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Simulation and fabrication of micro-scaled flow channels for metallic bipolar plates by the electrochemical micro-machining process

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ABSTRACT

In order to take better advantage of metallic bipolar plates for producing metallic fuel cells and make it a feasible technology, it is essential that we have an efficient and cost effective fabrication process for creating micro-scaled flow channels. In this study, an electrochemical micro-machining (EMM) process is developed. In order to have better process control a finite element analysis is employed to ensure machine tool platform rigidity; an electric field analysis is applied for the electrode design; and an electrolytic flow analysis is carried out for the fixture design and the selection of the operational parameter. Finally, flow channels measuring 200 μm in depth and 500 μm in width are fabricated on SS316 stainless steel sheets measuring 50 mm × 0.6 mm thick.

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1. Introduction

The electrochemical micro-machining (EMM), also called micro-electro chemical machining (μECM), is an electrochemical reaction of the anodic dissolution process. It is the reverse of electroplating. The work piece is the anode (work) and the tool is the cathode (electrode). The electrically conductive electrolyte fills in between the inter-electrode gap (IEG), and is a zero-stress fabrication process. Unlike the cutter in metal cutting or the electrode of the electrical discharge machining (EDM), the electrode does not wear out. The metal removal rate (MRR) is independent of the mechanical and physical properties of the metallic workpiece. Therefore, the proposed method is more efficient than computer numerical control (CNC) machining and EDM. This makes it a potential technology for micro-fabrication of micro-scaled flow channels of metallic bipolar plates [1,2].

Hirata [3] used Ultraviolet–Lithography (UV–LIGA) to make high precision and high aspect ratio structures by the electroforming process. Malek and Saile [4] pointed out that the electroforming process can be applied in the fabrication of metallic bipolar plates. However, it is not suitable for mass production as it is a slow process, but it is a suitable process for making electrodes for the EMM process.

There are many process variables that may affect the MRR and product quality. Datta and Landolt [5] reported the effects of the thermal field and the flow field on the efficiency of the ECM process. Kock et al. [6] studied the pulsed-ECM and found that a high pulse rate improved the geometrical accuracy of the finished part. Chengye and Liu [7] pointed out that during the pulsed-ECM process the pulsed-current may convert the polarization region from passivation into a transpassivation region. Li et al. [8] insulated the electrode which resulted in a localized electric field on the tip of the electrode, and which improves the geometrical accuracy. Hocheng et al. [9] presented the effects of IEG on the MRR in the ECM process.

Ganburzev and Appleby [10] analyzed the cost structure of a fuel cell stack and found that in a fuel cell the bipolar plates account for 15% of the cost and 70% of the volume. Therefore, a fuel cell stack design should also include the materials used and the flow channel fabrication method. Ihonen et al. [11] reported that the contact resistance is affected by the assembly torque, fuel pressure, current density and temperature distribution. Yan et al. [12] studied the manifold distribution and the GDL porosity on current transmission and found that a larger inlet opening provides a better cell performance.

In general, metallic bipolar plates have the merit of good electric and thermal conductivity, high mechanical strength and good machinability. Parallel to the development of a corrosion resistant metallic material, it is also necessary to develop an efficient and cost effective fabrication process of the flow field in order to make the production of metallic bipolar plates commercially viable. In this paper, an EMM process and a prototype system is developed

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for producing stainless steal bipolar plates. Numerical simulation procedures were established for electrode and fixture designs. The established system and the process simulation capability can be applied to any metallic bipolar material in the future.

2. Research procedures

This project started with the building of a prototype EMM machine for the fabrication of micro-scaled flow channels on thin stainless steel sheets. The electrically conductive electrolyte fills in between the inter-electrode gap (IEG). The cathode tool is the inverse shape of the desired product. When a potential is applied to the electrodes, the metal on the anode surface will become positive, and metallic ions are attracted towards the cathode. Because this proposal is intended for future mass production, a die-sinking structure and control system are included in the design. Since the maximum dimensions of the fixture is only 10 cm × 10 cm, they should be easy to load and unload and form a smooth flow passage for the electrolyte, and be corrosion resistant. The electrode is fixed on the adaptor plate of the *z*-axial driving mechanism, and must be electrically grounded. The fixture holds the work and is connected to the positive potential and should be electrically insulated from the other components. The fixture has an upward pressure loading due to the reaction force from the electrolyte flow. The deformation at the fixture site should be less than 10 μm.

