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Short Communication

Electrochemical Machining of Turbulated Cooling Channel Using Gelatinous Electrolyte

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The turbulated cooling channel in turbine blades is a typical special-shaped inner wall structure that can significantly enhance the cooling effect of gas turbine blades. The use of electrochemical machining to manufacture cooling channels has the advantages of high efficiency and no residual stress. However, the stray current removal cannot be completely avoided using liquid electrolyte. Consequently, an ideal inner wall structure, consisting of a turbulated cooling channel, cannot be obtained. In this paper, an electrochemical machining method is proposed in which a gelatinous electrolyte is used to meet the machining requirements. Through the cross-linking of polymers, a liquid electrolyte is filled into the gaps of the gelatinous network structure to form a gelatinous electrolyte. The stray current removal due to the flow of the liquid electrolyte is avoided. A gelatinous electrode of diameter 5 mm was prepared. A turbulated cooling channel with a rectangular cross section and rib height of 0.8 mm on nickel is obtained. The profile view of the experimentally prepared turbulated cooling channel structure has a rectangular cross section and maintains good straightness. The proposed machining method is expected to be widely applicable to electrochemical machining of the inner wall structures in narrow spaces.

Keywords: electrochemical machining; turbulated cooling channel; gel; electrolyte; rib

1. INTRODUCTION

In modern gas turbines, cooling air is transmitted through special flow passages inside the blades to obtain cooling effect of up to several hundred degrees. This method has become an important special field in gas turbines. Among several internal cooling methods, the turbulated cooling channel has received extensive attention and research [1-2]. The turbulated cooling channels in turbine blades are typical special-shaped inner wall structures. By increasing the heat dissipation area of the inner cooling hole, both thrust-to-weight ratio and pressure ratio of the engine are greatly improved, as shown in Figure 1 [3]. Recently, most research studies on cooling channels in blade inner walls have focused on the influence of the shape and parameters of the rib structure on the cooling effect. The effect of different shapes of cross sections on the heat transfer efficiency of the turbulated cooling channels in the blades has been studied. It is concluded that when the cross sections of the inner wall microstructures of the turbulated cooling channels are of rectangular or trapezoidal shape, the integrated cooling effect has apparent advantages [4-5].

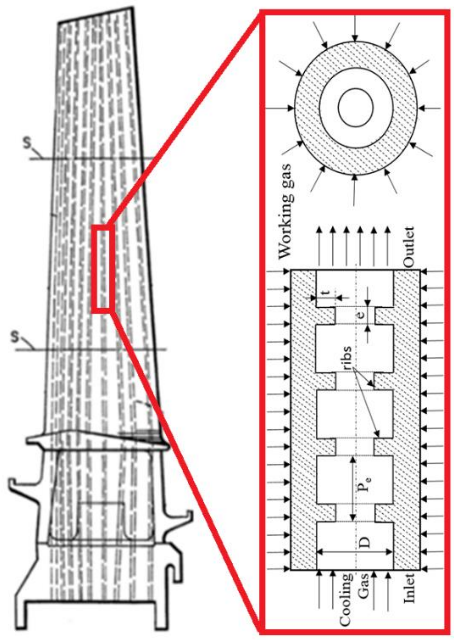

Figure 1. Schematic of turbulated cooling channel in turbine blade.

Electrochemical machining is a processing technology based on the principle of electrochemical ion removal to dissolve the workpiece in a small amount [6-8]. Because the technology requires no contact, it has the advantages of no residual stress, no recast layer, and no dependence on material hardness [9-10]. The electrodes for electrolysis are theoretically free of loss; therefore, electrodes that are small in size with a complicated shape can be used for machining in a narrow space. The infrared-heated electrolyte can be used to improve the accuracy of the electrochemical machining [9-10]. Meanwhile, a through-mask electrochemical machining process and electrochemical machining process using masked cathode have been investigated [11-15]. Electrochemical machining with auxiliary anode and iron coating have also been studied [16].

