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Fabrication of micro-flow channels for metallic bipolar plates by a high-pressure hydroforming apparatus

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ABSTRACT

High aspect-ratio micro-flow channels on bipolar plates have the advantage of improving fuel cell performance. This study forms micro-flow channels with a high aspect ratio by increasing the forming pressure during the hydroforming process.

This study designs and constructs a mechanical apparatus to enable a two-stage pressure increase in the hydroforming process. A high-pressure container is designed with three-layered tapered cylinders to sustain 1230.17 MPa working pressures, and a special seal component is designed to seal the high-pressure fluid and maintain high pressure. The feasibility of this high-pressure hydroforming technique is verified in preliminary tests.

The investigation indicates that the aspect ratio of micro-flow channels can reach 0.468 when a hydrostatic pressure of 250 MPa is applied. Compared with the maximum aspect ratio of 0.31 formed using the traditional hydroforming process, the aspect ratio of micro-flow channels in this study was 51% higher, which enables the fuel cells with metallic bipolar plates to meet both performance and manufacturing requirements.

1. Introduction

Despite the proven advantages of fuel cells, such as high efficiency, quiet operation, and near-zero pollution, they are not yet cost-competitive when compared to existing power generation technologies, especially in transportation applications [1–3]. Metallic bipolar plates have received considerable attention because of their excellent mechanical, electrical, and thermal properties and low thickness (0.1–0.5 mm). The cost of bipolar plates was estimated at 15–30% of the stack of fuel cell costs by using metal compared to graphite [1,4]. Hence, metallic bipolar plates offer advantages for proton exchange membrane fuel cells (PEMFC) and, in particular, for portable PEMFCs, replacing graphite bipolar plates in the near future.

Manso et al. [5] investigated the influence of the channel aspect ratio (defined as the ratio of the channel height to the width) on the performance of a PEM fuel cell with a serpentine flow field design. The obtained results indicated that the cell performance improved as the channel aspect ratio increased at high operating voltages, when the influence of mass transporting velocity was predominant. Our previous research [6] also indicated that the performance of portable PEMFCs with metallic bipolar plates may be improved if the aspect ratio of micro-flow channels is higher.

Current manufacturing methods of metallic bipolar plates include an electrochemical micro-machining process [7], a rubber pad forming process [8,9], a stamping process [10], and a hydroforming process [1,10,11]. However, the surface quality of the parts formed by electrochemical micro-machining was poor, and this method was inefficient. The formability of a rubber pad forming process was limited by the fluidity of the rubber pad. For the hydroforming and stamping processes, Mahabunphachai et al. [10] compared the two forming processes and formed 26 parallel microchannels on 0.051-mm-thick stainless steel 304 sheets (SUS304) with yield strength of 215 MPa. The results indicated that the maximum in-plate depth variation of the stamping process was 4.1% higher than that of the hydroforming process, which was 1.3%. The aspect ratio of micro-flow channels formed by the hydroforming process was 0.31, which is higher than that of the stamping process with an aspect ratio of 0.26. Specimens formed by the hydroforming process exhibited superior uniformity, repeatability, and aspect ratio compared to those by the stamping process. Furthermore, during the hydroforming process, no friction was observed between the high-pressure fluid and the specimen, reducing the friction force effect on the process and resulting in an optimal surface roughness for the specimens after the hydroforming process.

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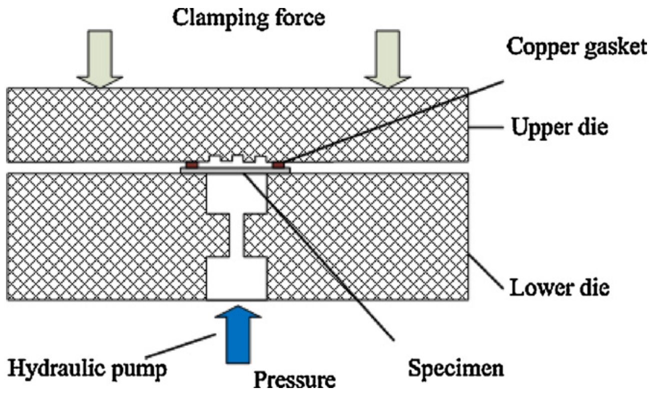

Fig. 1. Schematic representation of traditional hydroforming process.

