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ELECTROCHEMICAL MACHINING OF ADVANCED MATERIALS - A REVIEW

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ABSTRACT: For electrochemical machining (ECM) to be stable and accurate, the electrolytic flow field is essential. To improve the flow field, numerous studies have been conducted. This review study offers various enhancements to aero engine blade flow approaches. This report illustrates three different flow field models: one where the solution of electrolyte is introduced at the starting and trailing edges, another proposal that takes into account the effect of gravity on bubbles according to the bubble dynamics analysis, and the final one that uses electrochemical trepanning as a method of machining to create a radial blade via a constant area. Combining modelling and investigations, the suggested methods were assessed. The outcomes of the investigation demonstrate the suitability and applicability of these flow patterns for producing aero engine parts.

KEYWORDS: Machining, electrochemical machining, ECM, flow field, electrolyte

1. INTRODUCTION

The blade constitutes one of among the most crucial components of aero engines. The essential components that have the biggest impact on the blade's aerodynamic effect as well as efficiency of power conversion are the front and behind edges. The airflow splits and combines at the front as well as the rear borders of an aero-engine while it is running. The front and behind edges of the blade have the strictest standards for profile precision. The front and behind edges, on the other hand, are sophisticated, fragile, and inflexible constructions that are also incredibly thin, twisted as well, and have little bend [1]. Because of the hard environment conditions, the blades are typically manufactured from alloy which are resistant to high-temperature among which is titanium as well as nickel, and as a result, they are challenging to machine [2][3]. Furthermore, its dimensional precision is crucial in achieving the greatest performance. The high quality standards regarding the manufacture of blades, in addition to complex shapes or being very thin makes the use of conventional machining methods complicated. In this case, the use of ECM is suitable because of its advantages, such as: excellent surface quality, high material removal rates, ability to decrease tool electrode waste products, and ability to cut thin-walled structures with no cutting stress, ECM is an appropriate choice in this situation [4][5].

A well-designed flow field is essential for high efficiency. The quality of the flow field affects how stable ECM techniques are. The flow field is a significant element that directly affects the accuracy and stability. To initiate an electrochemical chain reaction, wash out the residues, and keep steady the conductivity, an electrolytic solution with high pressure could be used. The aim of flow field design is to improve the precision on anodic dissolution, maintain uniform flow, and enhance electrolytic flow parameters within the inter-electrode gap. The three most important flow modes used in the ECM of blades are the axial flow method [7], lateral flow method [6] where the solution of electrolytes runs from the front to the end edge [8], and flow field in the shape of a W [9]. By creating a condensed flow path between the margins of the electrolyte via lateral flow, by-product discharge is facilitated. The flow will be irregular, dirty, and less controllable at the inlet when the electrolyte is passively diverted at the intake (Figure 1a) [10]. During the axial flow field, the electrolytic solution enters the region between the blade tip and blade root.

Due to the electrolyte being divided by a workpiece, the pathways that include the concave along with convex parts will have poor velocity homogeneity [10]. The uneven speed that persisted throughout the lateral flow field approach is successfully corrected by the flow field in the shape of a W. A zone with an electrolyte mix may also be present at the leading and trailing margins (Figure 1b). Electrolyte solution flows in a W-shaped pattern into the cavity across the electrode, across the blade root as well as the body, and evacuate the cavity to the blade tip. The electrode deformation that occurred is lower during the W-shaped flow method as compared to alternative models due to the electrolyte pressures on both faces of the cathode layer are substantially comparable to each other [11]. It improves machining stability and precision as a result. The chaotic front and end edges that constitute the flow, on the other hand, have a negative impact on the quality of the samples (Figure 1c).