The inner wall structure of a turbulated cooling channel is currently being manufactured using electrochemical machining [17-19]. An electrode that has periodic insulating properties on the surface based on lithography was used for electrochemical machining to realize the processing of the turbulated cooling channels [17]. However, the photoresist surface resulting from this technology has poor adhesion, making it easy to fall off during the electrolytic processing. In addition, the machining process is complicated and the cost is high. Another electrochemical processing method has also been reported for the turbulated cooling channel. In this method, a metal tube sidewall is first processed to obtain several grooves, and then the grooves are coated with insulating glue to form a partially insulated cathode. Next, a turbulated cooling channel with an arc-shaped cross section is successfully manufactured [19]. However, owing to the limitations of the adopted processing methods, the existing processing methods for turbulated cooling channels use photoresist or insulating glue on the surface of the cathode such that the flow of the electrolyte still causes stray current removal, resulting in the inability to form an inner wall microstructure in the turbulated cooling channel, which is of rectangular or trapezoidal shape, thus affecting the cooling effect.

In this paper, an electrochemical processing method using gelatinous electrolyte is proposed to resolve the problem of stray current removal in the electrochemical machining process of turbulated cooling channels. Through the cross-linking in polymers, the liquid electrolyte is filled into the gaps of the gelatinous network to form the gelatinous electrolyte. The fixed-point electrolytic removal of a small amount of materials is achieved by positioning and moving gelatinous electrolyte while avoiding the stray current removal caused by the flow of the liquid electrolyte, and the processed product is discharged by flushing pure water.

2. MATERIALS AND EXPERIMENTAL

The schematic of the electrochemical machining of a turbulated cooling channel using gelatinous electrolyte is shown in Figure 2. The tool electrode is inserted and rotated in the original straight hole of the cooling channel. The tool electrode with gelatinous electrolyte is connected to the negative pole of the power supply, and the workpiece is connected to the positive pole of the power supply. Pure water flows from top to bottom in the gaps between the tool electrode and workpiece. The tool and the workpiece are connected to each other through a gel containing an electrolyte solution that has electrical conductivity, and thus, electrochemical processing can be performed through ion exchange.

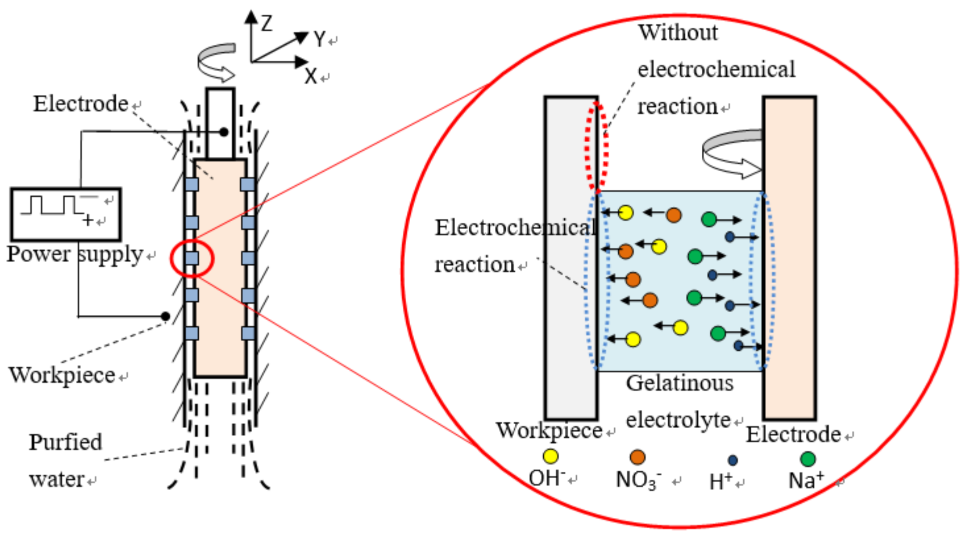

Figure 2. Schematic of the electrochemical machining of turbulated cooling channel using gelatinous electrolyte.

In the machining process, gelatinous electrolyte replaces the traditional electrolytic working fluid. The electrochemical machining is carried out only in the areas in contact with the gel, and no electrochemical reaction occurs in the areas that are not in contact with the gel, effectively alleviating or even eliminating the stray current corrosion during the electrochemical processing, thereby achieving the fixed-point machining of the turbulated cooling channel structure. In addition, the electrochemically processed product is discharged in time by the rotation of the tool electrode and the flushing of pure water.