Koc and Mahabunphachai et al. [1,11] formed micro-flow channels of various dimensions on 0.051-mm-thick SUS304 plates with the hydroforming process by using 55.2 MPa and 82.7 MPa, and observed the formability. The results indicated that the aspect ratios of micro-flow channels formed by 55.2 and 82.7 MPa may reach approximately 0.26 and 0.29, respectively, and the research also demonstrated that it was necessary to choose a larger rib and channel width, fewer flow channels, and higher hydrostatic pressure to obtain a high aspect ratio and excellent formability. Furthermore, Mahabunphachai et al. [11] used finite element software to simulate the hydroforming process, and the results revealed that it was necessary for the hydrostatic pressure to reach 843 MPa, to form micro-flow channels with a high aspect ratio of 0.72.

According to the literature, fuel cell performances could be improved by increasing the aspect ratio of micro-flow channels. However, previous research of the hydroforming process applied in forming metallic bipolar plates was limited to a hydrostatic pressure of 85 MPa on 0.051-mm-thick metallic plates with a maximum aspect ratio of 0.31, which cannot satisfy practical demands or reveal the full capability of the formability using the hydroforming process and the cell performance.

To improve cell performance, this study formed micro-flow channels with a high aspect ratio by increasing the forming pressure during the high-pressure hydroforming process. A novel patented apparatus [12] was designed and constructed to enable a two-stage pressure increase in the hydroforming process, with a working pressure that can reach 1000 MPa. To sustain this ultrahigh pressure, a high-pressure container was designed with three-layered tapered cylinders to sustain 1230.17 MPa working pressures, and a special seal component was designed to seal the high-pressure fluid and maintain the high pressure. A series of preliminary tests were subsequently conducted to verify the feasibility of this high-pressure hydroforming technique, and that all the components in the hydroforming apparatus work smoothly. Finally, the hydroforming experiments were conducted to form high aspect ratio micro-flow channels by using various hydrostatic pressures. This study used SUS304 as the material for metallic bipolar plates to overcome the corrosion in working environments [13–17]. Moreover, 0.051-mm-thick SUS304 plates used in the literature [1,10,11] did not suffice in thickness to meet practical demands; therefore, 0.1-mm-thick SUS304 plates were used as the specimens in this research.

2. The design of a high-pressure hydroforming apparatus

2.1. High-pressure source

Traditional hydroforming processes (Fig. 1) [1,10,11] formed the micro-flow channels with the forming pressure generated directly by a hydraulic pump and used the copper gasket as a seal component; therefore, the forming pressure was limited. Furthermore, the traditional pressure container used a single layer, which could not sustain the ultrahigh pressure, and posed an explosion risk.

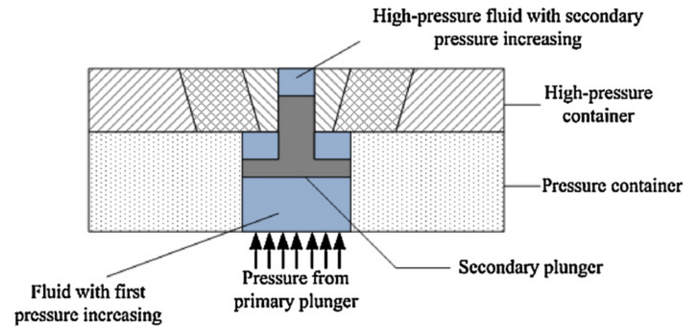

Fig. 2. Schematic representation of a high-pressure source.

To improve the forming pressure, a novel mechanical structure was designed and constructed to enable a two-stage pressure increase in the apparatus. According to our previous research [18], the high pressure of this experimental hydroforming apparatus is caused by compressed fluid in a high-pressure container. This cylindrical high-pressure container has an inner bore 60 mm in diameter fitted to the secondary plunger. When a servo hydrostatic pressing machine with a maximum capacity of 100 tons is used to compress the fluid in the pressure container through the primary plunger, the secondary plunger is pushed, and a magnified fluid pressure as high as 1000 MPa (approximately 10 000 atm pressure) is obtained in the high-pressure container (Fig. 2).

The fluid in the pressure containers has two functions, that is, to transmit pressure and to lubricate the interface between the plunger and the container. The fluid must be incompressible under high pressure, and have excellent lubrication and stability. Hence, this study chose circulation oil R68 with a maximum sustaining pressure of 1500 MPa from Chinese Petroleum Corp. as the pressure fluid.

