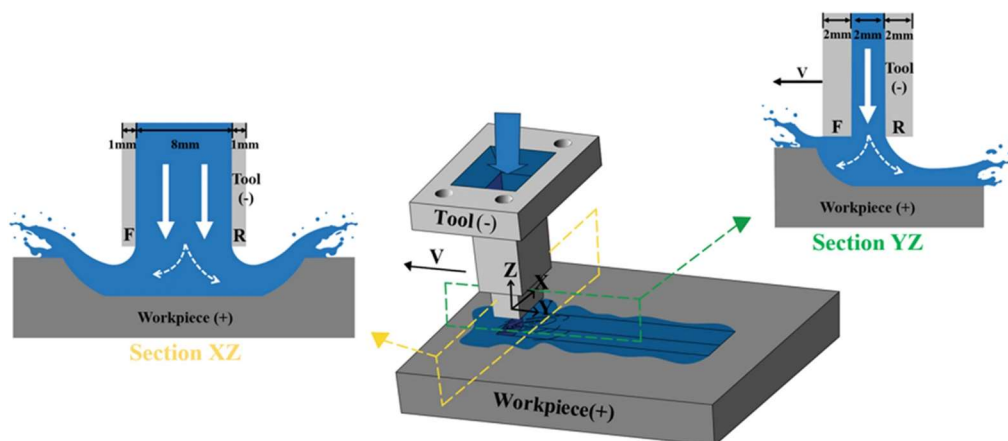


Figure 3. The processing principle of macro-electrochemical jet milling [17]

In TECM, different workpiece structures require the inverse design of various tool cathodes, which is labor-intensive and has several limitations. Large material removal areas or overly complex machining structures can lead to excessive accumulation of electrolysis products in the machining gap, limiting machining precision. However, in Macro-EJM, it uses a simple tool cathode structure but has a wide range of applications, attracting significant attention and research from scholars worldwide.

To improve the precision and surface quality of macro-EJM and reduce stray corrosion during processing, K. Mishra et al. [18] studied the effects of NaCl and NaNO₃ electrolytes on electrochemical milling. And using a mixed electrolyte of both, they achieved high-precision and high-surface-quality structural parts. N.S. Qu et al. [19] improved the flow field and electric field distribution during the machining process by altering the internal channel design of the tool cathode. Their experiments showed that triangular channels can enhance surface quality and reduce stray corrosion. Additionally, the team [20,21] investigated the effects of the liquid channel's tilt angle and the tool's tilt angle on electrochemical milling. The experiments indicated that a negative electrolyte injection angle increases the high-speed flow area at the rear, improving surface quality and material removal rate.

Macro-EJM is primarily influenced by the flow field. By continuously improving the tool cathode structure and optimizing the flow field and electric field distribution during machining, high-precision, high-surface-quality, and high-material-removal-rate electrochemical milling can be achieved.

3. Research Progress on Micro-Electrochemical Machining Technology

Micro-electrochemical machining technology is mainly used for high-precision machining of micro-sized structures (1 μm -1 mm) [22]. Based on the working method of the electrode, it can be divided into mask micro-ECM, immersion micro-ECM, and micro-electrochemical jet machining.

3.1. Mask Micro-Electrochemical Machining Technology

In mask micro-ECM, the surface of the workpiece anode is covered with an insulating layer with the patterns, selectively exposing the workpiece surface. During machining processing, material is removed from the exposed areas to form microstructures on the workpiece surface, as shown [Figure 4](#) [23,24].