The core difference between the electrochemical machining process of bamboo pore structure using gelatinous electrolyte and the conventional electrochemical processing is the use of gelatinous electrolyte. The properties of the gelatinous electrolyte directly affect the product quality and processing efficiency of the electrochemical machining process. In the experiment, a preparation method was used to machine the gelatinous electrode with periodic gel zones, as shown in Figure 3. (1) Gel composition preparation stage (Figure 3a): Solid sodium nitrate, dimethylallylamine (DMAA), clay, and diethyl allylphosphonate (DEAP) are weighed separately according to the given ratio (4.75% DMAA, 0.25% DEAP, 5% Clay, 8% NaNO3), sequentially added to 5% and 8% sodium nitrate solution, and then stirred until a clear solution is obtained. Due to the influence of factors such as temperature and dispersion of the medium, the stirring time ranges from 30 min to 60 min. (2) Gel suspension treatment stage (Figure 3b): The prepared suspended gel liquid is introduced into the gel preparation mold. In particular, to obtain good contact properties between the electrode and prepared gel, the electrode is used as the core of the gel preparation mold in the experiment. The entire mold is then placed under ultraviolet light to achieve an internal cross-linking reaction in polymers of the suspended gel liquid, and thus, to obtain a gelatinous electrolyte with good solid forming ability, as shown in Figures. 3c) and 3d). After the prepared gel is wetted, the mold is disassembled to obtain a gelatinous electrode that integrates the electrode and gel. (3) Repeated preparation of several gel segments (Figure 3e): The gel preparation process in step (2) is repeated to obtain a single-electrode multi-gel structure. The number of gel segments is decided according to the number of rib structures in the bamboo joint, and the gel electrode finally prepared is shown in Figure 3f).

The gel forming performance is mainly affected by the mass fractions of monomer, initiator, crosslinker, and electrolyte solution concentration inside the gel system. The prepared gel shown in Figure 4 is mainly composed of a multi-layered three-dimensional network structure formed by stacking monomers. Certain channels are formed between the network structure, and their diameters are mainly affected by the concentration of the electrolyte solution and constituent materials of the gel. A larger pore size not only corresponds to more electrolyte solution that can be stored in the gelatinous electrolyte, but also promotes the flow of electrolyte solution, ion transfer, and improves the machining ability and conductivity of the gelatinous electrolyte.

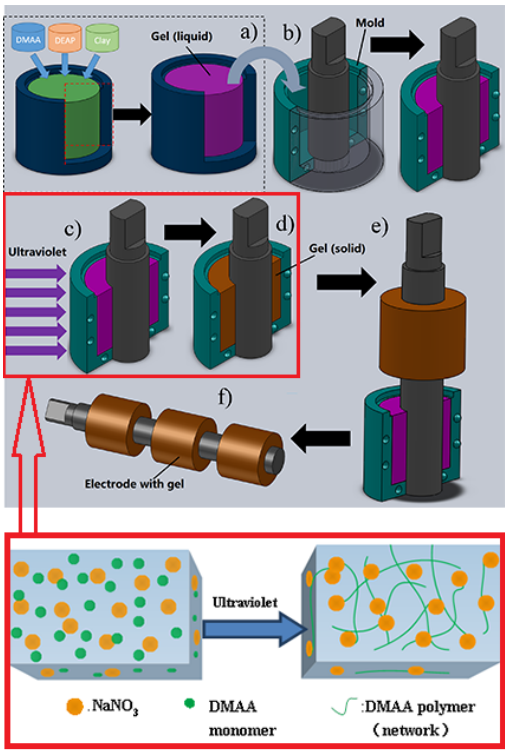

Figure 3. Preparation of electrode with gelatinous electrolyte: a) Gel composition preparation stage; b) Gel suspension treatment stage; c) The entire mold with gel liquid; d) The entire mold with gel solid; e) Repeated preparation of several gel segments; f) Electrode with gelatinous electrolyte.