After building the prototype, the FEA model is established to compute the stress and the deformation at critical locations. The results of the simulated data are then compared with the measured data for verification. Then the electric field analysis is performed on the electrode (cathode) for various insulation conditions. It will help in the electrode design and in the selection of the IEG. The smooth flow of the electrolyte through the reaction area to flush out the reactant and refresh the electrolyte is important for maintaining consistent operating conditions. The fluid flow analysis will help with the understanding of the flow pattern and flow velocity

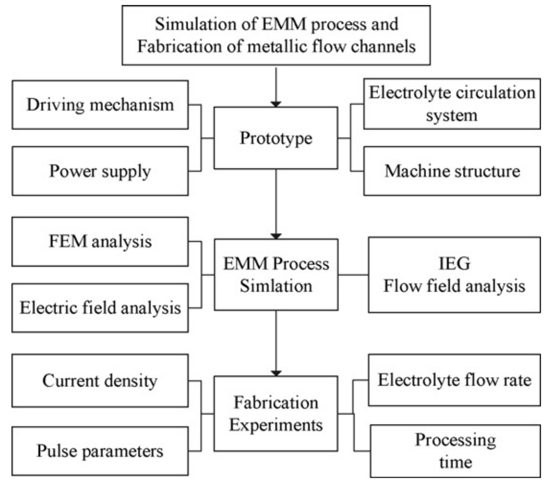


Fig. 1. Flow chart of the research procedures.

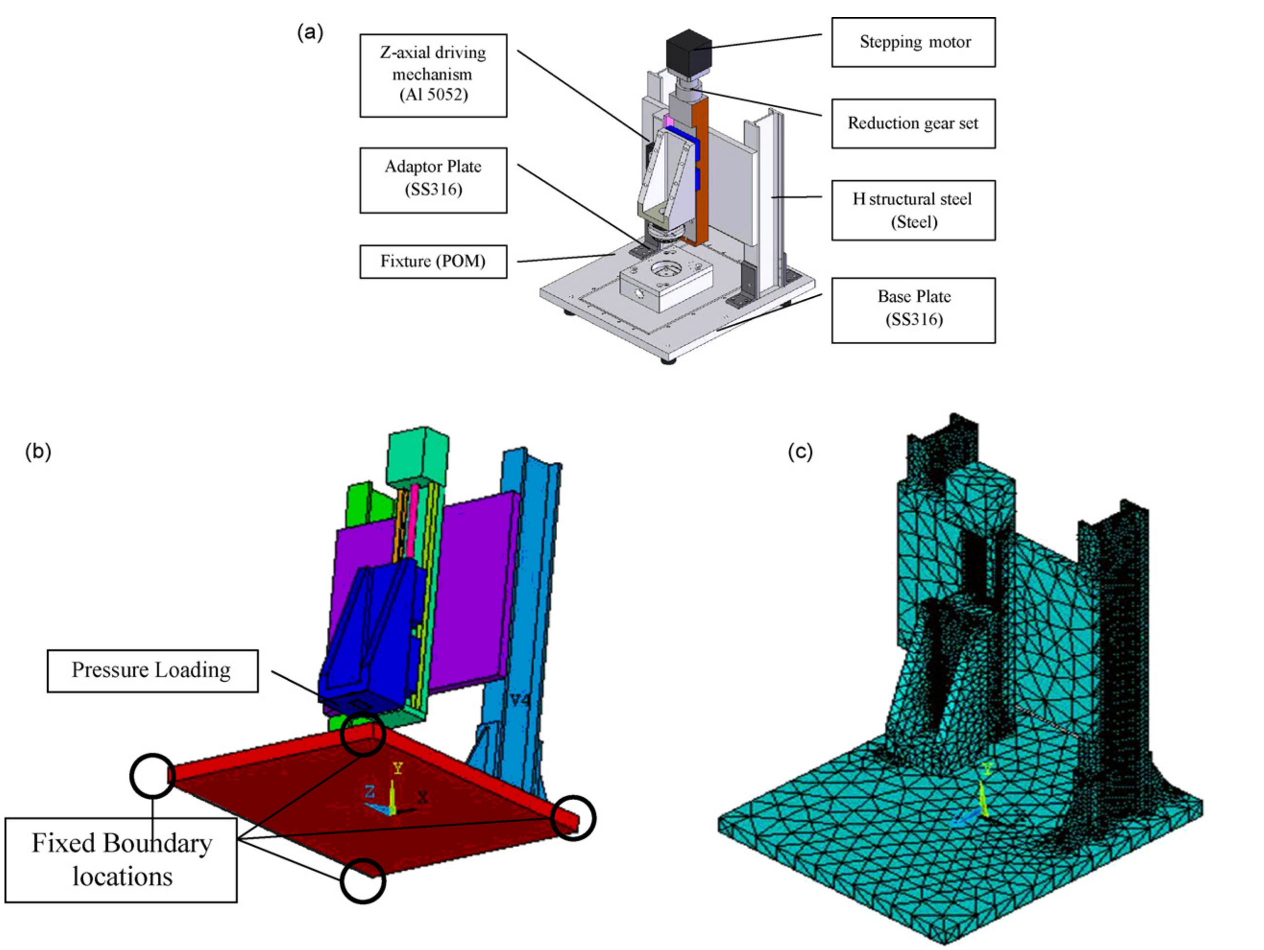


Fig. 2. The EMM prototype machine (a) CAD design of the EMM machine; (b) simplified structure for the FEA model and (c) auto-meshed model for the FEA analysis.

