Research on Electrochemical Machining Technology of Deep Small Hole using Suction Electrode

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Abstract. Aiming at the problem of deep small hole machining for difficult-to-machine material, a suction electrode electrochemical machining method is used to solve the problems of slow electrolyte renewal and poor stability during the electrochemical machining of deep small holes. This paper mainly uses the multi-physics coupling software COMSOL to establish a multi-physics coupling model for the electrochemical machining of deep small holes with a suction electrode and simulates the forming process of the deep small hole and the distribution of the flow field and electric field during the machining process. This model verifies the feasibility of electrochemical machining technology of deep small holes using a suction electrode.

1. Introduction
In recent years, with the continuous development of science and technology, the deep small hole structure has been widely used in aviation, aerospace, shipbuilding, chemical industry and other fields, including cooling holes on aero-engine turbine blades, group holes in combustion chambers, oil passages of guide vanes hole, trailing edge deep hole, and fuel injector. The aspect ratio of these holes is greater than 20, and the diameter is between 0.2 and 3 mm [1]. Nickel-based superalloys are widely used in aerospace engines and other fields due to their good high-temperature mechanical properties, thermal stability, and heat-corrosion resistance, and these components have great deep hole machining requirements. However, nickel-based superalloys are a typical difficult-to-machine material with high hardness, high tensile strength, high cutting stress, large cutting deformation, and severe work hardening. Therefore, it is difficult to achieve high-efficiency and high-precision deep small hole processing using traditional processing methods.

At present, the methods of special processing of deep small hole generally to include electrical discharge machining (EDM), electrochemical machining (ECM), laser machining, electron beam machining. The EDM method has high processing efficiency, but the processed holes have defects such as recast layer and surface cracks [2]. Laser processing is of high efficiency without any tool wear, but the processing accuracy is not high. There are also defects in the recast layer, and the processing cost is high. Electron beam machining efficiency is very high, but the equipment is expensive and the additional cost is high.

Electrochemical machining is widely used in the processing of difficult-to-machine material due to the advantages of no recast layer, no micro cracks and residual stress, and no loss of tool cathodes after processing. However, there are still problems in the field of deep small hole machining. In the process of processing deep small holes, it is difficult for machines with ordinary electrochemical machining because of the small machining gaps. Therefore, the problem of electrolyte renewal during the electrochemical machining process needs to be solved urgently. The general liquid supply method is
difficult to solve the problem of electrolyte renewal of the machining gap, which will reduce the accuracy of machining. The continued machining ability at the bottom of the hole becomes weak, which will lead to a series of short-circuit problems [3]. A suction electrode is applied to improve the efficiency of electrolyte renewal and realize the fabrication of deep small holes. The electrochemical machining method of the suction electrode is different from the traditional electrochemical machining method. The method of recovering the electrolyte improves the renewal efficiency of the electrolyte.

For methods to improve the machining accuracy and machining aspect ratio, researchers have conducted a lot of research, including the use of pulsed power to drain the liquid through the pulse gap, insulating the electrode, changing the liquid supply method, improving the electrode structure, and so on. Pawar [4] et al. studied Electrochemical Drilling Process (ECD) and developed a multi-physics model for ECD, and the effect of tool geometry on generated anode profile is studied to improve the dimensional control and performance of the Electrochemical Machining Process. Liu et al. [5] studied the electrochemical drilling of the rotating spiral electrode of GH4169 and processed micro-holes with a diameter of 186 μm and a depth of 500 μm without taper. Wang et al. [6] adopted the tube electrode processing method and improved the electrolyte renewal speed in the gap and the processing precision of the micro-holes through reverse flushing. Yamamura [7] proposed a method to collect electrolytes with concentric tube electrodes and two pumps. One was used for supplying pressurized electrolytes and the other was used for collecting discharged electrolytes. Natsu [8] proposed a selective electrochemical machining process with a new type of suction electrode, which realized the function of electrolyte restriction and gap detection in the ECM process. To improve the processing accuracy, the method of limiting the electrolyte has been continuously developed. Among them, the suction electrode is used as an effective electrolyte confinement method for processing tiny blind holes and micro grooves and can obtain good processing results. However, the electrochemical machining of the small blind holes and through holes with a relatively large depth of the suction electrode still lacks in-depth research, and there is still a lot of room for development.

This article focuses on the research on the process of electrochemical machining in deep holes with the suction electrode, aiming to explore the ability of the suction electrode to process deep small holes. To study the distribution of the flow field and the electric field in the process of the suction electrode machining, a multi-physics model of the flow field and the electric field considering the transfer of dilute material is established in this paper. Through the model, the deep hole processing characteristics of the suction electrode is deeply studied, which improves the stability and processing efficiency in the processing process.