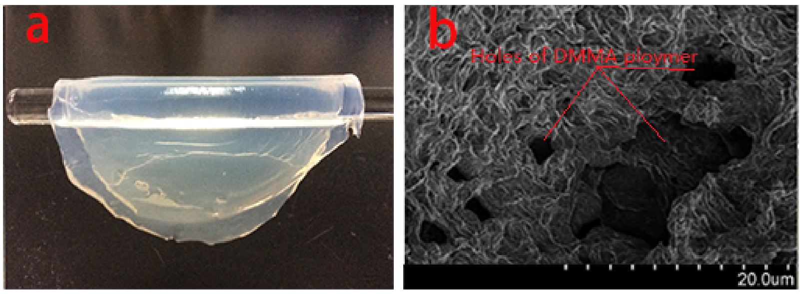

Figure 4. Different visual representations of gel (4.75% DMAA, 0.25% DEAP, 5% Clay, 8%NaNO3): a) photo of gelatinous electrolyte; b) SEM of gelatinous electrolyte.

Figure 5(a) shows the diagram of the experimental system of the electrochemical machining process using gelatinous electrolyte, mainly consisting of a machining controller, tool setting and machining inspection, (direct current and pulsed) power supply, and motion system. During the machining process, the machining controller sends a control signal to the motion control system, thereby realizing the XYZ axial movement of the entire experimental setup, and simultaneously sending and receiving signals to/from the power supply through the machining controller to control the on/off of the machining process using gelatinous electrolyte. Figure 5(b) shows the voltage waveform during the machining process without significant fluctuations, which is always maintained within the range of 10±0.1 V. Figure 5(c) shows the curve reflecting current variation during the machining process.

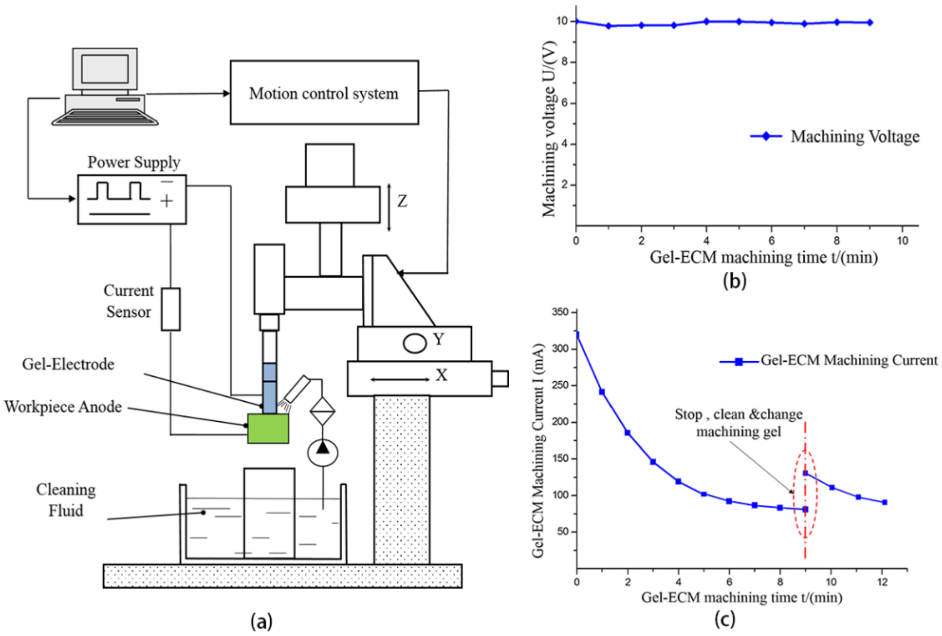

Figure 5. Machining system, current, and voltage during machining process: (a) schematic diagram of machining system; (b) voltage waveform during machining; (c) current waveform during machining.

In the initial stage, the machined contact surface is not covered with machined products, and hence, the gel electrolysis reaction is rapid, and the overall efficiency of the machining system is high. The current is stabilized above 200 mA in the first minute of the electrochemical machining process, and its peak appears at 320 mA in the initial stage of the gel electrochemical machining process. As the machining process progresses, the current gradually decreases and tends to stabilize. In the ninth minute of the machining process, the current is less than 1/4 of its initial value. During this time, the speed of the electrochemical machining is too low. Consequently, the electrode contact surface is cleaned by rotating the electrode and washing with the electrolyte. After the cleaning is completed, the current recovers from 80 mA to 132 mA, the product adsorbed on the gel surface is removed, and the conductivity of the electrolytic working gel is restored. As shown in the Figure 5(c), red circle represents the time when the system is shut down for cleaning during the gel electrochemical machining process, which is not included in the overall time of the electrochemical machining process.