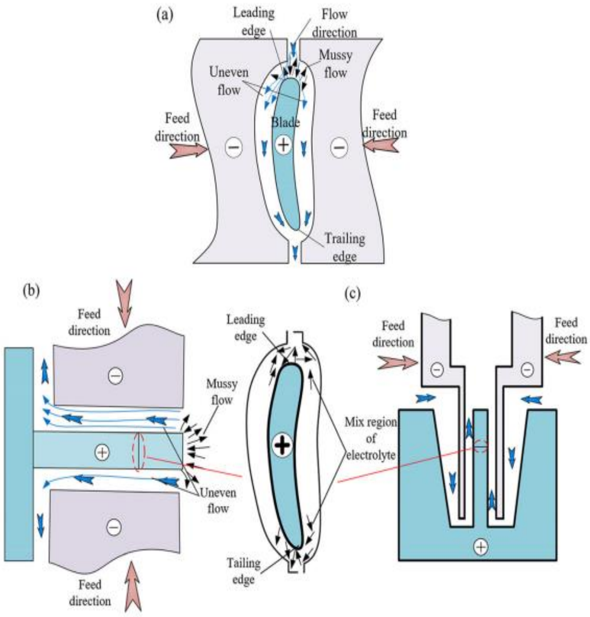


Figure 1. Difficulties with conventional electrolyte flow methods [10]

2. ELECTROCHEMICAL MACHINING AT BLADE LEADING/TRAILING EDGE WITH INDEPENDENT ELECTROLYTE SUPPLY

Many efforts have been made to increase the precision of the ECM blades. To increase the accuracy of the machining of the blade's front until it ends edges, a novel ECM technique centred on a feeding system with quadruple direction linked in sync with four cathodes has been developed [4]. It was suggested that a curved cathode sheet having micro-grooves could decrease the intensity produced by the stray electrical field by increasing the distance that exists between the cathode sheet's outer shells as well as the object that should be machined [12]. The effect of gap difference on blade deformation caused by tool vibration and electrolyte pressure is addressed in a further improvement [13]. Their findings suggested that they could guarantee machining precision while simultaneously increasing processing efficiency. Zong et al. enhanced the blade's precision using localized ECM having partly isolated cathodes [14], while Zhang et al. developed a cathode using a supplementary electrode that controls the field of electricity together with stray current [15].

In Figure 2 the flow method proposed by the Guo et al. where the electrolyte is provided at the front and end edges. Four inlets provide electrolyte flow to the pathways along the front and end edges as well as the concave plus convex regions of the surface. In this flow mode, the pace at which the front and end edges move can be varied. Both the flow line and speed are more uniform, therefore is better for material disposal, so that is one benefit.

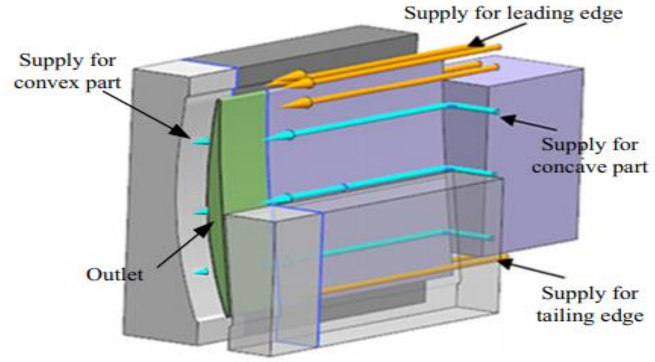


Figure 2. An illustration detailing the new flow method proposed [7]

2.1 Conditions at borderline

With the help of CFD calculations, the authors were able to create the mathematical model (Figure 3). Just like in the flow field in the shape of W, the concave as well as convex sections of this fresh flow method contain the fluid feed ports (ports 1 and 2) and an exit. The fluid feed ports (ports 3 and 4) are installed to offer a separate electrolytic feed at front and end edges. Boundary conditions include internal face boundaries, flow inlets, and flow exit boundaries. Throughout the experiment, there are changes in the pressure levels at the input and output borders.

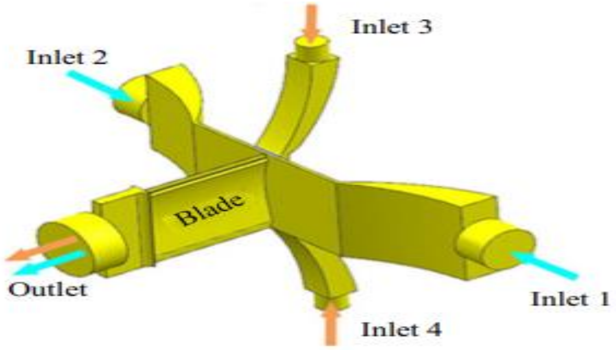


Figure 3. Mathematical model [10]

2.2 Optimizing flow area

The newly developed flow has a significant benefit over the flow mode in the shape of W in that it instantly influences the homogeneity of the fluid area pattern along all of the flow paths. A novel flow field proposal was created with the goal to efficiently regulate the reciprocal flow disturbance for various ways and to improve the homogeneity of the front and end edge borders.