2. Simulation Analysis of Electrochemical Machining of Deep Small Hole Suction Electrode

2.1. Principle of Electrochemical Machining of Suction Electrode

The principle of electrochemical machining and the electrolyte supplies method of the suction electrode are shown in figure 1. The electrolyte is supplied from the inner tube through the supply pump, and the electrolytic product after processing is pumped out with the electrolyte from the gap between the inner and outer tubes by a suction pump. At the same time, the entire electrochemical machining process of the suction electrode is very stable, and the suction flow field does not change with the change of the machining depth. Therefore, the processing of deep small holes can be completed well. The processing of small holes with various aspect ratios can be completed. For electrochemically machined deep holes, the electrolyte always exists in the deep hole gap, and the secondary corrosion of the hole wall seriously affects the machining accuracy of the deep hole. The electrode insulation can limit the secondary machining of the processed area, it is very important for the deep hole. For larger holes, the durability of the insulating layer greatly limits the ability of electrochemical machining of deep holes. For the electrochemical machining of the suction electrode, this method can solve the problem of secondary corrosion. It can be seen from the schematic diagram that the suction electrode can well confine the electrolyte to the bottom of the deep hole when processing deep holes. Therefore, there is no electrolyte in the processed area, and there is no corrosion. During the experiment, the liquid level in the hole can
be reduced by adjusting the supply flow rate and the recovery flow rate, and the anode workpiece cannot be corroded in the area without electrolyte.

![Figure 1. Principle of electrochemical machining of the suction electrode.](image)

2.2. Experimental device and sample description
As shown in figure 2, the cathode outer tube used is a 304 stainless steel metal tube with an outer diameter of 1.0 mm and an inner diameter of 0.9 mm, and the cathode inner tube is a 304 stainless steel tube with an outer diameter of 0.5 mm and an inner diameter of 0.4 mm. At the same time, to further prevent stray corrosion insulating paint and two polyimide tubes with different diameters are used to insulate the outer wall of the outer tube, which improves the durability of insulation.

![Figure 2. Insulated tube electrode.](image)

2.3. Geometric model
This paper uses COMSOL Multiphysics to simulate and analyze the electrochemical machining process. The simplified model of the electrochemical machining of the suction electrode is shown in figure 3. An axisymmetric model is established, where boundary 1 is the electrolyte inlet and boundary 2 is the electrolyte outlet. Boundaries 3 and 4 are open boundaries, boundary 5 is the metal anode surface of the workpiece, boundary 6 is the axis of symmetry, boundary 7, 8, and 9 are the tool cathode surface, boundary 10 is the surface of the insulating layer, and the entire area I is the gas-liquid two-phase (air and electrolyte) area.
2.4. Simulation parameters
The main parameters of the simulation process of the electrochemical machining model of the suction electrode used in this article are shown in Table 1. The simulation couples the flow field and electric field at the same time, and simultaneously stimulate the flow field and electric field distribution at every moment. Using COMSOL modules such as secondary current, transfer of dilute substances, deformation geometry, laminar flow level set, etc., complete the simulation of the electrochemical machining process of the suction electrode.

Table 1. Simulation parameter.

| Parameter                      | Numerical value |
|--------------------------------|-----------------|
| Anode material                 | Superalloy GH4169 |
| Cathode material               | Stainless steel 304 |
| Processing voltage $U$/V       | 12              |
| Electrolyte conductivity $\kappa$/$(S/m)$ | 12              |
| Initial machining gap $\Delta$/mm | 0.1             |
| Cathode feed rate $v_0$/$(mm/min)$ | 0.2             |
| Reference temperature $T$/K     | 293.15          |
| Electrolyte flow $v_1$/$(ml/min)$ | 1.5             |
| Suction pressure/Pa             | 200             |

3. Simulation results and analysis
The electrochemical machining model of the suction electrode analyzes the forming process of the machining and the distribution of each physical field, including the electric field, flow field, flow rate, ion concentration, etc. Finished the result processing of electric field and fluid distribution and geometric model forming process.

3.1. Analysis of flow field results
The flow field distribution during the electrochemical machining of the suction electrode is shown in figure 5, which is the flow field distribution during the initial time and the machining process. The whole simulation is multi-physics coupling, and also includes the change of the processing geometry, which reflects the change of the processed hole. It can be seen from the figure that as the processing progresses, the fluid can be well confined no matter the entrance or the bottom of the deep hole, which can improve the stability and electrolyte renewal rate during processing.
3.2. Analysis of electric field results

The electric field during the electrochemical machining of the suction electrode is analyzed, and the electrolyte current density distribution at the beginning of the machining is shown in figure 5. According to the results of the flow field analysis, in the initial stage of processing, the electrolyte is confined under the suction electrode, so the anode material under the electrode is removed, and there is no electric field distribution in the other parts. The electrolyte current density is zero, and the electric field is concentrated under the electrode which limited the processing area successfully.

The electrolyte potential distribution in the process of processing deep holes is shown in figure 6. The processing time is 400s. According to the results of flow field analysis, the electrolyte is distributed at the bottom of the hole. Therefore, there is no electric field distribution in the area where there is no electrolyte above the liquid surface. The corrosion of the workpiece will only occur under the electrode, which can ensure that no secondary corrosion occurs in the processed area. At the same time, an insulating layer is added to the simulation process. If the liquid level is not properly controlled during the processing, the insulating layer can also ensure the morphology of the processed area.
4. Conclusions
By establishing a multi-physical field coupling model for electrochemical machining of the suction electrode, the distribution of each physical field during the machining process is studied. The simulation results confirmed the feasibility of electrochemical machining of deep holes by the suction electrode, which can successfully limit the electrolyte area and increase the electrolyte renewal rate.

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