2.2. High-pressure container

The high-pressure container was designed and constructed to sustain the ultrahigh hydrostatic pressure. Numerous problems were considered, such as surface finishing accuracy, material yielding, and seal design. According to Lame's equation for thick wall cylinders [19], the maximum stress at the internal wall of the high-pressure container reaches 1900 MPa when an internal pressure of 1000 MPa is applied. Expensive and rare material is required to design the high-pressure container with a single-layered cylinder. Consequently, a three-layered cylindrical container (Fig. 2) was used as the high-pressure container in this design, and the chosen material of each cylinder was SKD61 tool steel, which is economical and commercially available [18]. Finally, the finite element software Abaqus/standard and the preliminary tests were used to verify the equation-based design.

The yield stress for SKD61 was approximately 1600 MPa, with a safety factor of 1.5, as indicated in the literature [18]. Therefore, 1060 MPa was derived as the design working stress during the design phase.

The Tresca yield criterion was used to analyze a compound cylinder with more than two elements [20–24]. Based on the Tresca yield criterion, the pressure difference across an nth element at yield at the bore of the element is calculated as follows:

$$P_n - P_{n+1} = \frac{\sigma_{yn}}{2}\left(1 - \frac{1}{K_n^2}\right) \tag{1}$$

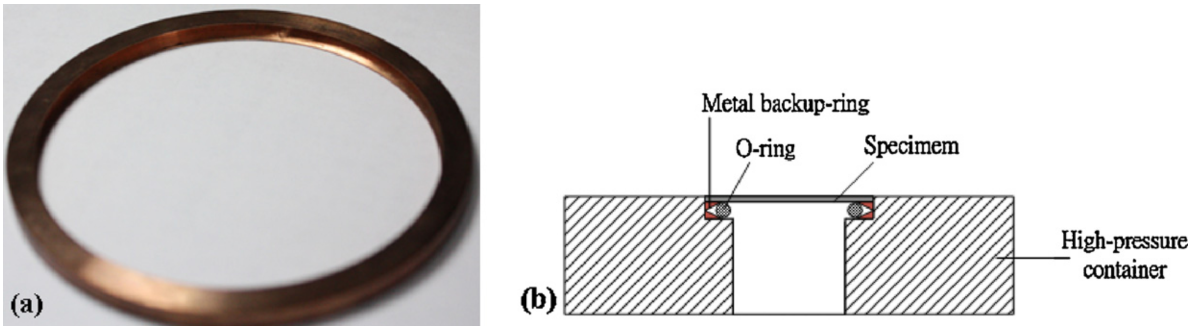

Fig. 3. (a) The metal backup-ring and (b) schematic representation for the assembly of the high-pressure seal and the high-pressure container.

where σ_{yn} is the design working stress of the material for each element, and K_n is the diameter ratio of each cylinder. If m elements and no external pressure on the outer element occur, that is, $P_{m+1} = 0$, the internal pressure to produce simultaneous yielding in all cylinders is calculated as follows:

$$P_y = \sum_{n=1}^{m} \frac{\sigma_{yn}}{2}\left(1 - \frac{1}{K_n^2}\right) \quad (2)$$

The maximum value of P_y is determined by differentiating (2) regarding K_n and equating to 0, using the relationship $K_1 \times K_2 \times K_3 \times \cdots \times K_n = K_t$

$$\frac{\sigma_{y1}}{K_1^2} = \frac{\sigma_{y2}}{K_2^2} = \cdots = \frac{\sigma_{yn}}{K_n^2} = \frac{1}{\beta^2} \quad (3)$$

where

$$\beta^m = \frac{K_t}{\left(\sigma_{y1}\sigma_{y2}\cdots\sigma_{yn}\right)^{1/2}} \quad (4)$$

Therefore, the maximum yield pressure is

$$P_{y\,\max} = \frac{1}{2}\sum_{n=1}^{m}\sigma_{yn} - \frac{m}{2}\frac{\sigma_{y1}}{K_1^2} \quad (5)$$

Three elements were used in this study, and the material of each cylinder was the same. Eq. (5) becomes

$$\frac{P_{y\,\max}}{\sigma_y} = \frac{m}{2}\left(1 - \frac{1}{K_t^{2/m}}\right) \quad (6)$$

where σ_y is 1060 MPa, m is 3, K_t is $K_1 \times K_2 \times K_3$, K_1 is the diameter ratio of the inner cylinder, K_2 is the diameter ratio of the middle cylinder, and K_3 is the diameter ratio of the outer cylinder.

