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ORIGINAL ARTICLE

Fabrication of metallic bipolar plates in PEM fuel cell using semi-stamp rubber forming process

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Abstract Metal is considered to be a good material for a bipolar plate due to its good electrical conductivity, excellent mechanical properties, and low cost. In this study, fabrication of metallic bipolar plates with serpentine flow field microchannels was investigated by a novel rubber pad forming process. Stainless steel 316 with thickness of 0.1 mm was used. Polyurethane rubbers with the hardness of shore A40, A55, A65, and A90 and the thickness of 10, 20, and 30 mm were used in this study to manufacture bipolar plates. At first, convectional rubber pad forming process was used to produce bipolar plates by some experimental tests. In this step, the effect of applied force, rubber hardness, and rubber thickness on filling percentage, thickness distribution, and dimensional accuracy was investigated. The results showed that filling percentage would increase by rising applied force, but channel depth was not equal in different directions. Increases in rubber hardness led to improving uniformity in channel depth. In addition, decreases in rubber hardness and increases in rubber thickness caused higher filling volumes. However, maximum filling percentage, dimensional accuracy, and thickness distribution in convectional rubber forming process were not satisfying. Thus, a novel method was developed in this study in order to improve the quality of fabricated bipolar plates named semi-stamp rubber forming. The results indicated that using semi-stamp rubber forming instead of convectional rubber forming would lead to 11.7, 9, and 1.075% improvement in filling percentage, thinning percentage, and dimensional accuracy, respectively. According to the results, the developed model (semi-stamp rubber forming) could be a feasible technique in fabricating metallic bipolar plates.

Keywords Fuel cell · Metallic bipolar plates · Metal forming process · Semi-stamp rubber forming

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1 Introduction

In recent years, due to increases in using renewable energy sources as an alternative to fossil fuels in various industries, scientists have tried to investigate different challenges in fuel cell technology to enhance output and decrease manufacturing cost.

Proton exchange membrane fuel cells (PEMFCs), fuel cells using hydrogen and oxygen as energy sources, have attracted much attention mainly because of their higher efficiency, higher current density, and lower activation temperature than others [1, 2]. A fuel cell generally consists of various components, among which bipolar plates allocate approximately 60 to 80% of PEMFCs weight and 30 to 45% of their cost to themselves [3], hence one of the most important components of PEMFCs due to their volume and cost.

Because of the importance of these plates in the performance of fuel cells and their costs, extensive research has been done into a suitable method and cost of them, e.g., graphite [4], composite [5], and metal plates [6] were used to manufacture bipolar plates.

Among different types of bipolar plates, metallic bipolar plates have received significant attention in PEMFCs due to their appropriate mechanical, electrical, and thermal properties [7].

Production methods of bipolar plates are generally divided into three groups: molding, machining, and metal forming.

Molding is used for producing composite plates, machining is used for creating metal and graphite bipolar plates, and finally metal forming is used for metallic bipolar plates with low thickness [8–10].

Hydroforming processes [11, 12], stamping [13], and electroforming [14] are some metal forming techniques regarded as processes to fabricate microchannels of bipolar plates.

In addition to the mentioned methods, rubber forming could be used to fabricate microchannels of metallic bipolar plates in thin sheets. Due to its simplicity, high production speed, and low tooling cost compared to others, rubber pad forming would resolve their drawbacks, such as cost, forming limitation, and productivity.

Figure 1 shows schematic of rubber pad forming process. As can be seen, the process consists of an upper die with a machined pattern of microchannels used as punch and a lower die, a container with a rubber pad. A metal sheet is placed between rubber and the upper die. In order to start forming process, the upper die moves downward. Then, the rubber pad is deformed to fill the cavity (machined path) on the upper die and provide counter pressure. As a result, the rubber and thin metal sheet flow into the cavity of the upper die. Finally, the metal sheet is deformed to the desirable pattern of microchannels machined on the punch.

In this process, features of the rubber layer would play an important role in the quality of produced samples, having significant impact on the cost of rubber forming process as well. Therefore, some research has been conducted into the behavior of the rubber layer and the effect of different variables on forming process.

Liu et al. [15] investigated bipolar plate forming by rubber pad forming process. They used 2D simulation of the process to evaluate the influence of die radius, draft angle, and rubber layer hardness. The results showed that increasing the outer and inner radii would lead to better filling percentage as well as reducing the risk of rupture. As a result, rubber hardness might not have great effects on stress distribution, and increases in draft angle would reduce forming force.

Lim et al. [16] fabricated aluminum 1050 bipolar plates. Firstly, they studied the effect of channel cross-sectional area on flowing gas in the channels. They also investigated the effect of punch speed, applied force, rubber thickness, and hardness on channel depth. The results showed that increasing rubber layer thickness would reduce its hardness, and increasing applied force and punch speed would lead to rises in channel depth.

Kang et al. [17] studied forming titanium plates with rubber pad forming process. In this research, the effect of punch speed, applied load, thickness, and hardness of rubber and draft angle on the depth of channels was studied. According to the results, increasing the thickness of rubber layer and reducing hardness would lead to improving channels depth. Ultimately, according to the effect of variables on channel depth, appropriate values of forming variables were selected.

Jung et al. [18] investigated the effect of punch speed, applied load, rubber thickness, and hardness on fabricating bipolar plates with stainless steel 304. The results indicated that channel depth would show direct proportion to punch speed, pressure, and rubber thickness. Reducing rubber hardness would improve forming condition, as well. Increasing draft angle, especially between 10° and 20°, would also improve forming process condition. Variations in draft angle between 20° and 30° did not have significant effects on channel depth. The effect of draft angle on dimensional accuracy of the samples was studied, and it was shown that increasing draft angle would lead to improvement in dimensional accuracy and uniformity of channel depth.

Elyasi et al. [19] examined the effects of concave and convex dies on rubber pad forming process. In their research, stainless steel sheet 316 with a thickness of 0.1 mm and a rubber layer with hardness of 85 shore A were used to form samples. According to the results, for an equal applied load, concave die would show more filling depth than the convex one. In addition, by increasing forming force to maximum amount, filling depth would become stable in the concave die, and increasing the force would cause damage in rubber.