Table 1
Material properties of the FEA model

EMM machine	Metal type	Element type	Modulus of elasticity (GPa)	Poison ratio
H structural steel	Medium carbon steel	Solid 95	205	0.29
Base plate, Adaptor plates	Stainless steel 316	Solid 95	200	0.29
Driving mechanism	Al 5052	Solid 95	68	0.33

at critical locations of the electrolyte flowing through the fixture. Finally, the flow channels are fabricated on SS316 stainless steel thin plates. The flow chart of the research procedures is shown in Fig. 1. The FEA consists of a computer model of a material or design that is stressed and analyzed for specific results. Modifying an existing product or structure is utilized to qualify the product or structure for a new service condition. In case of structural failure, the FEA may be used to help determine the design modifications required to meet the new condition.

3. Finite element analysis of the EMM prototype structure

Rigidity of the prototype structure is essential for maintaining positioning and machining precision. All components must be corrosion resistant or be shielded against the electrolyte. The reaction force from the rapid flow of the electrolyte inside the fixture creates an upward pressure on the electrode, to the adaptor plate and is then transmitted to the z-axis driving mechanism. The deformation at the electrode location should be kept as much as possible to a minimum.

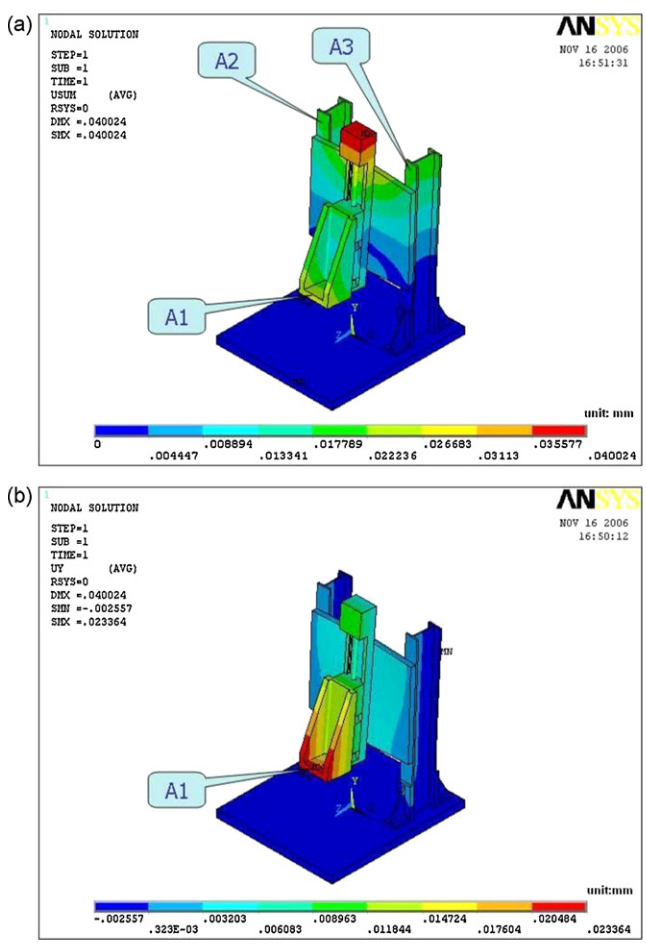


Fig. 3. Deformation contours of the prototype machine (a) deformation plot – combined and (b) deformation plot – y-axis.

Table 2
Deformation values at critical locations

Location	Simulation (μm)	Experiment (μm)
A1 (total deformation)	18–25	10–12
A2 and A3 (total deformation)	18–20	<1
A1 (y-axis)	11–14	10–12
A2 and A3 (x- and z-axis)	3–6	<1

Fig. 2a represents the computer aided design (CAD) design of the prototype. It consists of a stainless steel base plate, fixture, adaptor plate for the electrode on the z-axis, driving mechanism, supporting plate for the driving mechanism, and a structural column. The materials of the major structural components are listed in Table 1. Omitting non-loading bearing components, a simplified