Because of limitations on the dimension of the apparatus and requirements for fuel cells, the designed diameters for the bore of the internal cylinder and the outer diameter of the outer cylinder were 60 mm and 500 mm, respectively, for this experimental hydroforming apparatus, and subsequently, $K_1 = K_2 = K_3 = 2.027$. The upper limit to this analysis occurs when the compressive residual stress at the bore of the inner cylinder, which is caused by the shrinkage stress produced by adding an outer element, exceeds the yield strength of the material. In this design, $P_{y\,\max}$ was up to 1203.17 MPa, which sustained a high-pressure fluid of 1000 MPa.

The radial interferences among the three cylinders were smaller than 0.21 mm, which is difficult to accomplish with a direct or shrink fit of the three cylinders. Tapered cylinders were subsequently used to solve the problem, and a small taper angle of 2° was chosen for this purpose. A substantial axial force of approximately 700 tons was required when the tapered cylinders were fitted into each other. After fitting, the surface publishing process was performed on the high-pressure container.

2.3. High-pressure seal

The high-pressure seal component was designed and constructed to seal the high-pressure fluid and maintain the high pressure. The high-pressure seal consists of an O-ring backed by a metal backup ring [25]. The friction between the backup ring and the container increases in conjunction with the pressure, resulting in an additional torsion moment [18,25]. To overcome this problem, Whalley [26] and our previous research [12,18] developed a ladder-shaped and a V-shaped cross-section ring, respectively. To prevent leakage caused by the high pressure, the seal used for this hydroforming apparatus was an O-ring, which is a P series and can be used in pressures of up to 21 MPa, with a V-shaped metal backup ring made of beryllium copper, which has a hardness of HRC40, with a yield strength of 1172 MPa (Fig. 3a and b). The inclined plane of the backup-ring was tightly fitted onto the O-ring, and thus,

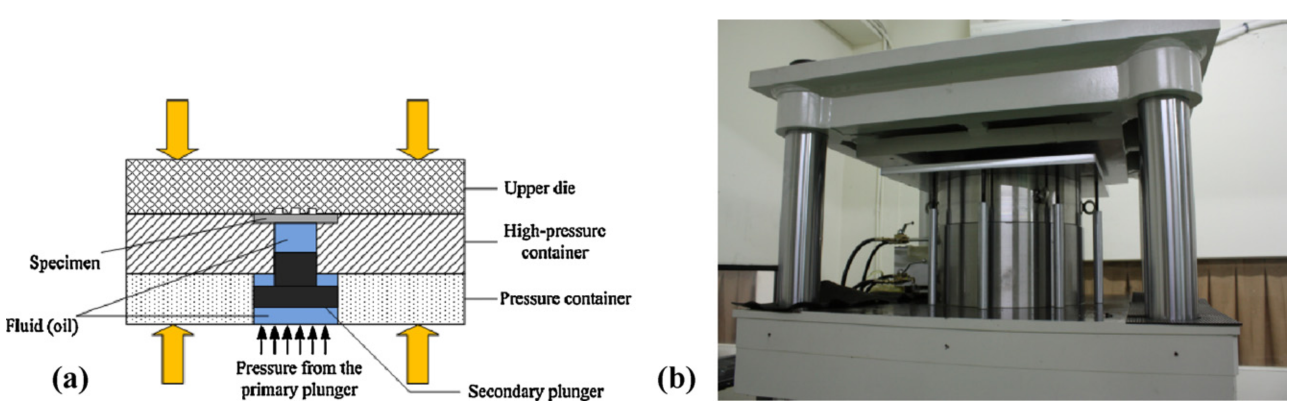

Fig. 4. (a) The hydroforming manufacturing process and (b) a hydroforming apparatus.