All mentioned research investigated the effect of geometric variables of die, rubber layer feature, and forming force on channel depth. However, more studies into fabricating metallic bipolar plates by rubber pad forming process could be necessary since the performance of fuel cells might be affected by depth and shape of microchannels [20]. The goal of this research was to produce a metallic bipolar plate with serpentine flow field by rubber pad forming process and improve channel depth and quality of final shape of fabricated bipolar plates due to their

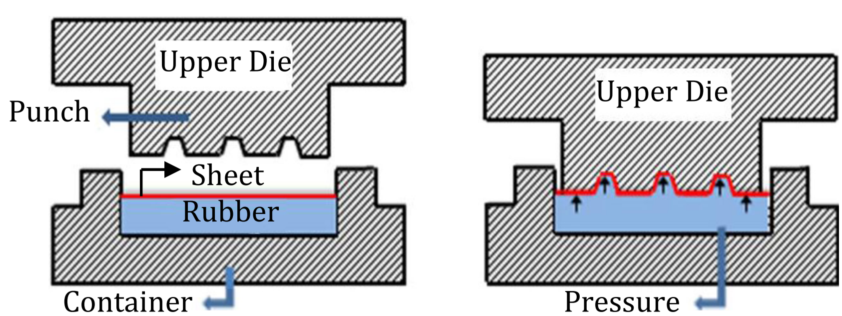


Fig. 1 Schematic of rubber pad forming process

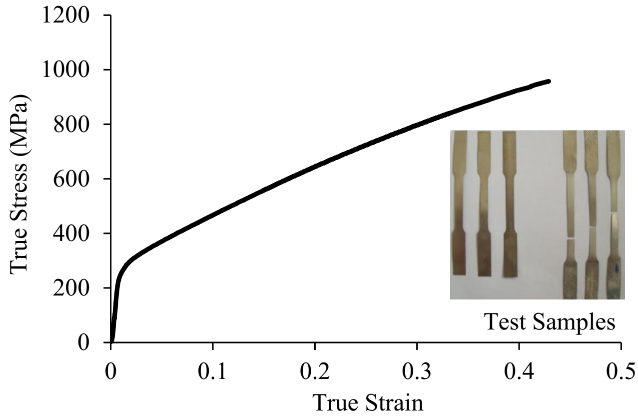


Fig. 2 True stress-strain curve

Table 1 Mechanical properties of SS316 sheet

Material properties	Value
Young's module (E (GPa))	200
Poisson's ratio (ν)	0.3
Yield stress (σ_y(MPa))	296
K (MPa)	1512
n	0.53
ε_0	0.04

importance in increasing the efficiency of fuel cells. To this goal, the effect of rubber characteristics on formability of bipolar plates in convectional rubber pad forming process was investigated. At first, the effect of force, rubber hardness, and rubber thickness on filling depth, thickness distribution, and dimensional accuracy was investigated. The value of filling depth in three different directions (longitudinal, diagonal, transverse) was measured. In the end, a novel method (semi-stamp rubber forming) was represented in order to achieve higher channel depth, dimensional accuracy, and uniformity of thickness distribution in bipolar plates compared to convectional rubber pad forming. The results showed that the method would have significant effects on improving the quality of metallic bipolar plates regarding their final shape.

2 Experimental

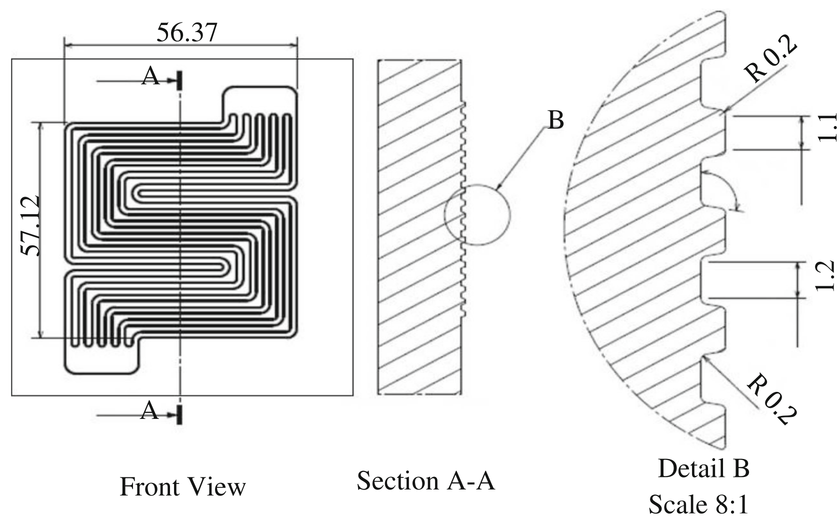
Rubber pad forming process was used to manufacture metallic bipolar plates, through which serpentine flow field bipolar plates were made. Stainless steel 316 sheet with the thickness of 0.1 mm was used in this study. In order to define mechanical properties of the material, samples were investigated via uniaxial tension test according to ASTM E8M standard. Stress-strain curve is presented in Fig. 2. SS316 tensile plastic deformation could be obtained by curve fitting and linear regression method by Eq. (1). The value of parameters in Eq. (1) and mechanical properties of the metal sheet used in this process are shown in Table 1.

$$\sigma = k(\varepsilon + \varepsilon_0)^n \tag{1}$$

Serpentine flow field bipolar plate was studied in this research. It was selected due to its suitable contact area between the bipolar plate and the electrodes and reducing pressure drop compared to other flow field types [21]. Figure 3 shows pattern and detailed dimensions of the upper die. Value of draft angle and outer and inner radii were found to be 10° and 0.2 mm, respectively, based on previous studies [15, 16, 19].

Figure 4 shows the experimental instrument that was used in this study. As can be seen, the system consists of an upper die, a container, punch, rubber, and 200 t of hydraulic press. In order to perform the process, punch surface was machined with CNC milling machine to create serpentine flow field pattern, microchannel surface, and anode-cathode surface. The machined surface, microchannel surface, anode-cathode

