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Short communication

Studies on the fabrication of metallic bipolar plates—Using micro electrical discharge machining milling

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ABSTRACT

Owed to the advantages of highly precise and flexible machining, micro electrical discharge machining milling (micro EDM milling) can machine higher aspect ratio micro flow channels than the micro flow channels made from etching or deposition techniques, which have aspect ratio of only 0.5–0.7.

This study reports on the production of micro flow channels in metallic bipolar plates, using micro EDM milling. Through the use of micro EDM milling with tungsten carbide electrodes, this study succeed in machining channels with a depth and rib width of 500 μm, and height of 300 μm, 600 μm (aspect ratio of 0.6 and 1.2), respectively, in a reaction area 20 mm × 20 mm, on 50 mm × 50 mm × 1 mm SUS 316L stainless steel.

In single cell tests, the cell performance in metallic bipolar plates with aspect ratio of 1.2 is higher than that of other tests, and this result shows that the aspect ratio can promote performance of micro fuel cells. Moreover, under the same condition regarding cell size, single cell performance in metallic bipolar plates of aspect ratio of 1.2 with micro EDM milling in this study is higher than the performance in metallic bipolar plates with electroforming or electrochemical machining techniques, and the metallic bipolar plate can promote power per unit volume.

1. Introduction

Fuel cells show great promise in the future of energy conversion techniques. Fuel cells are highly efficient, are a suitable fuel source to a wide range of applications, and emit almost no pollution. Bipolar plates compose nearly 60–80% of the stack weight, 50% of the stack volume, and 35–45% of the stack cost [1,2]. Bipolar plates are usually made of graphite, a material that is difficult to handle due to its low mechanical strength and brittleness, causing the formation of micro flow channels in graphite to be a challenging, and expensive process. Graphite bipolar plates cannot produce high densities of energy per unit volume. By contrast, steel bipolar plates offer excellent mechanical, electric, and thermal properties. Steel plates can be formed into thin sheets with a plate thickness within the range of 100–500 μm. Such advantages contribute to an increase in power per unit volume [3–6]. However, metallic bipolar plate corrosion is a serious problem influencing the performance and life of fuel cells. The problems of ohmic polarization and poison must be improved by the approaches of material selection, surface treatment, and coating [7–10].

Recently, for 3C products and low pollution green energy source research and development, the potential in portable miniature fuel cells for its applications and market has attracted great attention, and the smaller and thinner bipolar plate plays an important role in miniature fuel cells. Many scholars have adopted MEMS to machine silicon-based bipolar plates instead of graphite bipolar plates to develop miniature fuel cells [11–14]. Yu et al. [14] developed a bipolar plate with dry etching process, RIE, on silicon wafers for a 400 μm wide and 200 μm deep flow channel and 5 cm^2 reaction area. Metal sputtering created the surface conducting film, and the current density of the fuel cell was 250 mA cm^{-2}. However, the silicon-based bipolar plate was so brittle that it broke easily when fabricating, and had conductivity of only0.5 S cm^{-1}, which was 10,000-fold smaller than 5000 S cm^{-1} of a metallic bipolar plate. Lee et al. [15–17] investigated the SS304 stainless steel as the substrate instead of a silicon wafer to machine micro metallic bipolar plates with a 4 cm^2 reaction area, 300 μm wide and 200 μm deep flow channel by Lithography Galvanik Abformung (LIGA) manufacturing processes with electroforming technology. In single cell tests, the fuel cell performed 195 mW cm^{-2} power densities, and showed that the cell performance of the single cell with SS304 metallic bipolar plates exceeds similar size single cell with silicon or glass fiber substrates. Hsieh et al. [18–20] machined 650 μm thick copper bipolar plates with 5 cm^2 reaction area, 300 μm wide and 200 μm deep serpentine flow channel, and 150 μm rib width by LIGA-like manufacturing processes with electroforming techniques. In

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single and double cell tests, the maximum power densities were 60 mW cm^{-2} and 100 mW cm^{-2} respectively.

Micro electrical discharge machining milling (micro EDM milling) is a novel fabrication method. This technique was adopted from many studies to machine a micro structure and component. The principle behind this form of machining is similar to that of traditional electrical discharge machining, except that micro EDM milling uses lower power with a narrower electrical discharge gap achieving a higher degree of precision, thereby allowing the fabrication of more intricate designs. micro EDM milling works with electrically conductive materials, and is effective even with extremely hard metals. Electrical discharges occur, as a rapid series of pulses remove material from both the workpiece-electrode and the toolpiece-electrode. The removed material is carried away by a constant supply of a dielectric liquid flowing between the electrodes. During the machining process, a small gap is maintained, ensuring that the workpiece and toolpiece never come into contact. The smaller forces involved in micro EDM milling prevent vibration and mechanical stress. Therefore, this technique is an appropriate approach to machine high aspect ratio, intricate 3D micro structure.