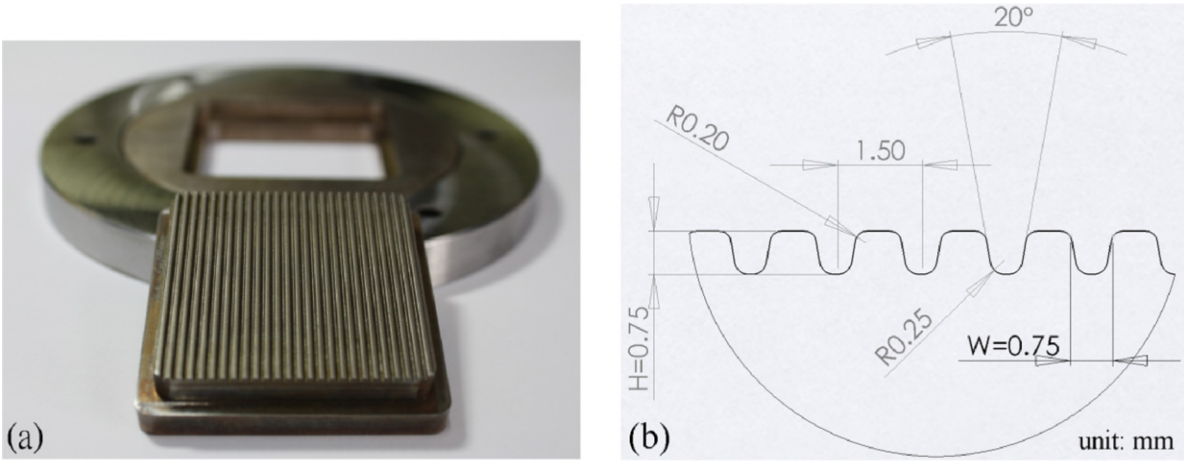

Fig. 5. (a) Mold for hydroforming and (b) geometries of micro-flow channels on the mold.

prevented the O-ring from being squeezed into the gap between the specimen and the high-pressure container.

2.4. Experimental setup

Hydroforming experiments were conducted using the apparatus to test its practicability, as well as to observe the formability of materials after high-pressure hydroforming. The hydroforming apparatus was set up with the following steps (Fig. 4a and b). The hydroforming apparatus provided the holding force to seal the working region, and the primary plunger in the hydroforming apparatus provided the pressure to induce the high-pressure fluid, forming the micro-flow channels. The pressure was released immediately after forming.

Thin SS304 blanks with dimensions of 100 mm × 100 mm × 0.1 mm were used as specimens for the hydroforming experiments. Before the experiments, all the specimens received the solution heat treatment to remove work hardening effects. The material properties of yield strength and Young's modulus were 550 MPa and 195 GPa, respectively, and were obtained by material tests. A mold composed of SKD61 was developed, as shown in Fig. 5a. The mold had an array of 26 parallel microchannels on an area of 40 mm × 40 mm. The selected microchannel size used in this study was 0.75 mm in channel width, height, and land area (Fig. 5b) [10].

A series of experiments was conducted to assess the capability and repeatability of the hydroforming process for fabrication of metallic bipolar plates, with various hydrostatic pressures from 60 to 250 MPa applied to the specimens, with a speed rate of 13 MPa min^{-1}. For each case, three replications were conducted to examine the repeatability of the process. To observe the formability of the hydroforming process, a laser sensor (Keyence LK-H020) with a high repeatability of 0.02 μm was used to measure the formed microchannel profiles (Fig. 6).

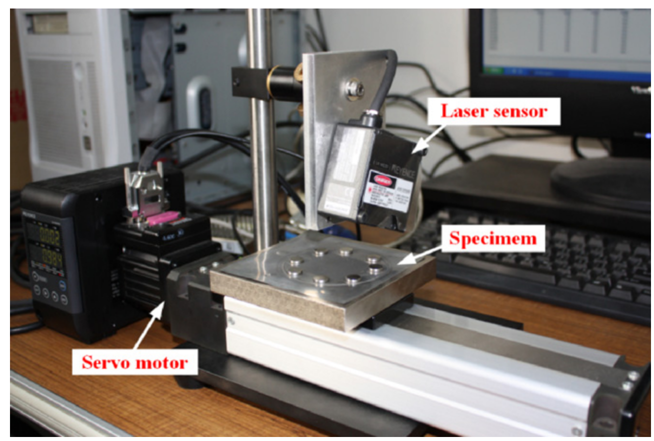

Fig. 6. Laser measurement system (Keyence LK-H020 laser sensor).