2.3 Experimental conditions

Table 1 displays the specific circumstances that were applied in the experiment.

Table 1. Specific circumstances applied in the experiment [10]

Parameter	Condition
Workpiece	1Cr11Ni2W2MoV
Solution of electrolytes	20 wt% $NaNO_3$
Temperature of the electrolyte	30 °C
Conductivity of the electrolye κ	15.2 S/m
Entering pressure P_I	0.9 MPa
Discharge pressure P_O	0.15 MPa
Feeding v_c	0.4 mm/min
Current	20 V
Frequency	1000 Hz
Work cycle	75 %

The newly formed flow field mode proposed below (Figure 4a) was used to design and build the ECM fixture. The fixture's exterior is secured with anticorrosive materials epoxy glue as well as a plate of stainless steel with greater strength to avoid deformation over time. To facilitate pressure adjustments, the enter/exit tube, valve, as well as the pressure gauge are all connected to the enter/exit liquid channel (Figure 4b). The fixture was used to hold a blade blank while it was being machined. The exact water sealing and insulating function of the epoxy fastening ensures that electrolyte only flows through a specific flow channel.

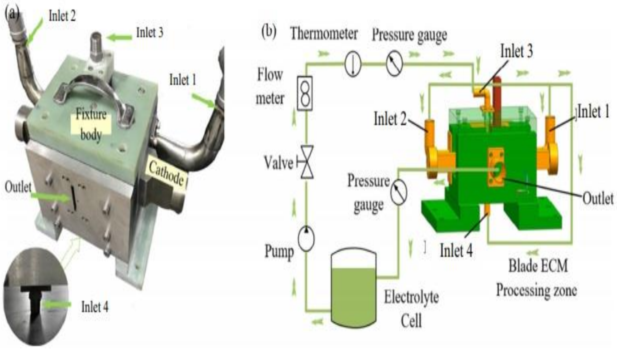


Figure 4. Diagram of the study configuration [10]

2.4 Processing stability analysis

As can be observed in Figure 5, the present state of both flow patterns changed throughout the machining operation. Additionally, during the start of the treatment, the current rises swiftly. The process equilibrium is reached in the proposed flow mode while the machining spacing is almost 4.8 mm. In addition, when employing the W-shaped flow approach, the electrical current varied and a short-circuit happened while inter-electrode gap was greater than 2.3 mm. In Figure 5 is shown that during the initial phase, manufacturing voids were distributed extremely unevenly, with tiny, localized voids that led to speed homogeneity at the front and end edges. The process equilibrium in the newly created flow method results in little current fluctuation. The cutting area gradually decreased and the current swiftly decreased as the cutting edge reached its ultimate stage. According to the study's findings, the process was more stable and the flow field was more evenly distributed than it was when the flow was in a W shape.

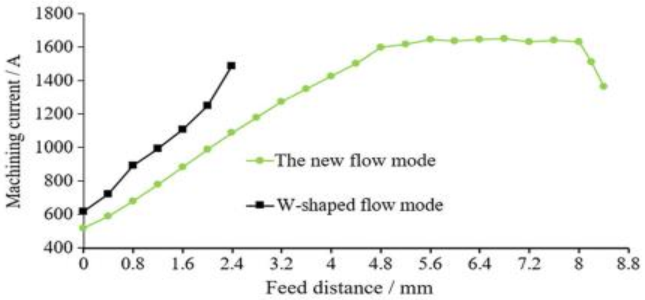


Figure 5. Modifications occurring throughout the machining method [10]

The quality of a blade is impacted by temperature rise as well as bubble. The upper as well as lower deviations of front and end edges varied with section after processing. Figure 6 shows how, in the two distinct flow mode conditions, the blade chord length altered. The chord length has a dropping initial trend, gradually rises throughout the flow path, and peaks on the blade's tip. The maximum and minimum chord lengths for the new flow mode are 40.256 mm and 40.193 mm, with a difference of 0.063 mm between them. The W-shaped flow method's maximum and minimum chord lengths, which differ by 0.116 mm, are 40.212 mm and 40.096 mm. The distribution of the machining is implied by this.