Fig. 3 Microchannel flow field pattern and dimensions



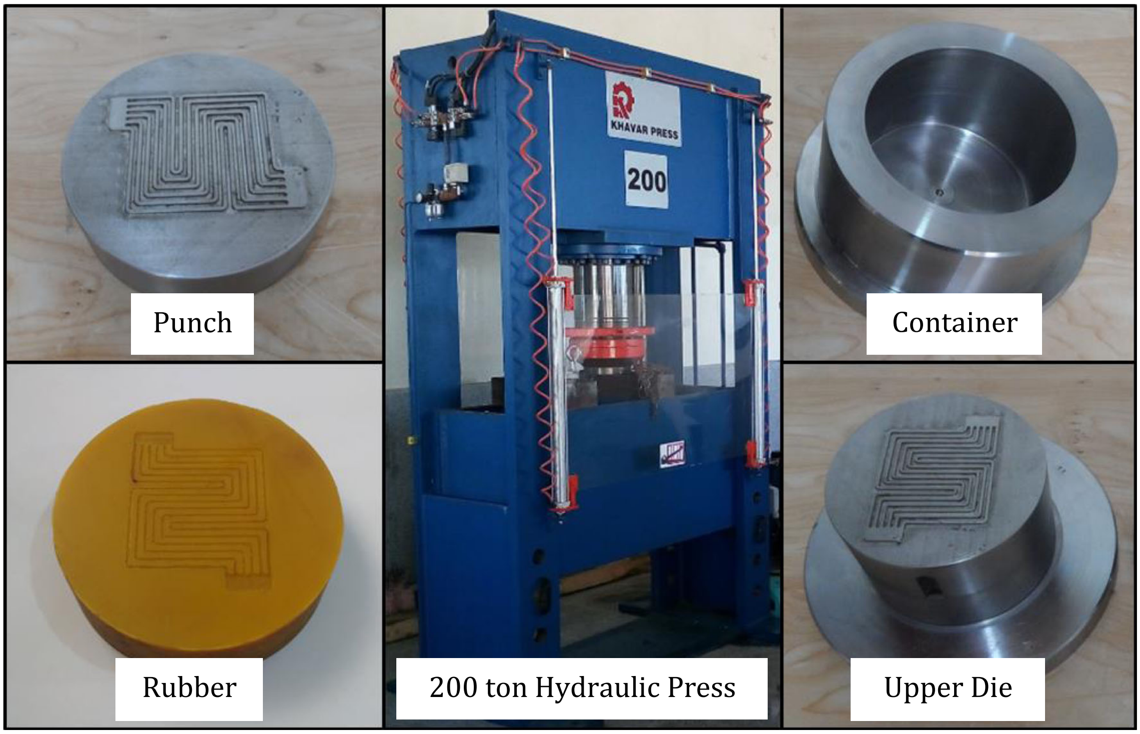


Fig. 4 Experimental instrument for rubber pad forming

surface, and different parameters of microchannels such as channel width (w), rip width (s), draft angle (α), and channel depth (h) are represented in Fig. 5. Values of channel parameters are shown in Table 2.

Fig. 5 Machined punch surface and its geometry

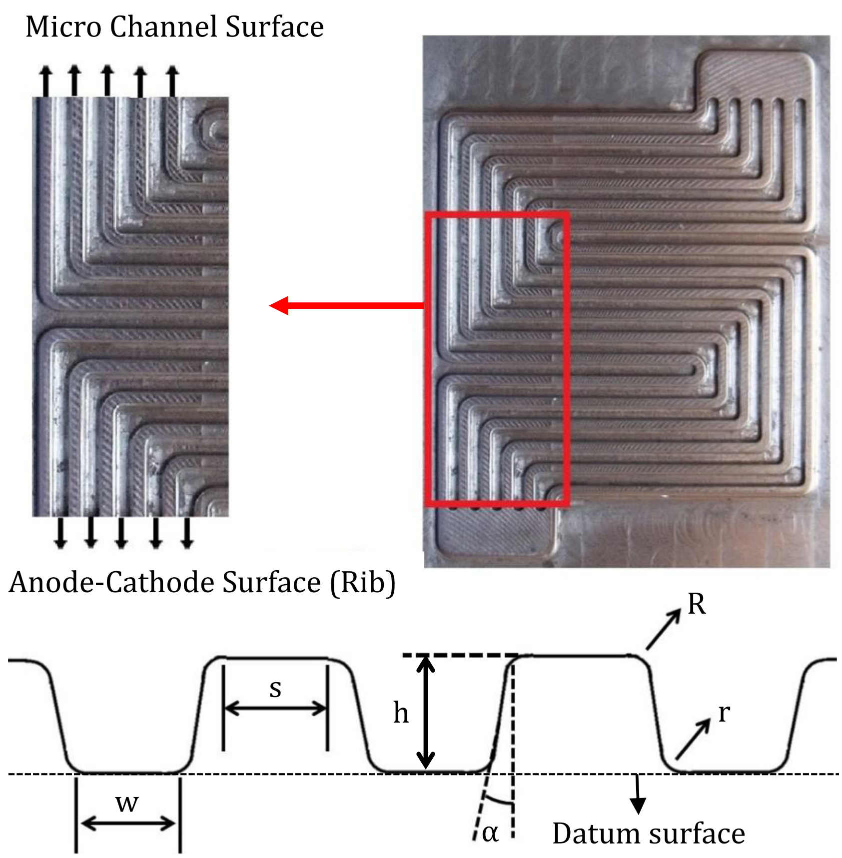


Table 2 Dimensional information of produced die

Geometric parameter	Value
Channels width (*w*)	1.1 (mm)
Rib width (*s*)	1.2 (mm)
Draft angle (*α*)	10°
Internal radius (*r*)	0.2 (mm)
Outer radius (*R*)	0.2 (mm)
Depth (*h*)	0.75 (mm)

Rubber is another important part in rubber pad forming process that helps to provide required pressure in order to fill die cavity leading to forming sheet metals and creating intended flow field pattern on them. Thus, rubbers used in this process should deform easily and return to their primary shape after forming process. The effect of rubber characteristics is considered significant because elastic deformation of pad during compression by punch would lead to flowing sheet metal into punch cavity creating serpentine flow field on the primary blank. In this study, polyurethanes rubber with different hardness and thickness were used. Cylindrical rubber pad with a diameter of 107 mm (equal to the container diameter) and shore hardness of A40, A55, A65, and A90 were tested to examine the effect of rubber hardness in formability of microchannels. Three thickness ranges of 10, 20, and 30 mm were used in each rubber to investigate the effect of rubber thickness on intended output. Then, a novel method (semi-stamped rubber forming) was used to improve the quality of fabricated bipolar plates. Unlike conventional methods, a machined rubber was used here. Figure 6 shows rubber forming die and different types of rubber used in this study.

In conventional method, a rubber with flat surface was used which would cause contact between the sheet and the punch in microchannel surface area (Fig. 7a). When the process started, the rubber pressed the sheet to the area, so metal sheet could not flow into the channel and just bulged into punch cavity (Fig. 7b). Due to this problem, samples formed by convectional process showed high thickness, reduction in ratio and low channel depth. However, in semi-stamp rubber forming, the sheet metal was free between the rubber and the punch (no clamping force) at the beginning of process (Fig. 7c). As a result, the material could flow from these areas to punch cavity and form anode-cathode surface. This would help to decrease thickness reduction in critical areas, prevent cracking, and increase channel depth.

To investigate the effect of rubber characteristics and forming load and compare conventional and semi-stamp rubber forming, different forces (300, 350, 450 kN) were used to form plates. All tests were done at the same press speed (5 mm/s) for an accurate comparison. Different process parameters are shown in Table 3.