3. RESULTS AND DISCUSSION

A gelatinous electrode of diameter 5 mm was prepared by applying a preparation method (explained in Section 2.2) that uses DMAA (4.75%), DEAP (0.25%), clay (5%), and NaNO3 solution (8%), as shown in Figure 6(a). The voltage of the power supply was 6 V, the electrode rotation speed was 50 rpm, and the electrochemical machining of the turbulated cooling channel was performed on pure nickel. The results are shown in Figure 6. As the machining process progresses, the cleaning process exhibits a nonlinear characteristic. At the beginning, the electrochemical material removal speed is relatively fast, which reduces when approaching the machining target size. After 12 min, a turbulated cooling channel with rectangular cross-sectional shape and a rib height of 0.8 mm is obtained, as shown in Figure 6(c). Using the above-mentioned concentration of liquid sodium nitrate electrolyte under the same power supply voltage (6 V), the material removal in the bamboo joint was uneven, thereby showing a serrated distribution. During the machining process, the surface roughness increased significantly and stability reduced, making the efficient machining of turbulated cooling channel structure impossible, as shown in Figure 6(d). Figure 7 shows the profile view of the experimentally prepared turbulated cooling channel structure has a rectangular cross section and maintains good straightness.

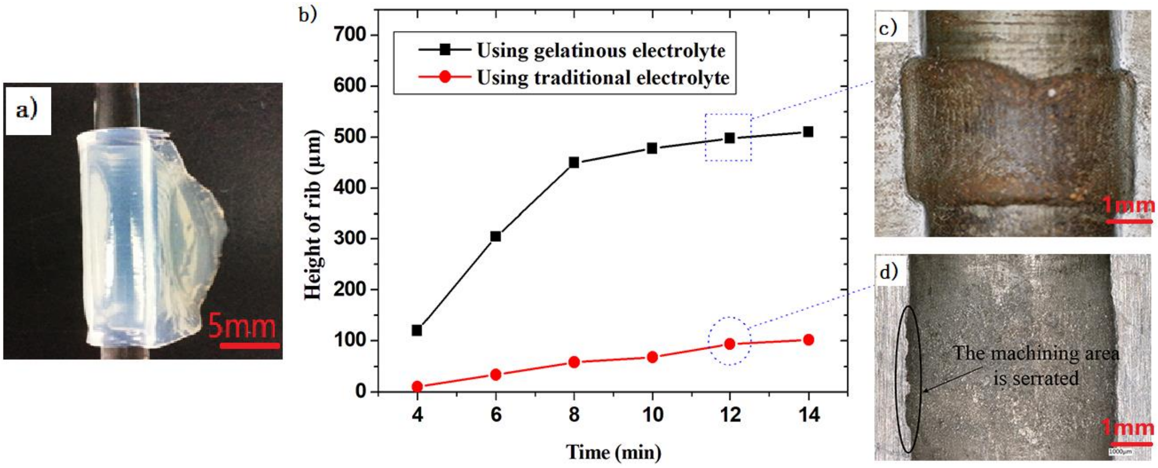

Figure 6. Comparison of electrochemical machining experiments using gelatinous electrolyte and traditional liquid electrolyte: a) the original electrode (4.75% DMAA, 0.25% DEAP, 5% Clay, 8%NaNO3); b) experiments results; c) machining area using gelatinous electrolyte (material: Ni, voltage: 6V, electrode rotation speed:50rpm); d) machining area using liquid electrolyte (material: Ni, voltage: 6V, electrode rotation speed:50rpm).