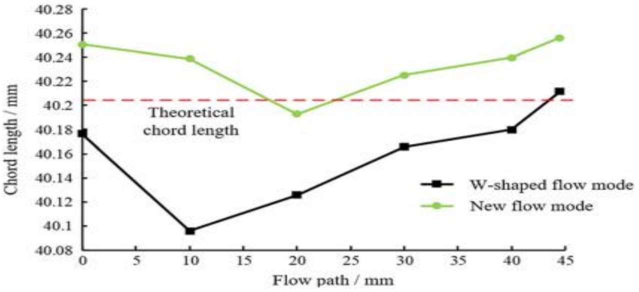


Figure 6. Blade chord size changes throughout the flow direction [10]

2.5 Surface quality

The concave section of the flow mode in the shape of W had surface roughness of Ra 0.303 m while the convex section had a surface roughness of Ra 0.307 m (Figure 7a). The concave and convex sections of the newly developed flow mode had surface roughness values of Ra 0.245 m & Ra 0.283 m, respectively (Figure 7b). The electrolyte quickly eliminates electrolytic by-products and bubbles as a result of the better flow mode, decreasing the blade's surface roughness values.

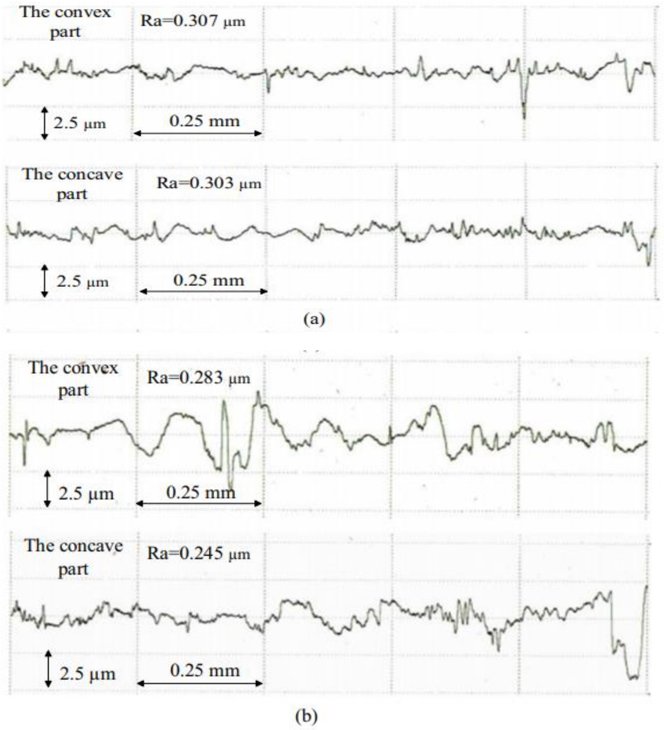


Figure 7. Blade surface quality [10]

3. MULTI-PHYSICAL MODEL OF BLADE ECM TO IMPROVE FLOW FIELD USING VERTICAL FLOW

According to the study of modeling and experimental outcomes, it might be inferred the fact that the primary cause of the errors is due to the fluid electrolytes flowing smoothly at the entrance port of the bent spherical groove. The electrolyte's exit port may become clogged with the bubbles produced by ECM, which lowers anode elimination of material and the electrolyte conductivity. In this case, an error happens on the bent spherical groove's exit port [16].

Another approach to improve the flow field, considers the impact of gravitational forces on hydrogen bubbles. A multi-physical model that considers fluid flow, the electric field, but also the temperature as well as reacting agent transportation was created in order to explore and analyze the shifts in the gas's void percentage and heat across the flow path.

Huang et al. [17] observed that the theoretical value of the modeling had been nearer to the real value obtained along with the error raised over time as the flow electrolyte direction increased during their modeling investigation into machining processes of the aero-engine parts such as blades using electrochemical machining. Overall, the study model of the ECM process can accurately simulate the real ECM technique, and the results of the modeling mostly agree with those of the test. As a result, it is possible to decrease the testing period as well as improve the ECM of curved holes [16].