To evaluate thickness distribution and filling percentage, samples were cut using wire cut machine in three different directions. Longitudinal, diagonal, and transverse cutting directions are shown in Fig. 8c. Due to the rough surface of samples after wire cut, they could not be suitable for measuring. To increase accuracy, samples were mounted with epoxy resin, and surfaces were sanded and polished to see their profile under optical microscope of ×4 magnifying. Microscope images were processed to determine channel depth and thickness distribution by image processing software connected to a microscope by computer. Wire cut, mounted, and microscope images of metallic bipolar plates are shown in Fig. 8.

3 Results and discussion

To implement the study and understand the effect of process parameters on the quality of bipolar plates and compare convectional and semi-stamp rubber forming, the result of filling

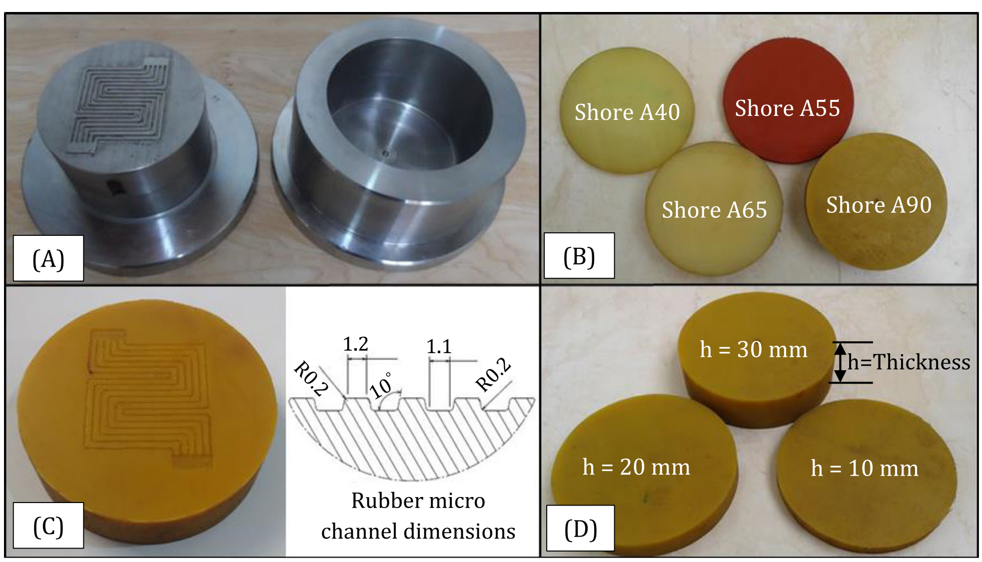


Fig. 6 **a** Rubber forming die. **b** Rubber hardness. **c** Machined rubber. **d** Rubber thickness

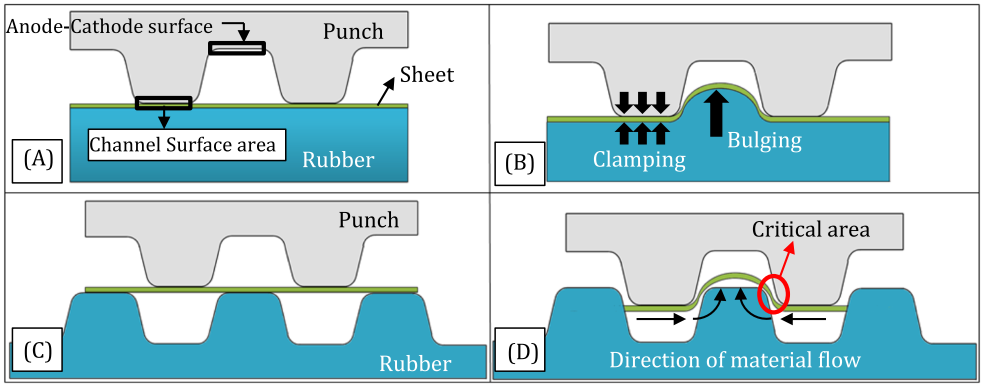


Fig. 7 **a**, **b** Schematic of convectional rubber forming. **c**, **d** Schematic of semi-stamp rubber forming

Table 3 Process parameters in rubber forming of bipolar plates

Process parameter	Value
Force (kN)	300, 350, 400
Punch velocity (mm/s)	5
Rubber hardness (shore A)	40, 55, 65, 90
Rubber thickness (mm)	10, 20 ,30

percentage, thickness distribution, and dimensional accuracy were compared. Before reporting the result, some criteria should be defined for calculation of thinning and filling percentages and dimensional accuracy. Thinning percentage was used to analyze formability and compare the effect of process parameters on dimensionless parameters (Eq. (2))

$$\text{Thinning percentage} = \left((t_0 - t_f) \big/ t_0 \right) \times 100 \quad (2)$$

where t_0 is sheet initial thickness, and t_f is final thickness after processing. Filling percentage was considered another parameter to compare channel depth defined by Eq. 3

$$\text{Filling percentage} = \left(\text{channel depth of formed plate} \big/ \text{channel depth of die} \right) \quad (3)$$

Dimensional accuracy was another parameter investigated in this study showing the uniformity of different channel depths. Equation (4) was used to determine dimensional accuracy in different conditions.

$$\text{Channel depth error} = \left(\frac{|h_k - h_m|}{h_m} \right) \times 100 \quad (4)$$

where h_k is the depth at each location, and h_m is average forming depth from h_1 to h_9 as shown in Fig. 17.

3.1 Filling percentage

The goal of this study was to achieve maximum and uniform filling percentage in formed bipolar plates in order to

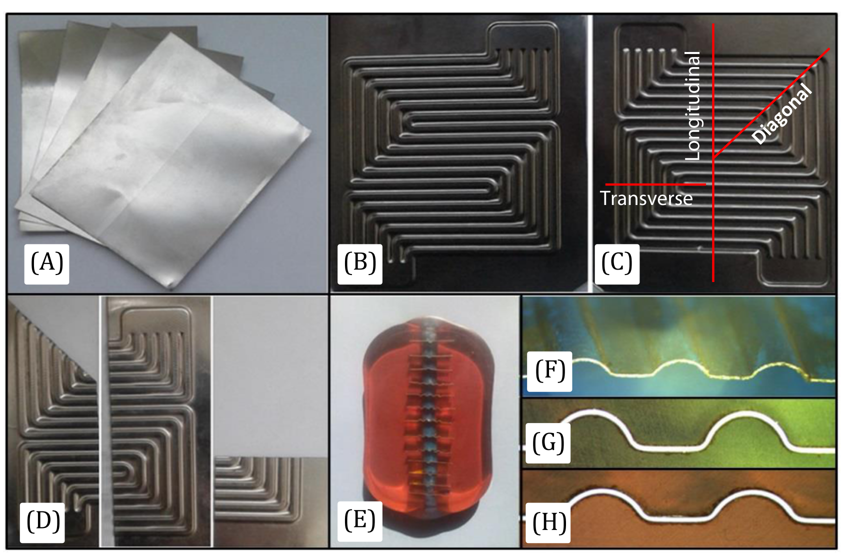


Fig. 8 Sample preparation steps in measuring **a** primary sheet, **d** produced bipolar plate, **c** cutting direction, **d** cut samples, **e** mounted samples, and **f**–**h** microscope images