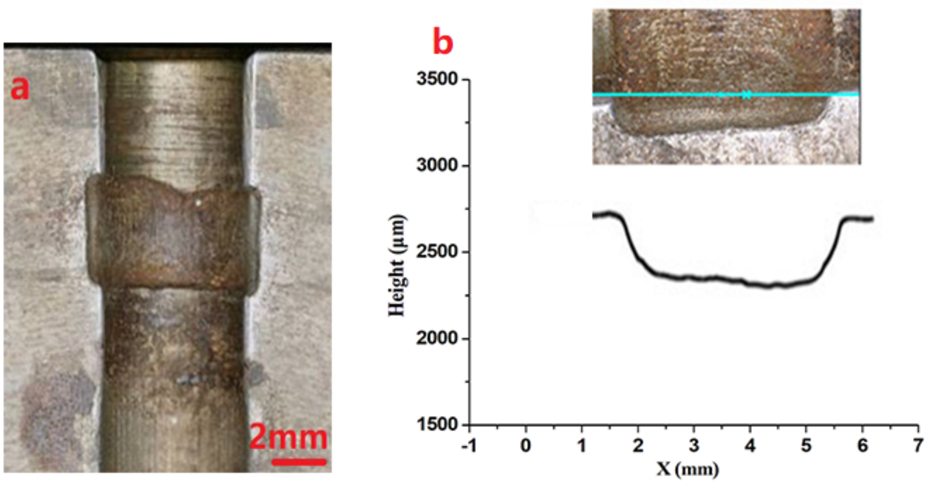

Figure 7. Profile of turbulated cooling channel after electrochemical machining using gelatinous electrolyte: a) photo of turbulated cooling channel; b) cross section and rib height of turbulated cooling channel structure.

In the process of electrochemical machining using traditional liquid electrolyte, the flow of electrolyte leads to the distribution of current in both the processing area and the non-processing area. The stray current in the non-processing area affects the machining accuracy, especially at the sharp angle and edge. Improvement on machining accuracy by using nonlinear electrolyte and ultra-short pulses power supply have been investigated. However, stray current removal at the sharp angle and edge cannot be avoided effectively. In electrochemical machining using gelatinous electrolyte, there is no electrochemical reaction between electrolyte and workpiece in the non-processing area, which can avoid stray current removal at the sharp angle and edge. Therefore, the proposed process is suitable for machining structure with obvious edge and sharp angle. It can be seen from Figures. 6 and 7 that the gelatinous electrolyte can effectively suppress stray current removal compared to the conventional liquid electrolyte, and is suitable for the electrochemical machining of the turbulated cooling channel structure.

In the process of electrochemical machining using gelatinous electrolyte, the voltage affects the machining speed and the processing quality. The processing speed increases effectively with the increases of the machining voltage, result in increasing the electrochemical reaction production. The production remains on the surface of the electrodes to worsen the machining stability. Meanwhile, the gelatinous electrolyte will breakdown due to the overall gel structure collapse and a large number of dehydration failure when the machining voltage is very high. For the experiment, the surface quality and processing speed of gel electrolytic processing can be controlled by optimizing the machining voltage.

During the machining process, the electrolyte solution concentration inside the gel will increase rapidly, which will destroy the internal structure of the gel, leading to the failure of the gel. In order to prevent the gel from the invalidation, and retain a good electric conductivity, the gel should be placed in the aqueous solution with the same concentration before and after the machining, the internal ions will exchange to keep the balance between them. Meanwhile, the gel should be inspected every five minutes, and it will be placed in the aqueous solution with the same concentration as the step one when the electrolyte solution inside the gel is oozed out. The machined surface will be covered with the gel, which not only decreases the recycling times of the gel, but also does great damage to the machined surface. To avoid the damage, it is essential to pour the special cleaning fluid with high speed into the primary-hole to clean the residual gel and the impurities generated in the process. The special liquid should be non-corrosive to the Aluminum to ensure the accuracy of surface.

Many methods of reducing stray corrosion of electrochemical machining have been studied to improve machining accuracy by researchers. Shaped cathode prepared by means of mask method is usually used. A through-mask electrochemical machining process has been developed to fabricate hole-array that are difficult to cut using traditional mechanical machining [11-13]. Electrochemical machining process of micro holes and grooves using masked porous cathode has also been investigated [14-15, 18-19]. The masked cathode is used to ensure that the distribution of electrical field on the machining surface is uniform relatively. Compared with these methods, this study changes the electric-field distribution by restricting the flow of electrolyte to solve the problem of the stray corrosion of electrochemical machining. The cathode with mask cannot shield the stray corrosion completely due to a gap between anode and cathode exists. There are many vertical or sharp corners in the cross section shape of the turbulated cooling channel, so the mask method cannot meet the requirements of machining of turbulated cooling channel. In additional, electrochemical machining with auxiliary anode has been studied to improve the localization of electrochemical corrosion significantly [16]. The auxiliary anode was consisted in the mask to reduce the lateral undercutting to improve localization of fabrication of surface texture. However, the inner wall structure of a turbulated cooling channel is very narrow. The auxiliary anode, which is out of touch with cathode, cannot be placed in processing area.