3.1 Blade ECM bubble dynamics utilizing vertical flow

The convex along with concave pathways within the blade experience uneven flow when using the lateral flow method, and the entry point has a chaotic flow (Figure 8). Since the electrolyte flows in individually via each canal from the two components, the amounts that flow in each channel can be independently controlled [5]. During its axial flow phase, the electrolyte typically flows laterally from base to top. Nevertheless, an important bubble rate arises close to the outflow as a result of the ECM-generated bubbles accumulating across the flow channel. As a result, the machining deviation increases towards outflow while the inter-electrode gap gradually gets smaller from the entrance to its exit (Figure 9(a)). The development of a vertical flow approach, in which its electrolyte moves uphill from base to top, addresses the drawbacks associated with existing flow systems. Vertically flow bubbles act differently from horizontally flowing bubbles because of gravity, having a higher bubble speed and a lower bubble frequency [18].

The gravity gradient causes buoyancy to rise vertically. Since buoyancy comes transverse towards the path of electrolytic flow, horizontal flow has an impact on bubble motion (Figure 9(b)). The buoyancy orientation coincides with the flow orientation as it can be seen in the Figure 9(c) when a vertical flow it's used. Since the density of the electrolytic solution in vertical flow is 1146 g/l, which is significantly higher than the density of air (0.089 g/l). The bubble speed and rate are both greatly influenced by buoyancy. Because of this, the bubble rate is low, which could improve the conductivity's even distribution. Vertical flow can enhance machining precision in the blade ECM because there is little machining fluctuation at the output (Figure 9(d)).

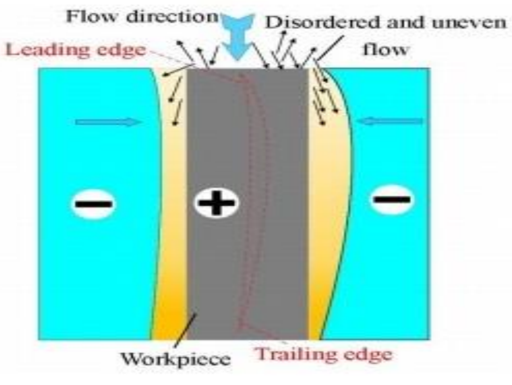


Figure 8. Lateral flow's drawbacks [18]

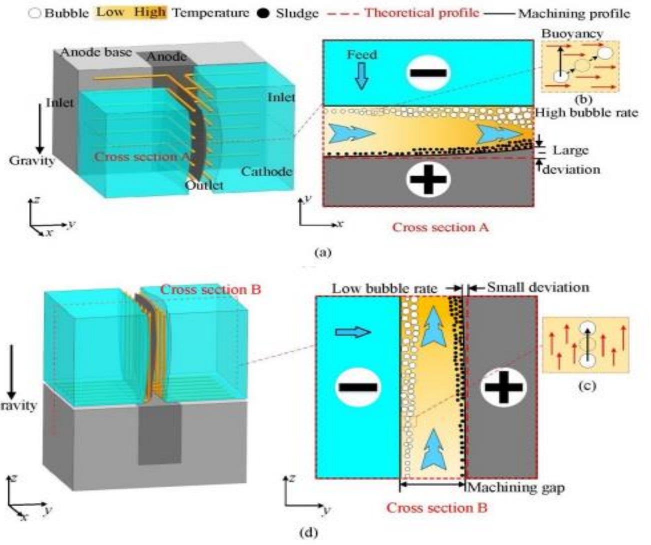


Figure 9. Illustration of a blade electrochemical machining using the axial flow approach [16]

The experimental set-up for this study's ECM of blade is shown in Figure 10(a). Neutral NaNO3 solution has the ability to passivate, making it useful for producing high-quality products [19]. The front and back portions of the fixture are composed of epoxy. As they are inserted in the housing via the supply passages along each side of the machine tool, the cathodes are fed to one another at a constant speed. Both sides of the bottom intake are used for the electrolyte's entry, while the top outlet is used for its escape. Electrolyte runs upward between the root and the tip, filling the space between the electrodes. The electrolyte flows in the direction that is counter to the gravitational pull.

With the use of experiments and a vertical electrolyte flow, the simulations' accuracy was confirmed. Table 2 contains a list of the experimental conditions.