3. Results and discussion

3.1. The feasibility of the design for the high-pressure hydroforming apparatus

Finite element analysis for the high-pressure container was conducted first to verify the feasibility of the design for the high-pressure hydroforming apparatus. Three steps were performed, as follows: the first step was to simulate the fitting of the middle cylinder into the outer cylinder. The second step was to simulate the fitting of the internal cylinder into the middle cylinder. The final step was to simulate the condition when a high pressure with a magnitude of 1000 MPa was applied to the inner surface of the three-layered high-pressure container. The final Mises stress contour (Fig. 7) indicated that the stress of 990 MPa in the inner surface of the high-pressure container was lower than the yield strength of the container material.

The high-pressure hydroforming apparatus was constructed after finite element analysis, and a series of repeated tests with

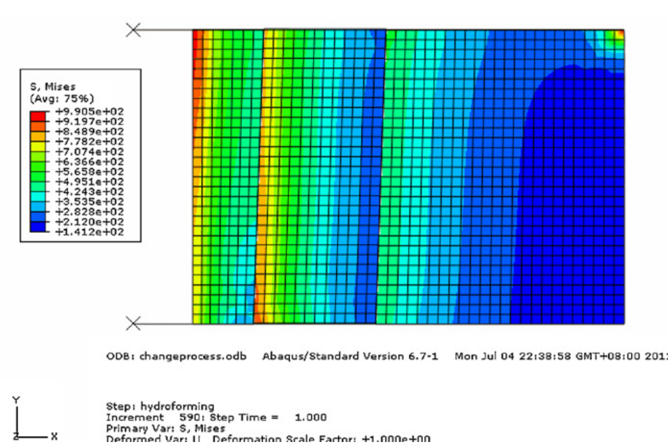

Fig. 7. The final Mises stress contour in the finite-element simulation of the high-pressure container (unit: MPa).

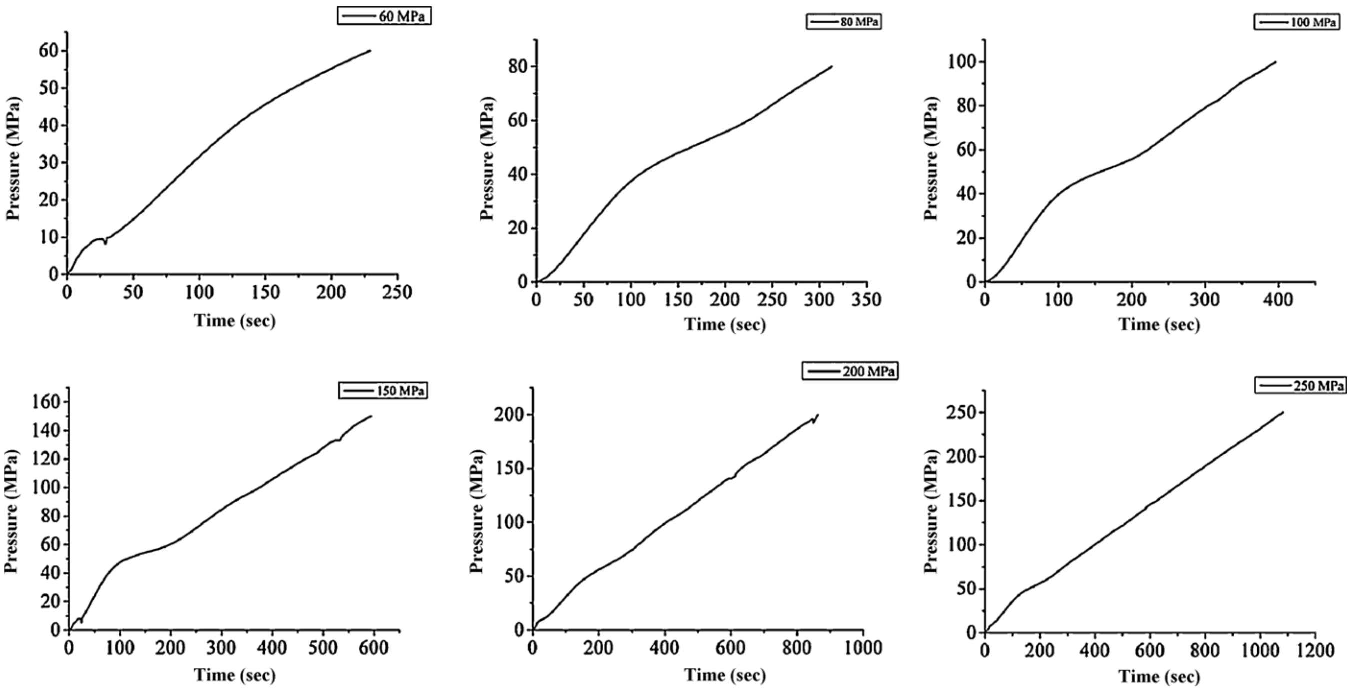

Fig. 8. Pressure versus time for a series of hydroforming tests.