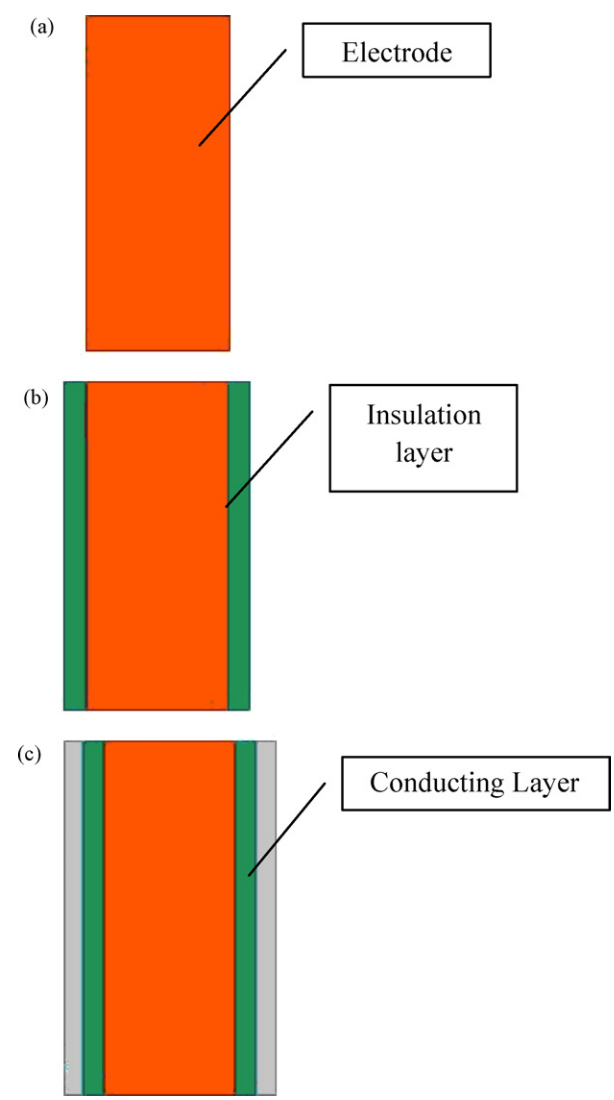


Fig. 4. Schematic plots of various electrode insulation conditions (a) no insulation; (b) insulated and (c) with conducting layer.

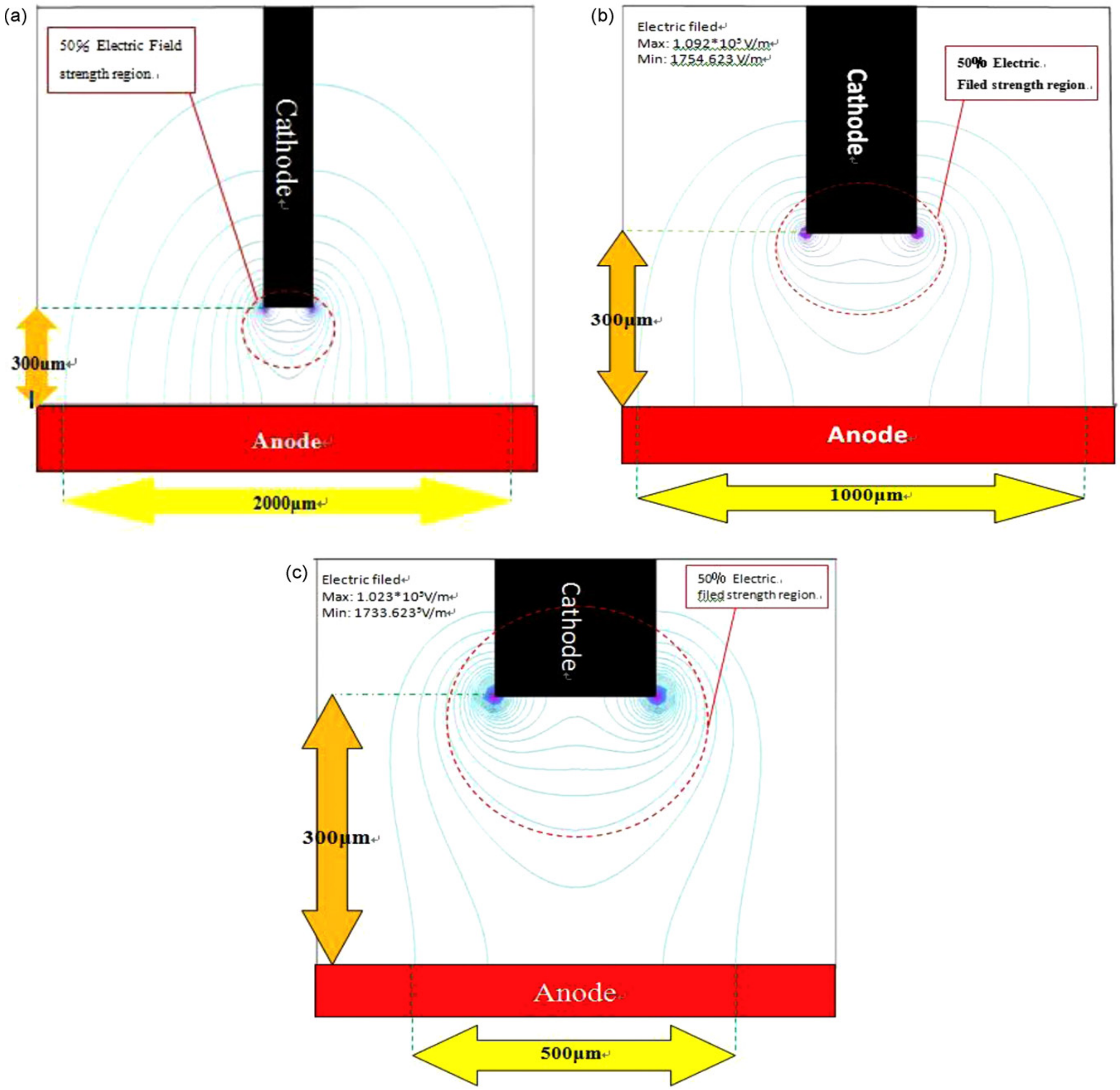


Fig. 5. Electric field contours of various electrode insulation conditions (a) no insulation; (b) insulated and (c) with conducting layer.

version for the FEA model is shown in Fig. 2b. A pressure of 5 kg cm^2 is applied to the surface of the adaptor plate. At the four bottom corners of the base plate, the *x*, *y*, and *z* degrees of freedom are fixed for the boundary conditions. The "automesh" scheme in the ANSYS commercial software is employed to generate mesh of all Solid95 element type. Fig. 2c represents the meshed model for FEA analysis.