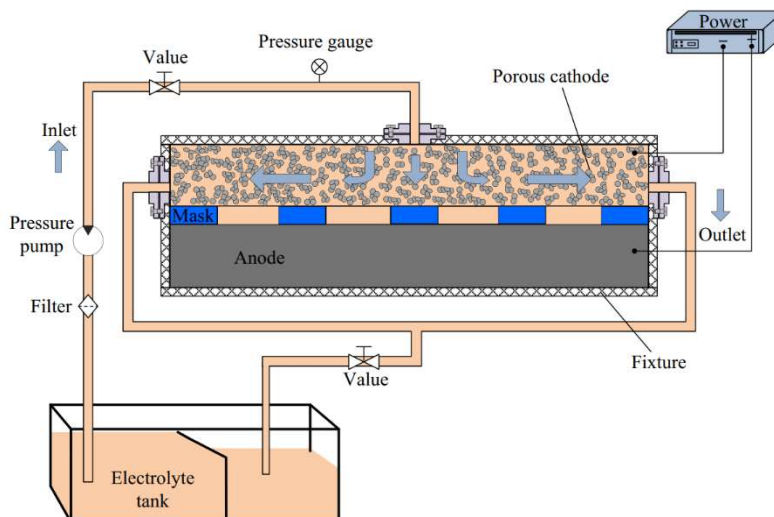


Figure 4. The processing principle of mask micro-electrochemical machining [24]

Photolithographic mask micro-ECM uses photolithography technology to coat the workpiece anode surface with a layer of photoresist, and then develop the photoresist to create a mask with the hollow microstructures [25]. This method offers high precision in microstructure machining; however, the mask preparation is cumbersome since all workpieces to be machined must be coated with the mask layer. To address this, D. Zhu et al. [26] proposed the active mask micro-ECM technique, where the mask is not dependent on the electrode and can be reused. The prepared mask is tightly adhered to the workpiece surface for microstructure machining. However, the machining quality is influenced by the adhesion of the mask. To ensure tight adhesion, P.M. Ming et al. [27] proposed an inter-electrode filling mask ECM technique, where a flexible porous material is added in the inter-electrode gap to ensure stable electrolyte supply and close contact between the mask and the workpiece.

To further improve the precision of mask micro-ECM, P.M. Ming et al. [28] and G. Qin et al. [29] respectively proposed the linear cathode mask micro-ECM technique and the rotating mask micro-ECM technique. These methods optimize the electric field and flow field in the inter-electrode gap, promote the removal of electrolysis products, and enhance the precision and surface quality of microstructure machining.

Mask micro-ECM offers high precision and can be used for both planar and curved surfaces. However, in this process, the tool cathode cannot feed, limiting the depth of microstructure machining. Current research in mask micro-ECM focuses on improving the flow field environment or designing new tool cathodes to optimize the machining electric field and enhance the precision of microstructure machining.

3.2. Immersion Micro-Electrochemical Machining Technology

In immersion micro-ECM, the machining end of the tool cathode and the area to be machined on the the workpiece anode are immersed in the electrolyte [30]. The tool cathode typically has a fine rod structure with its bottom end submerged in the electrolyte. In the machining process, it either moves parallel to the workpiece anode or remains stationary, see [Figure 5](#) [31].

The traditional immersion micro-ECM uses a tool cathode with an uninsulated surface immersed in the electrolyte. This setup lacks a sufficiently concentrated electric field, resulting in poor localization. Additionally, this technique employs a direct current power supply and the static or low-flow electrolyte, leading to electrolysis products adhering to the electrode surface and poor machining quality.

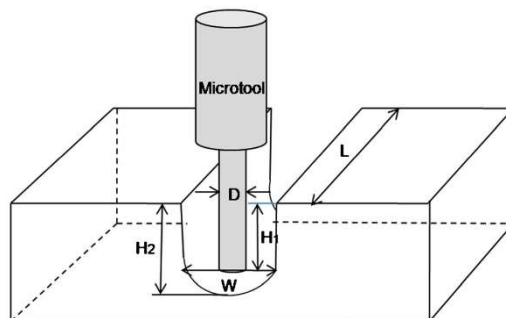


Figure 5. The processing principle of immersion micro-electrochemical machining [31]

To address this issue, R. Schuster [32] and M. Kock [33] used an ultra-short pulse power supply. By utilizing the double-layer physical model of electrochemical machining to control the processing, they reduced the accumulation of electrolysis products on the electrode surface. This method achieved high-precision microstructures, as shown in [Figure 6](#). Sueptitz et al. [34] analyzed the impact of the electrolyte on the formation of microstructures in micro-ECM and discussed the mechanism by which the electrolyte affects the electrochemical reactions. Thus, the appropriate electrolyte can be selected based on the composition of the metal material to improve machining quality. Y. Zhu et al. [35] used a vibrating tool cathode and pulse power supply to couple multiple physical fields, altering the response trend of the double layer in electrochemical machining. This controlled the electrochemical reaction process and facilitated the removal of electrolysis products, resulting in high-precision, high-quality microstructures.