various hydrostatic pressures from 60 to 250 MPa was performed with the apparatus. Fig. 8 shows that the pressure provided by the high-pressure apparatus in each test could reach the object pressure, and that all the components in the apparatus worked smoothly; the high-pressure container sustained a pressure of up to 250 MPa, and the high-pressure seal sealed the high-pressure fluid and maintained the high pressure. Finally, the feasibility of the high-pressure hydroforming technique, a two-stage pressure increase structure, a high-pressure container, and a special seal was verified.

3.2. Hydroforming of micro-flow channels

Samples of the hydroformed bipolar plates are shown in Fig. 9. The mold and typical profile measurements across the middle of the specimens obtained from the laser sensor are shown in Figs. 10 and 11. The measurements indicated that the dimension of the mold was approximately 0.76 mm and 0.75 mm in channel height and width, respectively, with a maximum in-plate depth variation of 0.78% (Fig. 10). The dimension of the mold was similar to that of the mold design, which was 0.75 mm in channel height and width; however, the profiles of specimens shown in Fig. 11 had a concave shape, in which the channels on both sides were bulging. This occurred because the specimens were not flat, especially after the solution heat treatment; however, the channel heights on both sides did not differ from other channel heights on the specimen. The formability among micro-flow channels within the same bipolar plate was uniform with a maximum in-plate depth variation of 2.5% (Fig. 11). The maximum dimensional variation between various samples formed at the same pressure was approximately 47 μm (Fig. 12). Thus, this study reached the conclusion that the process control and repeatability of the

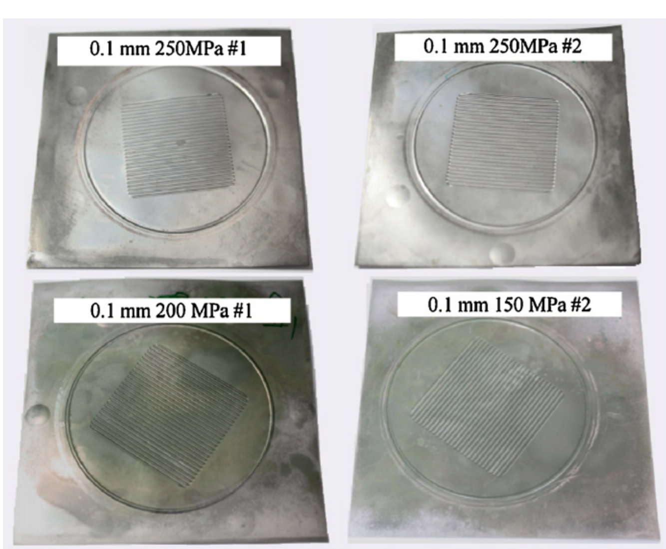

Fig. 9. Samples of hydroformed specimens.

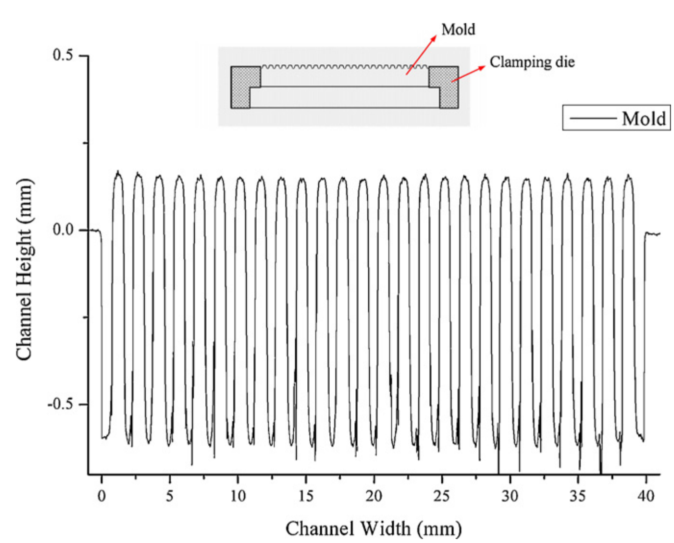

Fig. 10. Laser measurement profiles for the mold.