Table 3
Summary of the electric field analysis

Electrode type	Insulation condition	Influential width (µm)	Influential width/ electrode width
a	No insulation	2000	10
b	10 µm insulation layer	1000	5
c	5 µm conduction layer	500	2.5

The plots of the *x*, *y* and *z* combined deformation and the *y*-axis deformation of the prototype machine are presented in Fig. 3a and b. At the pressure loading location A1, the deformation values are 18–25 µm and 11–14 µm for the combined deformation

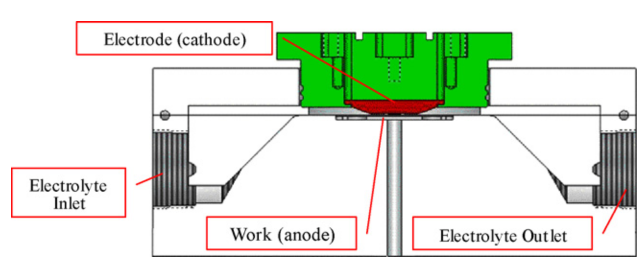


Fig. 6. Sectional view of the fixture.

and the y-axis deformation, respectively. At the top of the column on locations A2 and A3, the deformation values are 18–20 μm and 3–6 μm for the combined deformation and the x- and z-axis deformation, respectively. The amount of deformation is slightly larger than the design specification of 10 μm. The actual amount of deformation measured is much less than the computed results and is within specification. The values of the deformation are listed in Table 2.

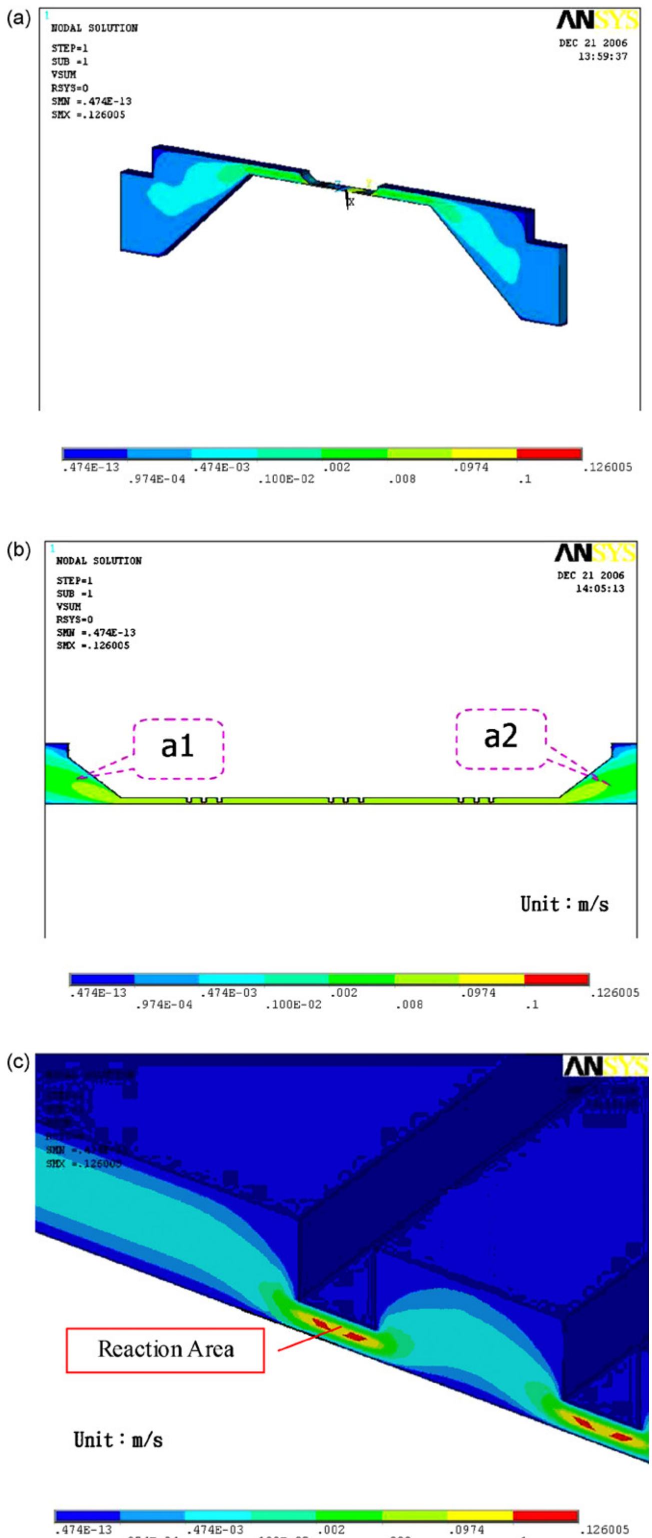


Fig. 7. Flow field simulation of the electrolyte (before) (a) sectional view of the flow field; (b) flow field of inlet and outlet and (c) flow field at the reaction area.