Masuzawa and co-workers [21–23] first proposed a wire electro-discharge grinding technique (WEDG). The electrode diameter was modified to 50–500 μm and the uniform wear method (UWM) was used to machining and compensating. Uniform wear method (UWM) used an ultra shallow machining depth to help maintain the profile of the electrode and ensure a uniform rate of wear. The compensation per unit electrode length was determined by combining data regarding the electrode consumption analysis, and the size and shape of the machined profile. Finally, the intricate 2D, 3D micro structure machining was made with aspect ratio up to 10.

Owed to the advantages of high precision and flexible machining, micro EDM milling can machine higher aspect ratio micro flow channels than the micro flow channels made from etching or deposition techniques, which have aspect ratio of only 0.5–0.7. Therefore, this study focused on developing a machining method using micro EDM milling to prepare the high aspect ratio micro flow channel structures in metallic bipolar plates for use in micro proton exchange membrane fuel cells (micro PEM fuel cells) and discusses the aspect ratio effect on performance of micro PEM fuel cells.

2. Fabricated on metallic bipolar plate

This study was performed in two stages. In the first part, this research machined flow channel structures into the steel plates using UWM. This study optimized the electrical discharge parameters, polarity (P), peak value current (I_p) and continuous pulse duration (τ_{on}), and analyzed the associated material removal rates, as well as the electrode consumption rates. In the second stage, this study tested and verified the performance of the PEM fuel cells, using the steel bipolar plate machined in the first phase.

2.1. Equipment

The equipment used in our research was a high precision 4-axis CNC micro EDM milling. The equipment was made of granite, and its maximum machining range was 250 mm (X) × 250 mm (Y) × 150 mm (Z). Every axis was driven by linear motor actuators with the guide of air bearings and the linear scale of resolution of 0.1 μm, and those that could make the precision of equipment up to the precision of sub-micron. This equipment combined with a fourth rotation axis and a wire electro-discharge grinding (WEDG) device could modify the electrode geometry and achieved micro EDM and micro die sinking EDM machining.

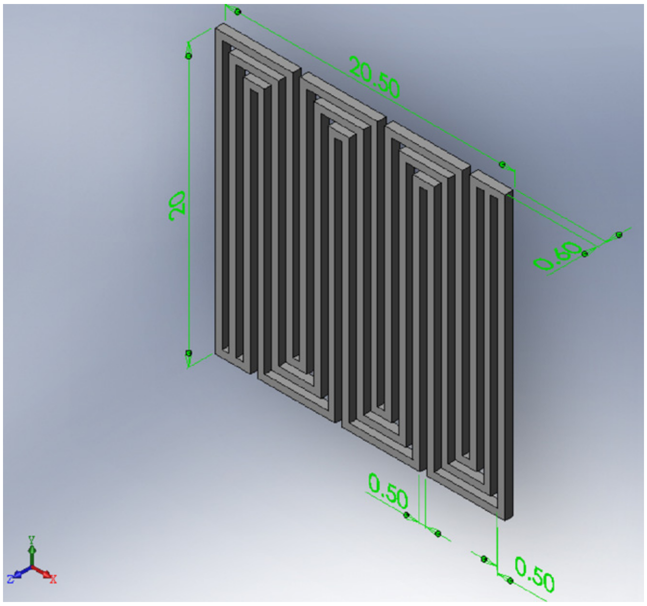


Fig. 1. Schematic representation of micro flow channels (unit: mm).

2.2. Materials

Tungsten carbide has high strength and heat-resistance properties. Electrodes made of this material can effectively reduce the rate of electrode consumption.

The tungsten electrode must be aligned before micro EDM milling commences. The center of the electrode axis and rotational axis coaxial were calibrated to ensure precision and reduce error. Due to the potentially corrosive environment of fuel cells, bipolar plates may deteriorate, thereby reducing cell performance and lifetime. To reduce the potential for corrosive damage, this study chose SUS316L steel as a material for our metallic bipolar plate.

2.3. Machining the micro flow channel

Studies [24,25] claimed that serpentine flow fields have outstanding cell performance and drainage characteristics, but serpentine flow in a single channel can concentrate polarization problems. This is due to excessive channel length, which can reduce the performance of the cells. For this reason, this study used a three-channel design, with serpentine flow field. The cell reaction area was 20 mm × 20 mm, the channel width was 500 μm, the rib width was 500 μm, the channel height was 600 μm (as shown in Fig. 1), and the open area ratio was 52.527%.