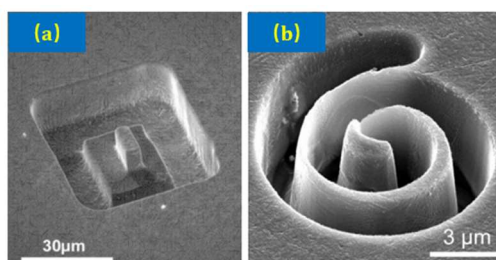


Figure 6. Microstructures produced by ultra-short pulse micro electrochemical machining; (a) Micro-pillar structure [32], (b) Micro-helix structure [33]

Depending on specific machining needs, the shape of the tool cathode can be adjusted for efficient forming of high-precision microstructures. D. Zhu et al. [36] used a tool cathode with an array structure to achieve efficient and precise array microstructures on the workpiece anode.

Since increasing the pulse frequency can enhance the localization of pulse micro ECM, the current research mainly focuses on the development of ultra-short pulse power supplies.

3.3. Micro-Electrochemical Jet Machining Technology

In micro-electrochemical jet machining, the electrified electrolyte is sprayed onto the surface of the workpiece anode through a hollow tool cathode, thereby connecting the anode and cathode. This technique is primarily divided into micro-electrochemical jet machining by capillary and micro-electrochemical jet machining by metal tube electrode.

Capillary micro-electrochemical jet machining uses extremely fine glass tubes with electrode wires inside. Due to the insulated sidewalls of the tool, this method achieves high machining precision and is commonly used for nanostructure fabrication. L.Z. Xu et al. [37-39] employed this tool for electrochemical machining, achieving high precision in microstructure machining

by controlling the response of electrode potential within the double-layer physical model of electrochemical machining.

Metal tube electrode micro-electrochemical jet machining utilizes high-velocity electrolyte flow, see [Figure 7](#) [40]. The flow effectively removes electrolysis products from the inter-electrode gap, thereby improving the surface quality of machined microstructures. Additionally, this technique can enhance material removal rates by applying high potential voltage, enabling efficient machining of microstructure. However, the high-pressure liquid jet in micro-electrochemical jet machining can cause the jet leap phenomenon upon impacting the workpiece surface. As machining depth increases, this jet can reflect back to the outer wall of the tool cathode, indicating a need for improved flow field conditions.

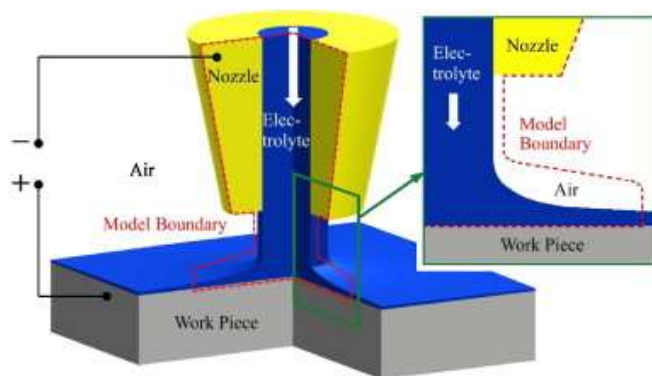


Figure 7. The processing principle of micro electrochemical jet machining by metal tube electrode [40]

Wataru Natsude et al.[41] proposed a coaxial dual-pipe tool cathode to achieve recirculating electrolyte supply, mitigating the jet leap problem and enhancing flow field localization, thereby improving machining precision. P.M. Ming et al. [42] utilized a coaxial kerosene wrapping technique to restrict electrolyte diffusion, improving flow field conditions and machining precision. S. Niu et al. [43] used ethylene glycol as the electrolyte solvent, enhancing the surface quality of microstructures.

Current research in micro-EJM focuses on improving flow field conditions and reducing stray corrosion during machining to achieve high surface quality in microstructures.

4. Conclusion

Electrochemical machining technology is well-developed and widely used in the metal manufacturing industry. However, precision and efficiency in ECM are often difficult to achieve simultaneously. It is necessary to optimize the working environment based on specific machining requirements to achieve the desired structural component formation.

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