4. Electric field analysis for the electrode design

In the EMM process, the electric field distribution between the electrode and the work greatly affects the accuracy of the final geometry. The electric field depends on the IEG, the conductivity of the electrolyte and the electric insulation conditions of the elec-

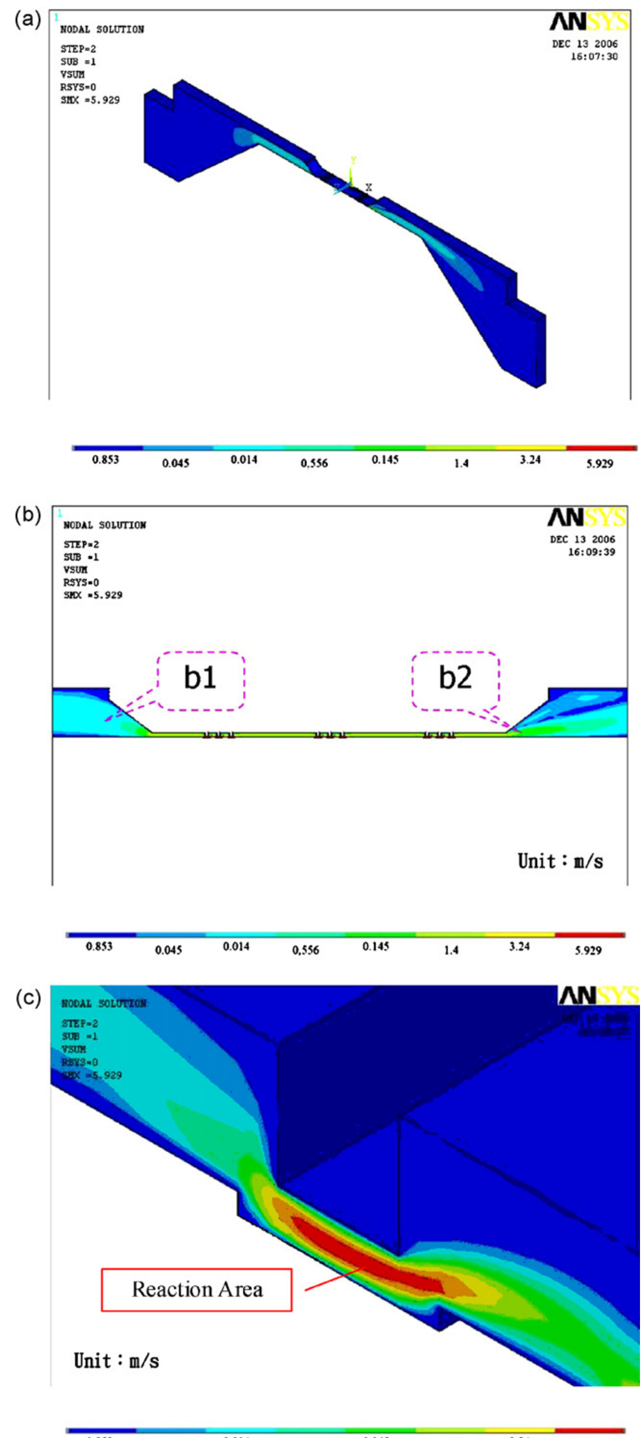


Fig. 8. Flow field simulation of the electrolyte (in process) (a) sectional view of the flow field; (b) flow field of inlet and outlet and (c) flow field at the reaction area.

trode. Three electric insulation conditions are considered in this study, and are shown in Fig. 4. Fig. 4a shows an electrode without any insulation. Fig. 4b shows an insulated electrode which is the cathode used in the flow channel fabrication. Only the reaction area at the bottom is exposed. In Fig. 4c, the insulated electrode in Fig. 4b is coated with a conductive layer and is connected to anode. It is the proposed cathode for further channel fabrication.

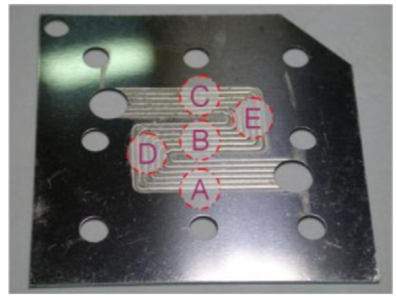
The ANSYS commercial software is employed in the 2-D electric field analysis. The width of the electrode is 200 μm and the length is 500 μm. The IEG is 300 μm. There is an operational potential of 10 V between the electrodes. Conductivity of the electrolyte is 9.67 S m. The effects of thermal variation and fluid dynamics are neglected.