This study modified the profile of the tungsten carbide toolpiece electrode with great precision using the WEDG method, as shown in Fig. 2. The channel width was 500 μm and the electrical discharge had to cross an electrode gap; therefore, the diameter of the

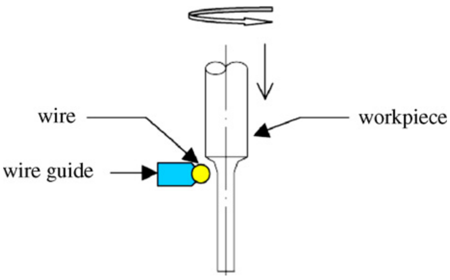


Fig. 2. Wire electro discharge grinding method (WEDG).

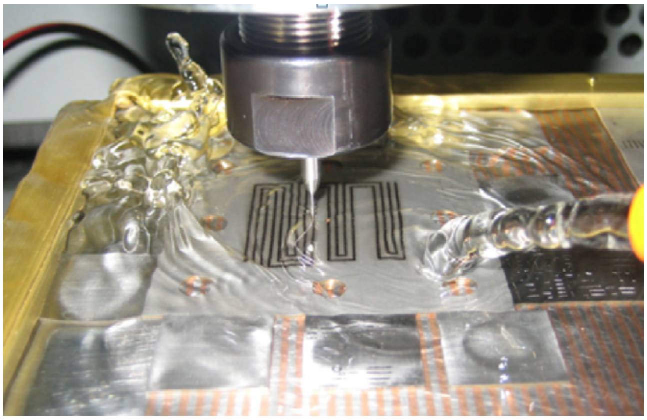


Fig. 3. Machining the flow channel with micro EDM milling.

Table 1
Electrical discharge parameters.

Electrode	Tungsten carbide
Workpiece	Stainless SUS316L
Machining depth (mm)	0.07,0.05,0.02
Peak current (A)	2.25, 3, 4.5, 6, 7.5
Pulse duration (μs)	0.5, 1, 1.5, 2, 3, 5, 8, 12
Pulse off time (μs)	8
Open voltage (V)	120
Gap voltage (V)	50
EDM dielectric	Kerosene

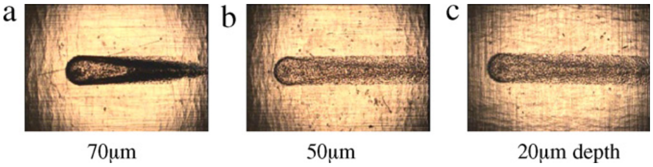
electrode was adjusted to 480 μm. The flow channels were then machined using micro EDM milling, as shown in Fig. 3.

The aim of this study was to determine a set of electrical discharge parameters that would optimize toolpiece electrode consumption. This study examined the effect of electrical discharge parameters, electrical discharge depth, polarity (*P*), electric current (I_p), and pulse duration (τ_{on}) on electrode consumption. Table 1 provides the actual values used for these parameters. Using UWM enabled us to overcome non-uniform electrode consumption problems, and further improve the electrode compensation ratio and electrical discharge depth parameters. Finally, this research machined the flow channels of the metallic bipolar plate using to-and-fro scanning, which helped to maintain the profile of the electrode.

3. Results and discussions

3.1. Machining results using micro EDM milling

Fig. 4 shows machining results for 70, 50, and 20 μm electrical discharge depths using micro EDM milling. For an electrical discharge depth of 70 μm, the depth and width of the flow channel, reduced as the length increased, as shown in Fig. 4(a). For electrical discharge depths of 50 μm and 20 μm, non-uniform flow channel depth and width reduced, as shown in Fig. 4(b and c). The micrographs show that during micro EDM machining, the electrode eroded from the outer edge, towards its center. Lateral electrical discharge from the electrode caused non-uniform consumption and produced a flow channel with non-uniform width. At a shallower discharge depth, the effect of lateral electrical discharge was reduced and the electrode consumption was uniform. Although electrode consumption was less uniform at a depth of 50 μm than at 20 μm, the uniformity of the flow channel and efficiency of the machining remained unaffected. In this work, this study used an electrical discharge depth of 50 μm together with the UWM, to overcome the problem of non-uniform flow channel width.



70μm 50μm 20μm depth

Fig. 4. The machining results for 70 (a), 50 (b), and 20 μm (c) electrical discharge depth with micro EDM milling.