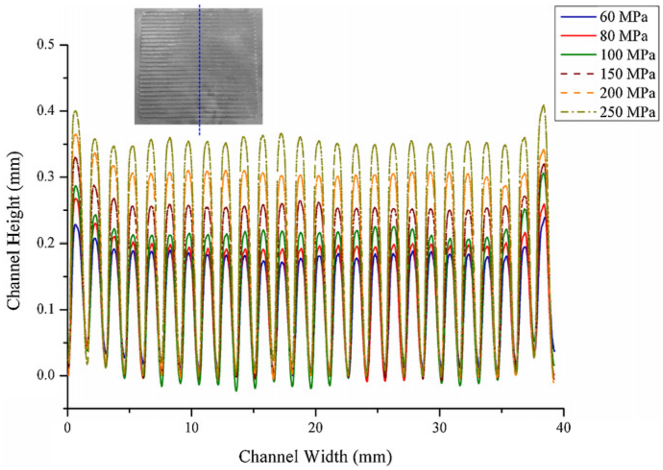

Fig. 11. Laser measurement profiles for hydroformed specimens.

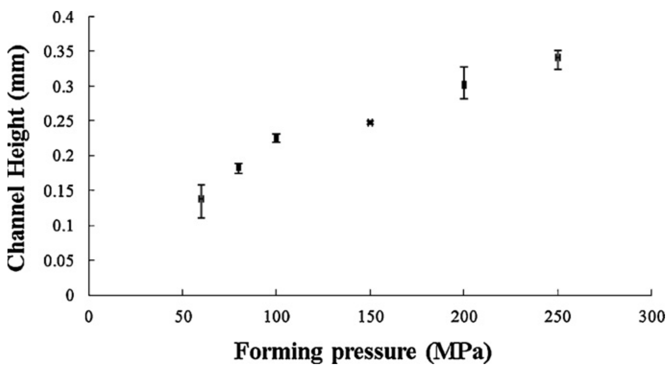

Fig. 12. The dimensional variation between specimens in each test (unit: mm).

micro-flow channel hydroforming were reasonably acceptable. In this research, a forming depth of 0.351 mm and an aspect ratio of 0.468 were achieved when 250 MPa of hydrostatic pressure was applied to a metallic plate with a thickness of 0.1 mm.

In previous studies traditional hydroforming processes had been limited by the forming pressure, and formed micro-flow channels on 0.051-mm-thick SUS304 plates and a maximum aspect ratio of 0.31, which prevented the cell performance from being revealed effectively. However, the aspect ratio of the micro-flow channels formed on the 0.1-mm-thick SUS304 plates reached 0.468 by using the proposed high-pressure hydroforming technique, and this result revealed that the high aspect ratio micro-flow channel may be obtained using this high-pressure hydroforming apparatus to meet both cell performance and manufacturing requirements.

4. Conclusions

In this study, an experimental hydroforming apparatus was designed, built, and modified, with an emphasis on structural simplicity using commercially available materials. A series of experiments was performed to verify the practicability of the apparatus, and satisfactory testing results were obtained with information on the material behavior under various hydrostatic pressures. Although further investigation on the effects of hydroforming parameters will be conducted, two conclusions are offered, as follows:

1. The feasibility of this high-pressure hydroforming technique was verified; a high-pressure container with a three-layered tapered composite cylinder and a high-pressure seal component were designed and preliminarily proven to safely provide a working pressure of 250 MPa.
2. Fabrication of the 0.1-mm-thick metallic bipolar plates (SUS304) with the hydroforming apparatus is feasible, and we successfully formed micro-flow channels with an aspect ratio of 0.468. Compared with the maximum aspect ratio of 0.31 formed by the traditional hydroforming process, the aspect ratio of micro-flow channels in this study was improved by 51%, which enabled the fuel cells with metallic bipolar plates to meet both performance and manufacturing requirements. Furthermore, this result also proved that micro-flow channels with a high aspect ratio may be obtained by increasing the forming pressure.

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