4. CONCLUSIONS

Electrochemical machining using a gelatinous electrolyte can effectively suppress the problem of stray current corrosion. When this technique is applied to the electrochemical machining of a cooling channel, a turbulated cooling channel structure of rectangular cross section can be obtained.

The gelatinous electrolyte prepared using DMAA (4.75%), DEAP (0.25%), clay (5%), and NaNO3 solution (8%) is suitable for the electrochemical machining of pure nickel materials.

The removal speed of the electrochemical machining process using gelatinous electrolyte exhibits a nonlinear characteristic. At the beginning, the electrochemical removal speed is relatively fast. However, the material removal speed reduces when approaching the target size for machining.

In the future, we will use the gelatinous electrolyte to carry out research on the machining technology of other metal materials (i.e. steel, titanium). At the same time, the machining method proposed in this paper is expected to be widely applicable to the electrochemical machining of inner wall structures in narrow spaces.

AUTHOR CONTRIBUTIONS
Conceptualization, K.W.; Formal analysis, K.W.; Investigation, K.W., Y.W. and Q.S.; Methodology, Y.W. and Q.S.; Project administration, K.W.; Supervision, K.W.; Writing – original draft, K.W.; Writing – review & editing, Y.W.

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CONFLICTS OF INTEREST
The authors declare no conflict of interest.

References

1. P. Singh, Y. B. Ji and S. V. Ekkad, *J. Turbomach.*, 141 (2019) 071003.
2. J. Pattavanitch and S. Hinduja, *CIRP Ann.*, 61 (2012) 199.
3. C. P. Lee and R. S. P. Chiu, *U.S. Patent*, (2003) 6582584.
4. R. Kamali and A. R. Binesh, *Int. Commun. Heat Mass Transfer*, 35 (2008) 1032.
5. T. Alam, R. P. Saini and J. S. Saini, *Renewable Sustainable Energy Rev.*, 31 (2014) 289.
6. C. S. Gao, Z. Liu, Y. Qiu and K. Zhao, *Int. J. Electrochem. Sci.*, 15 (2020) 94.
7. D. Y. Wang and J. C. Zhang, *Int. J. Electrochem. Sci.*, 14 (2019) 9741.
8. Z. Wang, S. Q. Qian, H. B. Cao, H. Zhang and K. Bao, *Int. J. Electrochem. Sci.*,11 (2016) 6126.
9. R. Thanigaivelan, R. M. Arunachalam, M. Kumar and B. P. Dheeraj, *Mater. Manuf. Processes*, 33 (2018) 383.

10. S. Kunar and B. Bhattacharyya, *Mater. Manuf. Processes*, 3 (2019) 487.
11. S. Q. Qian, Y. Y. Wu, K. Bao, Y. D. Zhou, H. B. Cao and H. Zhang, *Int. J. Electrochem. Sci.*, 14 (2019) 9273.
12. X. L. Chen, N. S. Qu and H. S. Li, *Int. J. Adv. Manuf. Technol.*, 80 (2015) 1577.
13. G. Q. Wang, H. S. Li, N. S. Qu and D. Zhu, *J. Mater. Process. Technol.*, 234 (2016) 95.
14. X. L. Chen, G. C. Fan, C. H. Lin, B. Y. Dong, Z. N. Guo, X. L. Fang, N. S. Qu, *J. Mater. Process. Technol.*, 276 (2020) 116406.
15. X. F. Zhang and N. S. Qu, *Int. J. Adv. Manuf. Technol.*, 99 (2018) 1661.
16. S. Q. Qian, F. Ji, N. S. Qu and H. S. Li, *Mater. Manuf. Processes*, 29 (2014) 1488.
17. J. Wang, W. Chen, F. Gao and F. Z. Han, *P. J. Mech. Eng. B-J. Eng.*, 230 (2016) 466.
18. B. Wei, B. A. Knudsen, H. P. Wang and W. T. Carter, *U.S. Patent*, (2011) 6267868.
19. M. H. Wang, W. Peng and C. Y. Yao, *Int. J. Adv. Manuf. Technol.*, 49 (2010) 969.