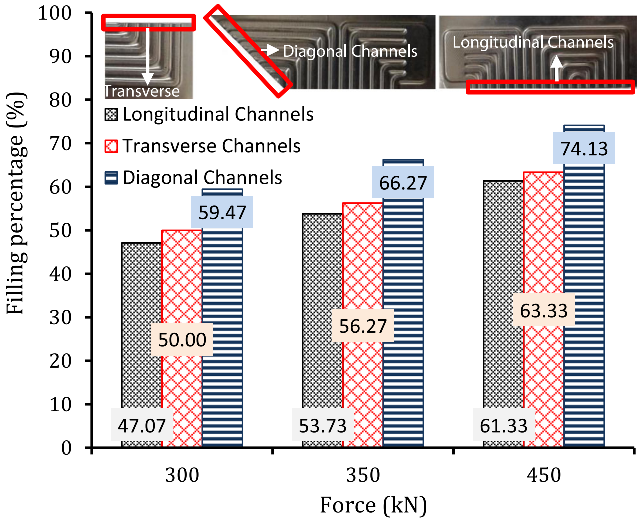


Fig. 9 Filling percentage of bipolar channels along longitudinal, diagonal, and transverse directions

avoid decreases in the efficiency of fuel cells. Figure 9 shows filling percentage of bipolar channels along longitudinal, diagonal, and transverse directions. Samples were fabricated by rubber with shore hardness of A90 and thickness of 20 mm. Applied force varied from 300 to 450 kN. As can be seen, by increasing the force, filling percentage rose and maximum filling percentage was 74.13% in diagonal direction. As obvious from the results, filling percentage (channel depth) was not uniform in different directions at equal forces. Filling percentage in diagonal channels was higher than longitudinal, and filling percentage in longitudinal direction was higher than transverse direction. Figure 10 shows differences between filling percentages in various samples fabricated by rubber with shore hardness of A40 and A90 at 450 kN. According to the results, differences between maximum channel depth (diagonal channel) and minimum channel depth (transverse channel) would decrease from 18.4 to 12.8% by increasing rubber hardness from shore A40 to A90. Results also indicated

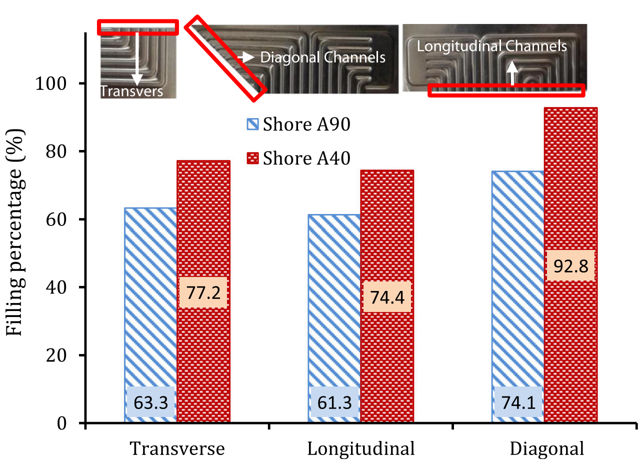


Fig. 10 Effect of rubber hardness on channel depth uniformity

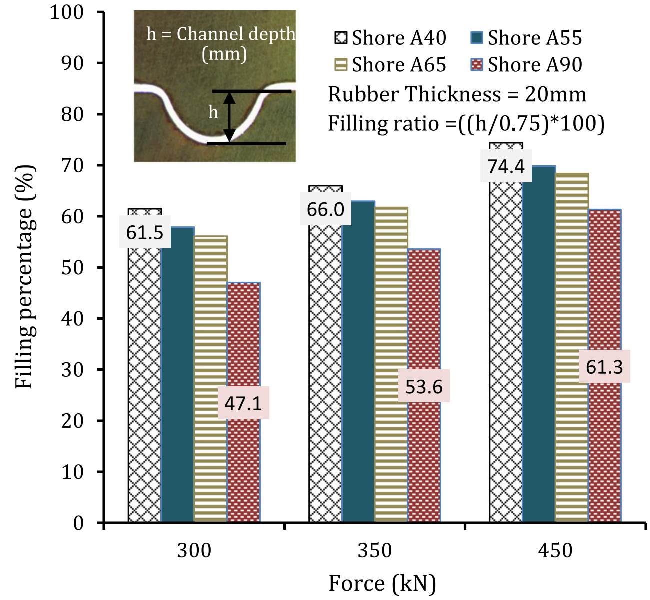


Fig. 11 Effect of rubber hardness on filling percentage

that increasing rubber hardness would lead to improving uniformity of bipolar plates (6% increase using shore A90 instead of shore A40).

Figure 11 shows filling percentage resulted from variations in hardness of the rubber pad. Punch velocity and thickness of the rubber pad were set to 5 mm/s and 20 mm, respectively, and all the results were in longitudinal direction. Different rubbers with hardness of shore A40, A55, A65, and A90 were investigated. As shown in this figure, reducing hardness could contribute to an increase in filling percentage. It could be due to the fact that at the same pressure, the deformation of the rubber with lower hardness was more than the rubber with higher hardness. Therefore, repulsive force of rubber to sheet