Table 2. Research circumstances [18]

Parameter	Setting
Workpiece	Inconel 718
Cathode	stainless steel (304)
Solution of electrolytes	$NaNO_3$
Temperature of the electrolyte	302.65 K
Feed rate	0.5 mm/min
Inter-electrode gap	9.76 mm
Current	DC-18 V

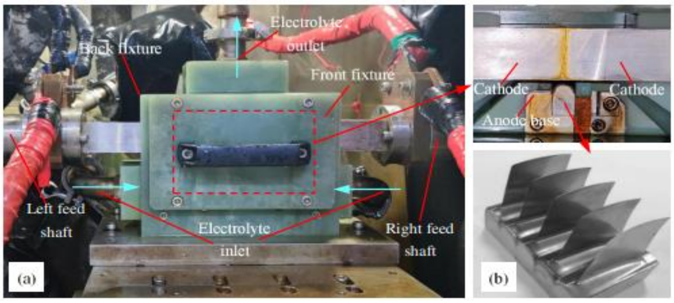


Figure 10. Novel method for the blade's ECM [18]

During investigation, there were no Left feed shaft Right feed shaft, 18 unusual short-circuit sparks, the current changed smoothly, and the machining time was 19.5 minutes. Figure 10(b) displays the machined blades that were the result of five processing tests.

3.2 Surface condition

Two rectangular parts (1, 2) and ten lines (D1–5, E1–5) close towards the blade's base and top were chosen for the experiment, as shown in Figure 11. The surface topography was viewed using a SEM (HITACHI Regulus 8220) and the Keyence 3D feature evaluation tool. The roughness was measured along each line with the help of a Taylor-Hobson profiler.

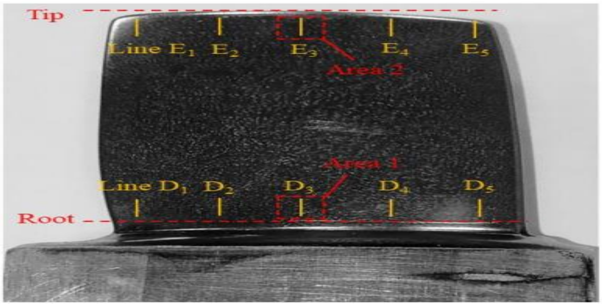


Figure 11. Electrochemical machining of the blade- points of observation and test sections [18]

The results of the topographic and roughness surface evaluations are shown in Figures 12 and 13. The small black patches present within regions 1 as well as 2 of Figure 12 are electrolytic pits caused due to the materials' unequal erosion. Wang J. et al. [20] also reached the same conclusions. It is clear that section 1 has greater smoothness because it is located next to the machined blade's base.

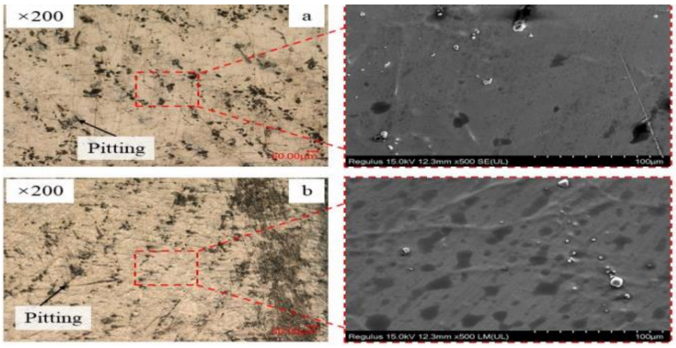


Figure 12. Topographic and roughness surface evaluations of the study [18]

In Figure 13 (a) along with Figure 13 (b) illustrates the surface roughness across the selected paths D1 to D5 and E1 to E5. Surface roughness Ra fluctuated between 0.193 m at the D3 line and 0.248 m at the D4 line at the base. At the top, the surface roughness Ra oscillated between the values and 0.282 µm at E3 to 0.349 µm, at E4.

