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The fabrication of high-aspect-ratio micro-flow channels on metallic bipolar plates using die-sinking micro-electrical discharge machining

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ABSTRACT

This study explores the feasibility of using a relatively rapid technique, die-sinking micro-electrical discharge machining, to fabricate miniature metallic bipolar plates. The flow field is a three-pass serpentine structure, of which both the rib and channel widths are 500 μm and the channel depth is 600 μm (aspect ratio = 1.2) in a reaction area of 20 mm × 20 mm. The material-removal rate of the proposed method can reach up to 7.2 $mm^3 min^{-1}$. However, a high material-removal rate also increases the surface roughness of flow channels. In single-cell tests, the peak power densities are 674 $mW cm^{-2}$ and 647 $mW cm^{-2}$ for flow channels with a surface roughness of 0.715 μm Ra and 0.994 μm Ra, respectively. Though the increase in surface roughness lowers cell performance, the effect is not statistically significant.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) have become the focus of energy conversion techniques due to their remarkable features, such as compactness, quiet operation, high power density, and lack of emissions. Since the rapid development of mobile computer, consumer, and communication (3C) applications, and because of the increasing demand for green energy, fuel cells have been considered promising alternatives for lithium-ion batteries. Several high-tech companies even released concept portable products featuring fuel cells. However, the problem of their bulky size must be resolved before fuel cells can be widely accepted in the market.

A typical PEMFC is composed of a proton exchange membrane (PEM), gas diffusion layers (GDL), and bipolar plates. Among them, the bipolar plates comprise almost 60–80% of the weight and 50% of the volume [1–3] and are, therefore, crucial to minimizing fuel cells. Both the materials and fabricating methods must be considered to construct a light, thin bipolar plate. Graphite bipolar plates have been adopted in traditional fuel cell technologies, but their brittleness causes difficulty in precision machining, especially at micro scales. Silicon-based and metallic bipolar plates were, therefore, developed as alternatives to graphite bipolar plates. The fabrications of silicon-based bipolar plates are primarily based on micro-electromechanical systems (MEMS) [4–7]. Though such technology can fabricate fine and complicated flow fields in miniature bipolar plates, the performance of silicon-based fuel cells is not appealing. The poor performance is primarily due to the significantly low electrical conductivity of silicon-based bipolar plates (0.5 $S cm^{-1}$) compared to that of metallic bipolar plates (5000 $S cm^{-1}$). Yu et al. [8] applied the dry etching process to silicon wafers to create flow channels with a depth of 200 μm. Metal sputtering was applied to increase electrical conductivity. The cell with the plates of Cu sputtering yielded the best result with a peak power density of 194.3 $mW cm^{-2}$. Park and Madou [9] applied the carbon-MEMS process to fabricate graphite bipolar plates. The polymer Cirlex® sheets were applied to prepare the micro-flow design through MEMS, and were then carbonized using furnace heat. The peak power density determined through cell tests was relatively high (773 $mW cm^{-2}$). Though this procedure bypasses the difficulties of directly machining flow channels on graphite bipolar plates, the problem of brittleness while assembling and using fuel cells remains.

In contrast, metallic bipolar plates provide high mechanical strength and can be formed into thin sheets with a thickness ranging from 100 to 500 μm [10–13], and thus have significant potential in the fabrication of miniature fuel cells. Lee et al. [14–16] used SS304 stainless steel as a substrate to form a channel mold via the Lithography Galvanic Abformung (LIGA) process. Ni was

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then electroformed into the mold, becoming a metallic bipolar plate. The average peak power density during various cell tests was 195 mW cm^{-2}. However, due to the high costs of both the equipment and the consumables required, the LIGA process is economically inefficient. Furthermore, the complicated photochemical procedures result in variances in the channel sizes and shapes, which consequently limit fuel distribution.

Micro-electrical discharge machining (micro-EDM) is a novel fabrication method for machining micro-structures and components. The maximum aspect ratios of this process associated with various tool pieces range from 10 to 100, and the minimum feature size ranges from 3 to 30 μm [17]. In our previous research [18], micro-EDM milling was used to create miniature SUS316L bipolar plates. During the single-cell tests, the peak power density achieved 723.5 mW cm^{-2}, and the volumetric power density is estimated to be approximately 315 mW cm^{-3}, demonstrating the feasibility of directly machining high-aspect-ratio flow channels on miniature SUS316L bipolar plates. However, micro-EDM milling is a point-processing technique that is time consuming and labor intensive. A relatively rapid process is required if repeated tests for various flow structures or mass production is desired. The primary purpose of this study is to explore the feasibility of using an area-processing technique—die-sinking micro-EDM—for fabricating high-aspect-ratio micro-flow channels. Additionally, because the increase in the processing rate also increased the surface roughness of flow channels, the intricate relationships between the material-removal rate, peak discharging current, surface roughness, and cell performance will be explored and discussed in this study.