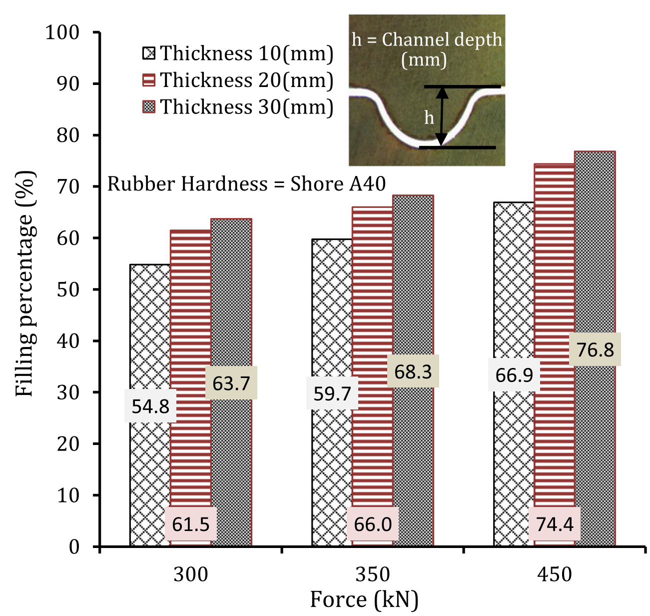


Fig. 12 Effect of rubber thickness on filling percentage

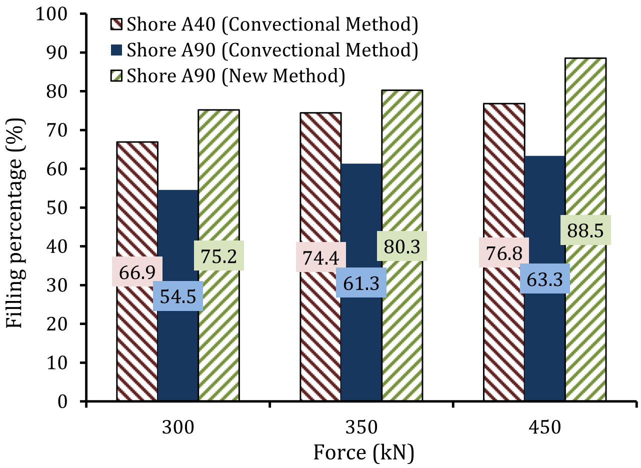


Fig. 13 Comparing filling depth of convectional and semi-stamp rubber forming

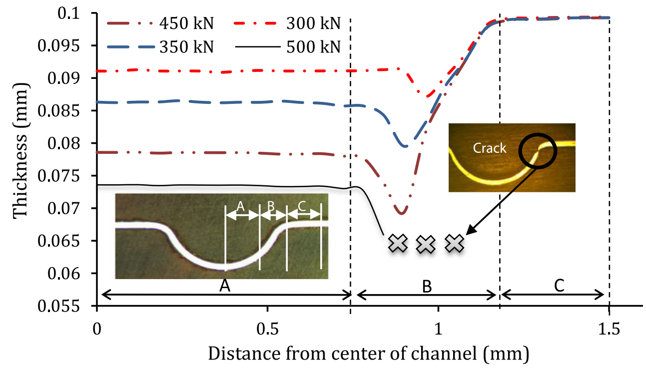


Fig. 15 Thickness distribution of produced samples by conventional method

increased which resulted in sizes in channel depth. Maximum filling percentage was achieved at 450 kN and shore A40 (74.4%) and minimum achieved at shore A90 (61.3%).

Since rubber thickness is considered an effective parameter in this process, the effect of rubber thickness pad was investigated on filling percentage (Fig. 12). Punch velocity and hardness of the rubber pad were set to 5 mm/s and shore A40, respectively. Different rubbers with thickness of 10, 20, and 30 mm were investigated. As can be seen in Fig. 12, filling percentage increased by rises in rubber thickness. As Figs. 11 and 12 show, maximum filling percentage in longitudinal direction (76.8%) was achieved in bipolar plates fabricated by rubber with shore A40 hardness and 30 mm thickness. Increasing the force to more than 450 kN caused rapture in samples.

This would confirm the necessity to develop a novel method to improve filling percentage and prevent rapture. Semi-stamped rubber forming was developed in this study. As mentioned, the surface of rubber was machined in this method. Schematic of this method is illustrated in Fig. 7c, d. It was expected that semi-stamp rubber forming would increase filling percentage and prevent rapture by allowing the flow of material into punch cavity unlike the conventional method, Fig. 7d.

To investigate the efficiency of the method, a rubber with hardness of shore A90 was machined (other rubber could not be machined), and bipolar plates were fabricated at 300, 350, and 450 kN. Punch velocity and thickness of the rubber pad were set to 5 mm/s and 30 mm, respectively. Figure 13 shows the comparison of filling percentage in semi-stamp rubber forming with convectional rubber pad forming (using rubbers with hardness of shore A40 and A90).

Figure 13 shows the noticeable effect of semi-stamp rubber forming on filling percentage, which led to increasing from 76.8% (maximum value in conventional method) to 88.5%, representing 11.7% improvement in filling percentage. Figure 14 illustrates channel depth of formed samples at 450 kN created by both convectional and semi-stamp rubber forming. As can be seen, maximum channel depth (0.664 mm) was achieved through the proposed method.

3.2 Thickness distribution

According to previous results, increasing the force to more than 450 kN would cause rapture in samples that were fabricated by rubber with hardness of shore A40 and thickness of 30 mm. This could be due to the fact that the thickness of the metal sheet would decrease more than the critical value in some areas. The plates should have uniform thickness distribution regarding many chemical reactions with MEA and high corrosion [10], so the area with lower thickness would be more sensitive to corrosion. Thus, thickness distribution was investigated in samples that were fabricated by rubber hardness with shore A40 and thickness of 30 mm because of their higher filling percentage. Figure 15 shows thickness distribution at 300, 350, 450, and 500 kN. As can be seen, thickness distribution area is divided into three zones. Minimum

Fig. 14 Comparing channel depths

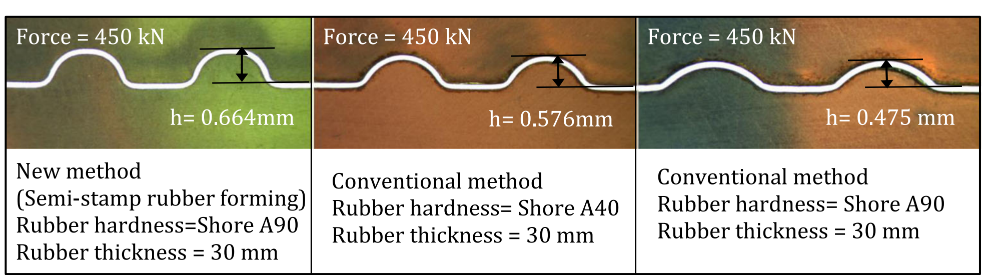


Table 4 Thinning percentage of produced samples by conventional method

Force (kN)	Rubber hardness (shore A)	Rubber thickness (mm)	Thinning percentage
300	40	30	31
350	40	30	21
450	40	30	13
500	40	30	Crack

thickness in all samples accrued in zone B due to larger deformation rate in this area than zones A and C. In addition, in convectional rubber pad forming, the sheet was clamped between rubber and punch (Fig. 7b), a condition not permitting the material to flow into punch cavity from section C to increase minimum thickness in section B (critical area). The value of minimum thickness in sections A and B decreased by increasing force due to stretches in the sheet metal to reach higher channel depth. Minimum thickness was achieved in zone B at 450 kN equal to 0.069 mm. Increases in the applied force to more than 450 kN caused rapture in zone B due to a high rate of reduction in this area. Despite this high rate, thickness value of formed samples in zone C was approximately equal to 0.1 mm because of clamping force in convectional rubber pad forming. Equation 2 was used to calculate thinning percentage. Table 4 presents thinning percentage according to thickness distribution. As the results showed, maximum thinning percentage was 31% at 450 kN.