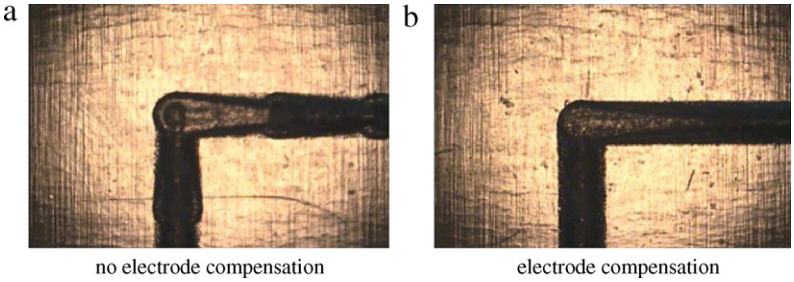
To quantify electrode consumption, this research conducted an electrode compensation experiment, wherein this study maintained uniform machining depth along the length of a channel. This study used a 50 μm discharge depth, with no compensation, to fabricate a 3mm length of channel. After machining, this study measured the rate of consumption of the electrode length. This study found that the rate of consumption was 10 μm length for 1mm of machining length. Fig. 5 compares the result of the electrode compensation experiment. Without electrode compensation, the depth of the flow channel gradually diminished. When using electrode compensation however, the depth of the flow channel was uniform along its entire length. Finally, using a 50 μm electrical discharge depth with a 10 μm mm^{-1} electrode compensation rate, this study produced a flow channel using micro EDM milling with the UWM on a metallic bipolar plate, as displayed in Fig. 6.

3.2. Fuel cell performance test

3.2.1. Cell fabricating and test condition

In this study, the metal bipolar plate with micro EDM milling was tested for performance. The membrane electrode assembly (MEA) materials involved the proton exchange membrane (DuPont NRE212); the gas diffusion electrode (E-TEK E-LAT®), and 0.25 mg cm^{-2} Pt for both the anode and cathode, and the area of MEA was 23 mm × 23 mm. The thickness of the gasket was 0.15 mm. The cell specifications are shown in Table 2. The cell was fabricated with an end plate, gasket, bipolar plate, gasket, and MEA, as shown in Fig. 7.

During testing, this study assembled a single cell, which had the dimension of 50 × 50 × 23 mm using a metallic bipolar plate, MEA,



no electrode compensation electrode compensation

Fig. 5. Comparison of electrode compensation experiment. (a) No electrode compensation and (b) electrode compensation.

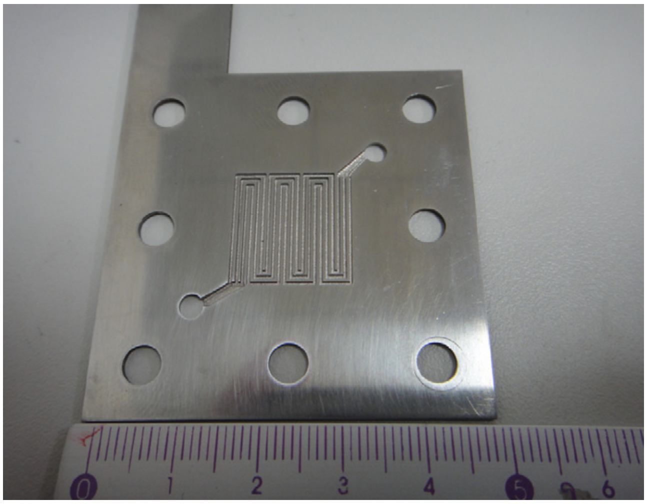


Fig. 6. Metallic bipolar plate.

Table 2
Cell specifications.

Part	Specification
Proton exchange membrane	DuPont NRE212 Dimension: 30 × 30 × 0.05 mm E-TEK E-LAT®
GDE	Pt 0.25 mg cm^{-2} Dimension: 23 × 23 × 0.3 mm
Metallic bipolar plate	Stainless steel SUS316L Dimension: 50 × 50 × 1 mm
Compression plate	PMMA Dimension: 50 × 50 × 10 mm

and a gasket, which was tightened to 20 kg cm^{-2} of torque. Leak indicator fluid was daubed around the cell. Hydrogen and oxygen were the fuels for the anode and cathode electrodes, respectively. The flow rate was 60 cc min^{-1}, at a pressure of 1 atm, at room temperature for both fuels.