2. Design and production of metallic bipolar plates

2.1. Materials and design

The materials for metallic bipolar plates should be carefully selected. Some metals, such as Cu, may be sufficient electrical conductors but they are easily corroded. Using easily-corroded metal lowers the performance and shortens the life of fuel cells. In this study, stainless steel SUS316L was chosen as the plate material. Because SUS316L contains molybdenum, it demonstrates excellent heat and corrosion resistance. To prepare the bipolar plate, a 2 mm-thick SUS316L plate was cut into a 50 mm × 50 mm area using a wire machine. For unipolar plates, a plate with only 1 mm in thickness is required.

Regarding the flow structure, previous studies [19,20] claimed that the serpentine flow field has excellent drainage characteristics and cell performance. However, single-pass serpentine tends to cause polarization problems due to excessive channel length; while excessive passes tend to result in uneven fuel distribution. Therefore, the three-pass serpentine with six U-turns was adopted as the flow design. Fig. 1 shows the designed flow field, of which both the channel rib and widths are 500 μm, and the channel depth is 600 μm (aspect ratio = 1.2) in a 20 mm × 20 mm reaction area.

2.2. Die-sinking micro-EDM

2.2.1. The principle

Micro-EDM is a thermal process that uses electrical discharges to erode electrically conductive materials. During the process, material is removed through a rapid series of pulses from both the work and tool piece electrodes. A constant supply of dielectric liquid insulates the two electrodes within a small gap and transports the debris. Because the tool and work piece do not contact each other, adverse effects from mechanical force and vibrations are minimized.

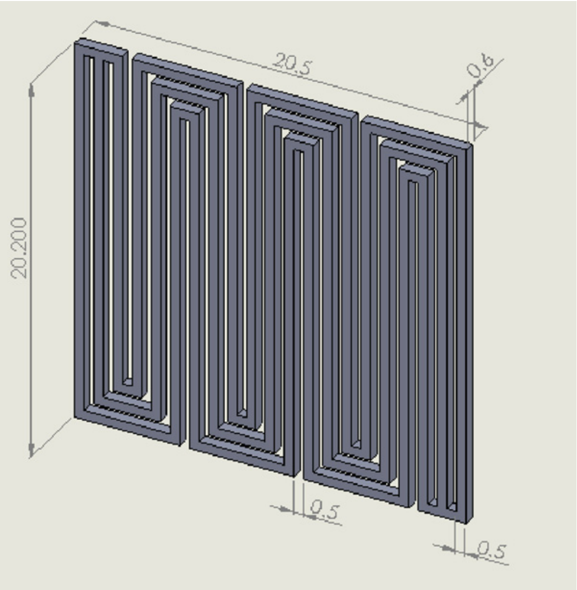

Fig. 1. Schematic representation of the flow design (unit: mm).

The primary difference between the micro-EDM milling applied in our previous research [18] and the proposed die-sinking micro-EDM is in the tool piece electrode, shown in Fig. 2(a) and (b), respectively, as an operational concept. The tool piece electrode of micro-EDM milling was a micro-tungsten rod, sharpened to the designed diameters using wire electrical discharge grinding (WEDG). The work piece electrode, specifically the plain metallic plate, was scanned by the tool piece electrode repeatedly along the paths until reaching the preferred depth. This process is a point-discharging technique and the material-removal rate is relatively slow. In contrast, die-sinking micro-EDM is an area-processing technique, in which a cubic electrode is used and the processing path is a single direction. In other words, the flow field is formed in one-step, which tremendously increases the material-removal rate.

2.2.2. Preparation of tool piece electrode

The tool piece electrode for die-sinking micro-EDM was manufactured using micro-high speed milling (micro-HSM), as shown in Fig. 3(a). A micro-end mill comprised of tungsten carbide with a diameter of 600 μm and a 30° helix angle was applied to form the channels. When using a mill with such a small diameter, an extremely high rotational speed is required to increase the processing rate. This experiment applied a high precision 4-axis CNC micro-HSM center with a maximum rotational speed of 60,000 rpm. A laser interferometer was used to calibrate the accuracy of processing. Meanwhile, the cutting depth and feeding speed must be carefully controlled to avoid breaking the micro-end mills and chipping the work piece.

The optimal operating parameters and the specifications for the electrode are summarized in Table 1. Chrome copper was selected as the electrode material because of its low cost and suitability for sharpening, and its high electrical conductivity. The flow field was sketched by 3D CAD and transformed into processing path through computer-aided manufacturing (CAM). The finished electrode is shown in Fig. 3(b). During the process of die-sinking micro-EDM, the tool piece electrode can be regarded as a complementary mold for flow channels. That is, the ribs in the mold form the channels in the bipolar plate, and vice versa. The channel and rib widths of the tool piece electrode were 600 μm and 400 μm, respectively. Considering the surplus discharge during the EDM process, the