It was necessary to decrease thinning percentage in order to prevent cracking at higher forces (more than 450 kN). Figure 16 compares thickness distribution in samples fabricated by rubber with hardness shore A40 and thickness of 30 mm in convectional process and rubber hardness shore A90 and thickness of 30 mm in semi-stamp rubber forming. Applied force in both methods was set to 450 kN. As found, thickness distribution in semi-stamp rubber forming was more uniform than in conventional method. In addition, in semi-stamp

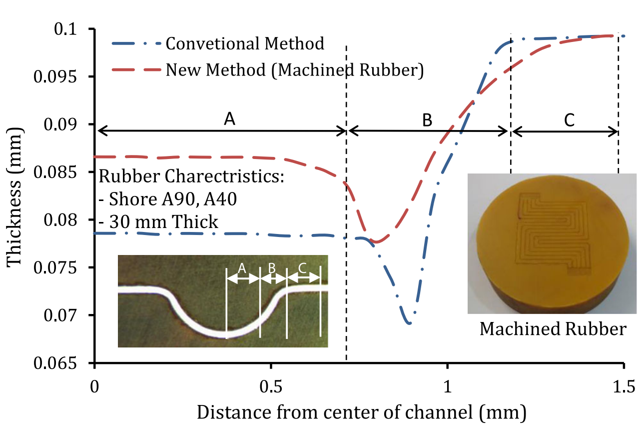


Fig. 16 Comparison of thickness distribution of produced samples with conventional method and semi-stamped rubber forming

Table 5 Comparison of thinning percentage of produced samples with conventional method and semi-stamped rubber forming

Process	Rubber hardness	Rubber thickness (mm)	Force (kN)	Thinning percentage (%)
Convectional rubber forming	Shore A40	30	450	31
Semi-stamp rubber forming	Shore A90 (machined surface)	30	450	22

rubber forming, minimum thickness in critical zone B was much more than minimum thickness in convectional rubber pad process. Equation 2 was used to compare thinning percentage. Table 5 shows the value of thinning percentage.

As the table shows, thinning percentage decreased from 31% in conventional method to 22% in semi-stamp rubber forming (developed method). This could confirm that semi-stamp rubber forming would have significant effects on uniformity of thickness distribution and prevent cracking in achieving higher channel depth compared to the convectional process. As mentioned, in convectional process (Fig. 7a, b), the sheet was clamped between punch and rubber in channel surface area from the start of the process. This would cause local thinning at zone B of formed samples. As shown in Fig. 7c, d, in the developed method, the metal sheet was not clamped from the beginning of the process. Thus, the material could flow and stretch from channel surface area (zone C) into punch cavity (zones B and A). This caused decreases in local thinning at zone B and finally led to 9% improvement in thinning percentage.

3.3 Dimensional accuracy

Since bipolar plates consist of several microchannels, to improve the efficiency of fuel cells, it would be better for the channels to be of the same depth and filling percentage. To study dimensional accuracy of bipolar plates, samples that were fabricated at 350 and 450 kN in convectional rubber pad forming and semi-stamp rubber forming were investigated. To compare the effect of convectional and semi-stamp rubber forming on dimensional accuracy, all samples were formed using the rubber with hardness of shore A90 and thickness of 30 mm.

At first, dimensional accuracy in conventional method was investigated. Figure 17 shows filling percentage of different channels in longitudinal direction. Forming depth was measured in nine positions, i.e., three channels in the left side (h_1, h_2, h_3), three channels in the middle of bipolar plates (h_4, h_5, h_6), and three channels in the right side (h_7, h_8, h_9), Fig. 17. Equation (4) was used to quantitatively evaluate dimensional

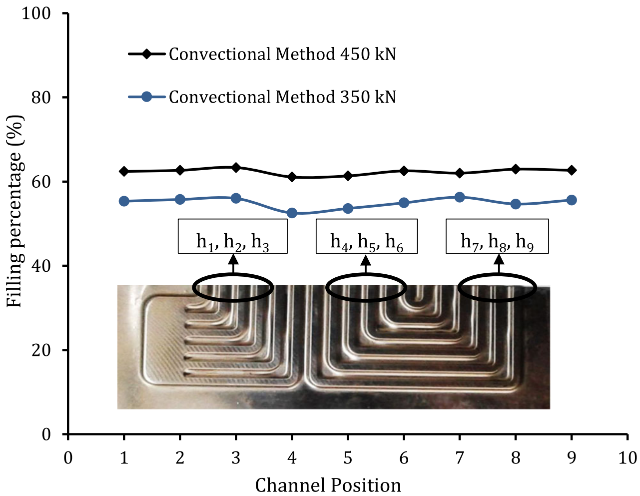


Fig. 17 Longitudinal channel filling percentage in conventional rubber forming

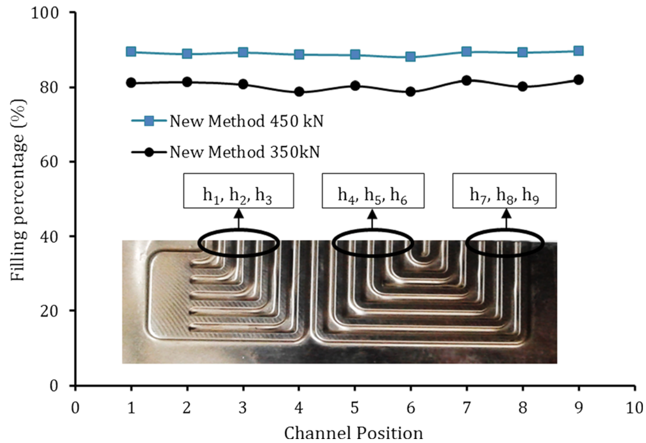


Fig. 18 Longitudinal channel filling percentage in semi-stamp rubber forming

accuracy of channel depths, representing variations of channel depth (h_1, h_2–h_9) based on average values. Channel depth error was calculated using Eq. 4 and is shown in Table 6. As can be seen, maximum channel depth error decreased from 4.420 to 2.020% by increasing forming force from 350 to 450 kN. Decreases in channel depth error showed that dimensional accuracy of samples would increase by raising the force.