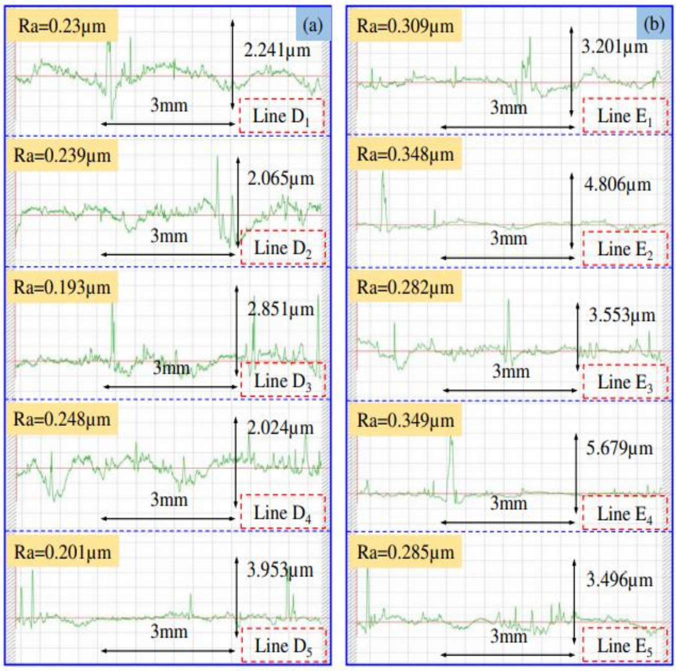


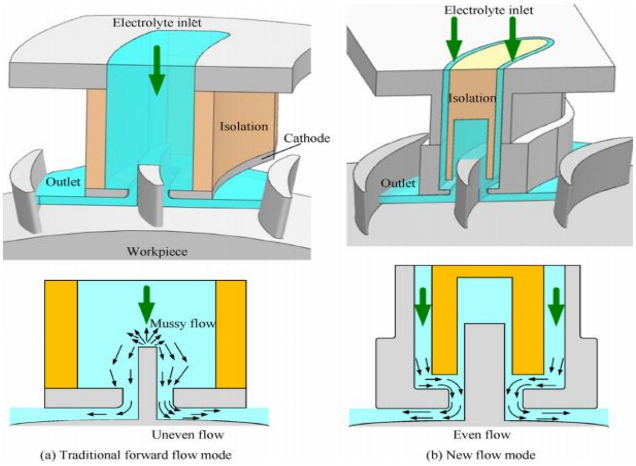
Figure 13. Surface quality of the experiment [18]

In ECM, the surface quality is influenced by the current density. Due to the significant potential gradient in the solution, the metal dissolves only where the surface roughness is greatest, leaving a smooth surface in its wake. The simulation's results demonstrate that the gas fraction of voids increases with the orientation of the flow. According to the study's results, the base part has a superior surface roughness than the top part. The quality of the surface similarly declines as the current density does. According to the experimental findings, reducing the gas vacancy percentage can enhance the precision of the machining. Surface roughness of 0.35 microns may be attained using a vertical electrolytic flow, while the machining variation ranged from 3.4 microns at the minimum to 75.6 microns at the maximum.

4. THE USE OF ELECTROCHEMICAL TREPANNING FOR MACHINING AXIAL BLADES

In the present study a flow field's stability was increased by using a significant flow rate. The suggested methodology was evaluated through both simulated and real tests. Electrochemical trepanning was the method of machining used to produce an axial blade having an unchanged area. Figure 14(a) provides a schematic representation of the conventional electrochemical trepanning technique. By this procedure, the blade is formed as a tool cathode, and a compartment that runs across of the cathode bottom protects the workpiece. The solution of electrolyte penetrates between the space of the cathode bottom and the protective compartment and then travels via the protective compartment and the cathode's inside. It eventually exits through the port near the area that is processed ahead of the cathode to ensure optimal operation. By extracting the dissolved metal and applying heat, it accomplishes this. In this conventional flow pattern, the electrolyte divides into several routes that pass via the concave portion pathway, the front edge pathway, along with end edge pathway as it collides with the blade. The streamlines of the electrolytic influx are disorganized. Furthermore, because different channels randomly get distinct quantities of electrolytic solution, the electrolyte quantity becomes unpredictable and causes variations in flow across the processing area. Low machining efficiency and process instability may result from these two occurrences.

The new flow mode enables controlled and constant electrolyte flow during operation as a result. Weak flow rates are particularly damaging because they prevent further ECM from occurring, particularly in locations lacking fluid within the machining area's flow field. The electrolyte velocity is a key variable for the electrochemical trepanning since it controls the increase in temperature as well as providing an unstable flow.