The simulated results show that the area influenced by the electric field is of 2000 μm width with an electrode without insulation, as shown in Fig. 5a. Fig. 5b shows that the area influenced with insulation layer is reduced to 1000 μm. The area influenced is further reduced to 500 μm if there is no conducting layer, as shown in Fig. 5c. Further investigation of the distribution of a 50% strength electric field shows that the area influenced is 300 μm wide and 180 μm deep for all three insulation conditions. It will not affect the MRR of the EMM process. Hence, the insulation layer on the electrode reduces the diffusive electric current and improves the accuracy of the geometrical profile of the finished works. The results are summarized in Table 3. In order to reduce the area influenced by the electric field, the operating voltage and the IEG of the insulated electrode used in the channel fabrication, after re-calculation, are reduced to 7.5 V and 100 μm, respectively.

5. Flow field analysis for the fixture design

Reactant is produced during the EMM process, and this electrochemical reaction will raise the temperature of the electrolyte. Therefore, a smooth and plentiful flow of the electrolyte through the reaction area is essential to flush out the reactant and to maintain consistent operational parameters. Hence, the flow field analysis of the electrolyte in the passage of the fixture is important in the design of the fixture and in the selection of the operational parameters.

Table 4
Measurement data at various channel locations



Location	Depth (μm)	Width (μm)	Roughness (μm)
A	213 ± 3	521 ± 13	2.8
B	206 ± 5	505 ± 16	3.6
C	208 ± 8	511 ± 18	3.9
D	212 ± 4	518 ± 11	2.9
E	210 ± 3	515 ± 14	3.1

A sectional view of the electrolyte passage and the locations of the electrodes are shown in Fig. 6. The electrolyte flows from left to right passing through the gap between the electrodes. The length of the cathode is 500 μm and the IEG is 100 μm. The flow pressure at the inlet is 10 000 N m^{-2}. The flow field is analyzed using ANSYS. Two flow situations are analyzed: the flow situation prior to the start of the operation, as shown in Fig. 7a–c, and then 50 μm into the process as shown in Fig. 8a–c. Figs. 7a and 8a are a sectional view of the flow field in the passage. Figs. 7b and 8b are close-ups of the flow field at the entrance and the outlet of the reaction area, respectively. Figs. 7c and 8c show the detailed flow field in the channel area.

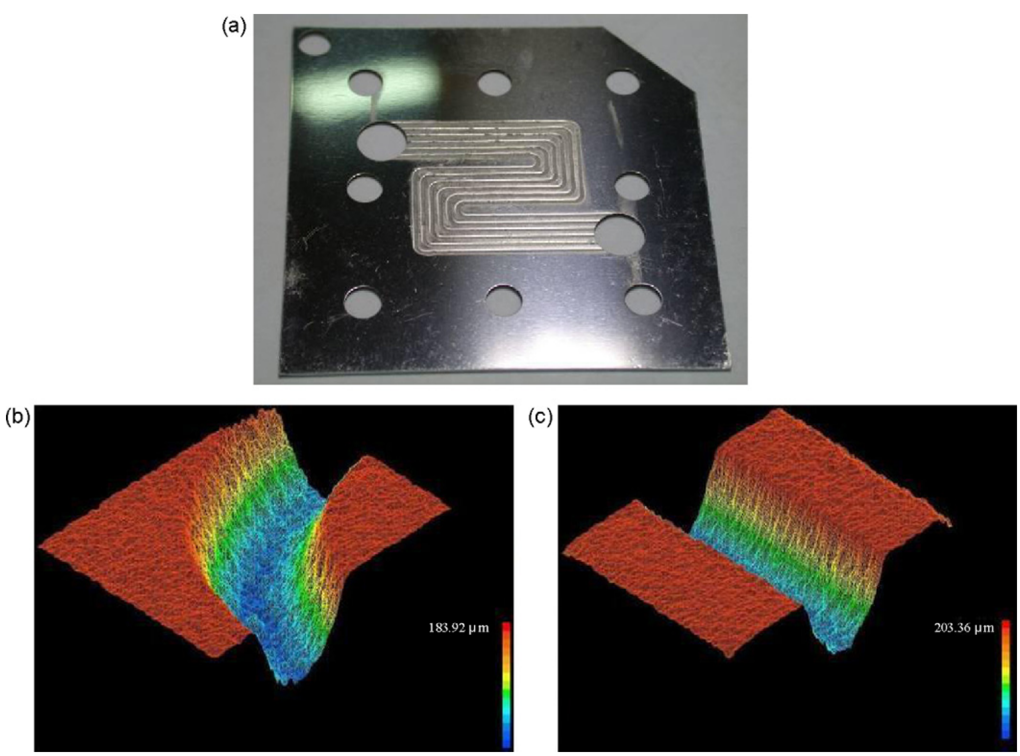


Fig. 9. SS316 bipolar plate (a) finished bipolar plate; (b) 3-D channel view at corner and (c) 3-D channel view at straight section.