3.2.2. The results of cell performance tests

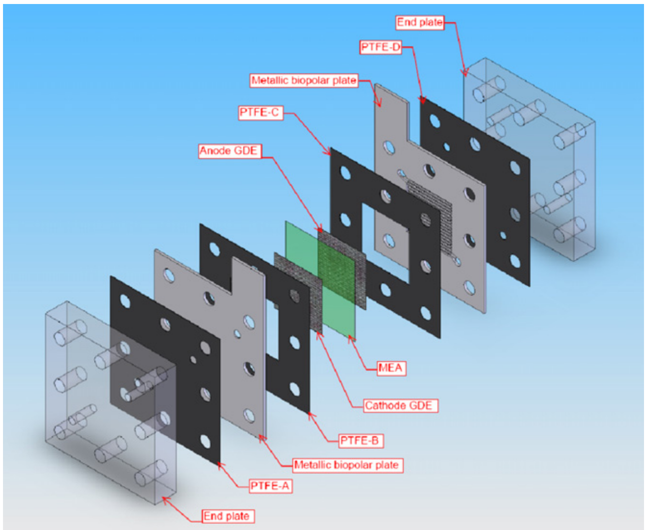


Fig. 7. Schematic representation of metallic bipolar plate fuel cell assembly.

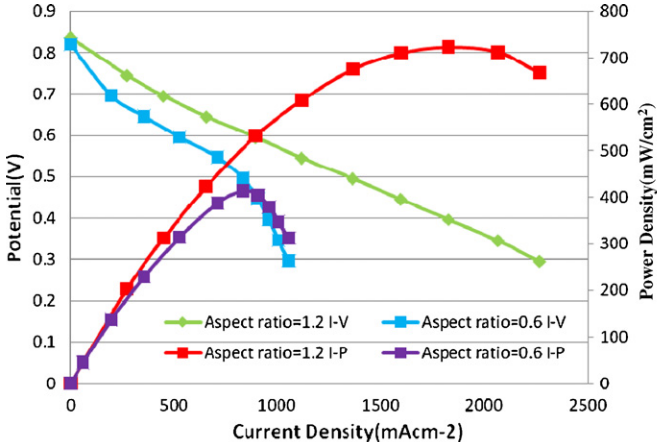


Fig. 8. Comparison of fuel cell performances.

Fig. 8 shows the comparison of stainless steel cell performances with micro flow channel of different aspect ratio. The figure showed the metallic cell with aspect ratio of 0.6 had the maximum power density of 413.8 mW cm^{-2}. The performance dropped off when the voltage was less than 0.5 V, perhaps due to the concentration polarization phenomenon of puddles in water in cell. The maximum power density in metallic cells with aspect ratio of 1.2 reached 723.5 mW cm^{-2}, and this result showed that cell performance could be promoted by increasing aspect ratio of micro flow channel. Therefore, this study inferred preliminarily the channel depth in metallic bipolar plate with aspect ratio of 0.6 was only 300 μm, and the gas diffusion electrode of MEA was deformed and pushed into the channel when cell fabricating resulting in decreasing the cross-section area of the flow channel. Therefore, reaction gas flowing and water draining were impeded causing low cell performance and the concentration polarization phenomenon.

Besides, comparing other relative researches [15–20], Lee et al. machined micro metallic bipolar plate with dimension of 40 × 40 × 2.6 mm, 4 cm^2 reaction area, 300 μm wide and 200 μm deep flow channel by electroforming technology. In single cell tests, the fuel cell performed 195 mW cm^{-2} power densities. Under the same reaction area condition, the metallic bipolar plate with aspect ratio of 1.2 (600 μm channel depth) using micro EDM milling in this study had 723.5 mW cm^{-2} power densities which was of higher quality than the metallic bipolar plate with aspect ratio of 0.6 (200 μm channel depth) using electroforming or electrochemical machining so far. Therefore, the metallic bipolar plate of high aspect ratio micro flow channel structure with micro EDM milling could provide an efficient approach toward promoting cell performance.

4. Conclusion

This study first used micro EDM milling to prepare high aspect ratio micro flow channel structures in metallic bipolar plates and discusses the aspect ratio effect on performance of micro PEM fuel cells. Our conclusions are as follows:

1. In this research, a metallic bipolar plate with a 20 × 20 mm reaction area, with rib, width, and depth of the micro channel structure measuring 500 μm, 500 μm, and 600 μm, respectively, was successfully machined using micro EDM milling.
2. From experiment results, the power density of the metallic bipolar with channel aspect ratio of 1.2, which reached 823.5 mW cm^{-2}, was higher than that with aspect ratio of 0.6; this result showed that the performance of micro fuel cell could be promoted by increasing aspect ratio of micro flow channel.
3. A single cell performance test verified that metallic bipolar plates could promote fuel cell power per unit volume.

4. The metallic bipolar plate of high aspect ratio micro flow channel structure with micro EDM milling could provide an efficient approach toward promoting cell performance.

Acknowledgement

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