(a) Traditional forward flow mode
(b) New flow mode

Figure 14. Illustrations of the flow method in the electrochemical trepanning [21]

4.1 Experiments and analysis

The epoxy resin-built protective container was fixed within the cathode base. An alloy of tungsten and copper, which can survive the sparks produced during machining, was created to manufacture the cathode. Figure 15 depicts the layout of the laboratory where the blade was machined as well as the model's design. In Table 3 is a list of the properties of the electrochemical trepanning technique. The object being worked on was 37 mm thick, was made of a nickel superalloy and with an exradius of 242 mm. The research equipment's constraints led to a maximum flow rate which reaches a value of 4.5 m^3/h. Additionally, the experiment also employed flow rates that included 1.0 m^3/h and 3.0 m^3/h. Variations in the cathode's feeding rate for each of these three flow rates were looked into. To investigate how the flow rate influences the machinability, the rate of feed was first set at 0.5 mm/min. Furthermore, the investigation was used also to determine how well the machining process works and how well the finished blade turns out. Following that, the speed was raised progressively at a rate equal to 0.5 mm/min.

Tabel 3. Electrochemical machining conditions [21]

Condition	Value
Current	20 V
Electrolyte solution	20 wt% $NaNO_3$
Temperature	30° C
Machining depth	8.2 mm
Inter-electrode gap	0.5 mm
Feed velocity	0.5–4 mm/min

A new flow mode that incorporates partial separation for regulating electrolyte flow into several channels was created as a way to address the drawbacks of the classic flow mode (Figure 14(b)). In this mode, both the entering and ending edges of the blade's profile might have electrolyte flowing through them. In accordance with the geometry of the blades, the electrolyte flow is separated, resulting in is a big flow route which has the role to stabilize the flow. In addition, it has role of supplying electrolyte uniformly to each of the pathways. Altering the distance among the isolator along with the cathode is another way to improve the flow condition. This improvement corresponds with how the flow field is distributed within the cathode and workpiece gaps.

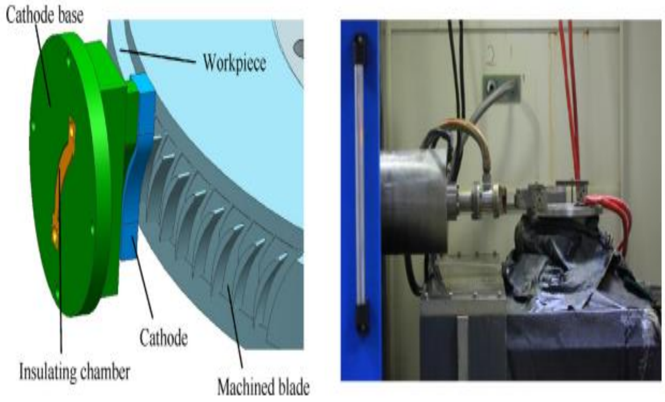


Figure 15. Modelling and laboratory installation for electrochemical trepanning of a blade [21]

5. CONCLUSIONS

There were three different electrolyte flow modes shown. Results from experiments and simulations showed that the flow field had improved and that the machining techniques and flow modes were appropriate. In order to improve the surface for future study, the cathode feed rate might be raised. Additionally, it is necessary to increase the precision of the machining across the flow channel in vertical flow.

By giving the enter/end edge machining area a distinct source of fluid, we may improve the flow field uniformity. The electrolyte flow became more consistent, according to the results, allowing for a more even flow throughout the processes. Moreover the new flow mode provided had better processing conditions. The stability and accuracy across the flow path are better than than the W-shaped flow method. Effectively increasing bubble velocity along with decreasing the gas void fraction may be accomplished using a vertical flow method. In comparison with horizontal flow, the vertical flow reduced both the output temperature and the gas void fraction. As a result, the conductivity increased, improving the machining precision. Due to the numerous bubbles that constantly get produced, the machining process is affected.

The simulation findings demonstrated that as the flow rate increased, the flow field's velocity rose significantly and its distribution became more uniform. It was shown that the rate of feeding limitation dramatically rose when the flow rate increased. Clearly, improvements were made to the surface roughness and blade taper.

The latest developments in electrochemical machining (ECM) of aeronautical parts are covered in this paper. These involve designing and developing a novel cathode tool, simulating the flow field, and designing for uniform electrolyte flow. Future research will focus on a number of critical areas, including dissolving characteristics, machining precision across the flow path, machine tool, and creating unique techniques for machining.

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