Figs. 7a and 8a demonstrate a smooth flow of the electrolyte at the outlet and inlet. The velocity profiles are continuous, without split-offs. The deep blue region means that the electrolyte is stagnant and the velocity is approaching zero. In Fig. 7a, the velocity profile of Figs. 7a and 8a show a smooth flow of the electrolyte at both the outlet and the inlet. In Fig. 7a, the velocity profile shows that the velocity increases gradually from the inlet toward the reaction area prior to the EMM process. However, during the EMM process the flow path becomes winding as the anode dissolves to create the flow channel of the bipolar plate. The velocity variation is focused on the reaction area. As a result, the electrolyte seems to be stagnant in most regions of the inlet and outlet, as shown in Fig. 8a. A sectional view in the reaction area of Fig. 7b shows that the velocity variations are generally small, meaning that the flow is smooth in both the inlet (a1) and the outlet (a2) regions. However, the velocity profile is split up into two regions in b2 of Fig. 8b. The upper region of the velocity profile indicates a swirl in the electrolyte flow. Fig. 7c, shows a close-up of the flow field at the channel area as the passage becomes smaller. This reduction in the passage will create a pressure drop when the flow exits the channel area and the velocity decreases. In Fig. 8c, the velocity difference becomes much more significant. The bigger pressure drop creates a tearing force on the insulation coating of the cathode. This phenomenon was observed after the experiments were completed. These simulation results provide detailed information on how to improve the fixture design and how to control the flow rate of the electrolyte.

6. Flow channel fabrication

EMM fabrication experiments were conducted by taking the simulation results as the EMM process parameters: the electrode shape is the serpentine use brass manufacture and side-wall insulation, the working potential is 7.5 V, the IEG value is 100 μm and the electrode feed-in speed is 200 μm. The electrolyte user $NaNO_3$ and is recirculated, filtered out and temperature controlled for recessed. The flow pressure at the inlet is 10 000 N m^{-2}.

The flow field channels were fabricated in less than 5 min. By means of a 3-D Confocal Microscope, Fig. 9a shows the finished part of the SS316 bipolar plates. Fig. 9b and c displays two 3-D views of the channel geometry. In order to verify the consistency and the accuracy of the EMM process, measurements were taken at five locations on the bipolar plate. Location A is nearest the electrolyte inlet, and the depth (206–213 μm) and the width (505–521 μm) values are slightly larger than the intended values of 200 μm and 500 μm, respectively. This may be due to the fact that the electrolyte is fresh and flows smoother at the inlet. However, the variations as these locations are small. However, the roughness values are larger than expected. The results are listed in Table 4.

7. Conclusions

This study established the detailed analyses procedures for the EMM process. The EMM process is an efficient fabrication method for micro-scaled flow channels on metallic bipolar plates. The results of the finite element analysis verified the robustness of the prototype machine. The electric field analysis demonstrated the importance of the insulation layer on the electrode for reducing the diffusive electric current and improving the accuracy of the geometric profile of the finished product. It should prove to be very useful in the electrode design. The flow field analysis helped to visualize the flow pattern in the EMM process. The flow in the channel area is especially important. Finally, it is important to note that the actual fabrication of flow channels on SS316 thin plate takes only 5 min. This demonstrates that the EMM process is an efficient method for creating micro-scaled flow channels on metallic bipolar plates.

References

[1] J.A. McGeough, Principle of Electrochemical Machining, Champman & Hall, London, 1974.
[2] J.F. Thorpe, R.D. Zerkle, Electrochemical Society, Princeton, 1979, pp. 1–39.
[3] Y. Hirata, Nucl. Instrum. Methods Phys. Res. B208 (2003) 21–26.
[4] C.K. Malek, V. Saile, Microelectron. J. 35 (2004) 131–143.
[5] M. Datta, D. Landolt, Electrochim. Acta 45 (2000) 2535–2558.
[6] M. Kock, V. Kirchner, R. Schuster, Electrochim. Acta 48 (2003) 3213–3219.
[7] Y. Chengye, Z.X. Liu, J. Nanjing Aeronautical Inst. (May 1988) 74–99.
[8] Y. Li, Y. Zheng, G. Yang, L.Q. Peng, Sens. Actuators, A 108 (2003) 144–148.
[9] H. Hocheng, Y.H. Sun, S.C. Lin, P.S. Kao, J. Mater. Process.Technol. 140 (2003) 264–268.
[10] S. Ganburzev, A. Appleby, J. Power Sources 107 (2002) 5–12.
[11] J. Ihonen, F. Jaouen, G. Linderbergh, G. Sundholm, Electrochim. Acta 46 (2001) 2899–2911.
[12] W.M. Yan, C.Y. Soong, F.L. Chen, H.S. Chu, J. Power Sources 125 (2003) 27–39.