To investigate dimension accuracy of semi-stamp rubber forming, filling percentage in nine positions (h_1 to h_9) was measured, Fig. 18. Samples were fabricated at 350 and 450 kN. Table 7 shows channel depth error. Table 7 and Fig. 18 show decreases in channel depth error and differences between central and lateral channel depths. Maximum channel depth error obtained from semi-stamp rubber forming at 450 kN was 0.963%, whereas it was 2.020% in the conventional method. This showed that the developed method caused 1.075% improvement in dimensional accuracy of bipolar plates. As shown in Fig. 16, channel depth in central channels was lower than left and right side channels. Decreasing channel depth differences between central and lateral channels in semi-stamp method caused improvement in dimensional accuracy, which could be due to more uniform deformation of rubber in semi-stamp rubber forming than the convectional process.

3.4 Produced bipolar plates

The goal of this study was to fabricate metallic bipolar plates through rubber pad forming process with maximum filling depth, minimum thinning percentage, and maximum dimensional accuracy. Both convectional rubber pad forming process and the developed method (semi-stamp rubber forming) were investigated to produce bipolar plates. Since samples formed by semi-stamp rubber forming showed more filling percentage, more desirable thickness distribution, and higher dimensional accuracy than the conventional method, it could be concluded that semi-stamp rubber forming method would be more suitable in forming bipolar plates. Figure 19 shows the best bipolar plates that were fabricated by both methods in this study. As can be seen, semi-stamp rubber forming that was developed in this research was capable of producing bipolar plates with higher quality than the conventional method.

Table 6 Longitudinal channel depth error in conventional rubber forming

Channel position	350 kN	450 kN
h_1	0.674	0.119
h_2	1.402	0.547
h_3	1.889	1.616
h_4	4.420	2.020
h_5	2.480	1.592
h_6	0.054	0.333
h_7	2.372	0.523
h_8	0.540	0.975
h_9	1.159	0.547

Table 7 Longitudinal channel depth error in semi-stamp rubber

Channel position	350 kN	450 kN
h_1	0.699	0.370
h_2	1.030	0.163
h_3	0.202	0.237
h_4	2.282	0.296
h_5	0.294	0.430
h_6	2.116	0.963
h_7	1.527	0.370
h_8	0.460	0.237
h_9	1.693	0.637

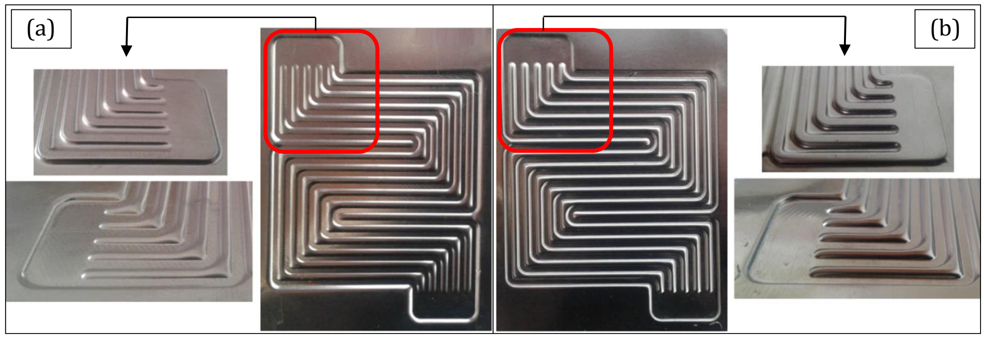


Fig. 19 Produced bipolar plates. **a** Convectional rubber forming. **b** Semi-stamp rubber forming

4 Conclusions

A novel method was developed in this study in order to improve the quality of fabricated metallic bipolar plates named semi-stamp rubber forming. The results of this method compared with convectional rubber forming process. It is shown that using semi-stamp rubber forming instead of convectional rubber forming would lead to 11.7, 9, and 1.075% improvement in filling percentage, thinning percentage, and dimensional accuracy, respectively. As the results shown, the developed model (semi-stamp rubber forming) could be a practicable technique in fabrication of metallic bipolar plates. The results were compared to determine the performance of the developed method in fabrication of bipolar plates and identify the advantages of it over the conventional method. The following results were obtained:

1) Filling percentage was different in longitudinal, diagonal, and transverse directions, and maximum filling percentage obtained in diagonal direction was 92.8%.
2) Filling percentage and rubber hardness inversely depended on each other. In the samples that were produced at 450 kN and rubber with thickness of 20 mm, filling percentage increased from 61.3 to 74.4% by decreasing rubber hardness from shore A90 to A40.
3) Increases in rubber thickness led to rising filling percentage. Channel depth and filling percentage raised from 66.9 to 76.8% using rubber with thickness of 30 mm rather than 10 mm. In order to investigate the effect of rubber thickness on filling percentage, rubber hardness was kept constant (shore A40).
4) Using semi-stamped rubber forming resulted in 11.7% improvement in filling percentage. Maximum filling percentage was 76.8 and 88.5% in convectional rubber forming and semi-stamped rubber forming, respectively.
5) Semi-stamp rubber forming showed more uniform thickness distribution than the conventional method. Maximum thinning percentage decreased from 31% in conventional method to 22% in semi-stamp rubber forming and hence 9% percent enhancement in thickness reduction using the new method.
6) Using semi-stamp method caused improvement in dimensional accuracy of produced bipolar plates. Maximum channel depth error in samples that were fabricated at 450 kN by conventional rubber forming was 2.020%. Maximum channel depth error decreased to 0.963% in semi-stamp rubber forming (1.057% improvement in dimensional accuracy).

References

1. Bar-On I, Kirchain R, Roth R (2002) Technical cost analysis for PEM fuel cells. J Power Sources 109:71–75
2. Costamagna P, Srinivasan S Quantum jumps in the PEMFC science and technology from the 1960s to the year 2000: part II. Engineering, technology development and application aspects. J Power Sources 102(2001):253–269
3. Matsuura T, Kato M, Hori M (2006) Study on metallic bipolar plate for proton exchange membrane fuel cell. J Power Sources 161:74–78
4. Yan X, Hou M, Zhang H, Jing F, Ming P, Yi B (2006) Performance of PEMFC stack using expanded graphite bipolar plates. J Power Sources 160:242–257
5. Minke C, Hickmann T, dos Santos AR, Kunz U, Turek T (2016) Cost and performance prospects for composite bipolar plates in fuel cells and redox flow batteries. J Power Sources 160:182–190
6. Hung JC, Chang DH, Chuang Y (2012) The fabrication of high-aspect-ratio micro-flow channels on metallic bipolar plates using die-sinking micro-electrical discharge machining. J Power Sources 198:158–163
7. Davies DP, Adcock PL, Turpin M, Rowen SJ (2000) Stainless steel as a bipolar plate material for solid polymer fuel cells. J Power Sources 86:237–242
8. Muller A, Kauranen P, Ganski AV, Hell B (2006) Injection moulding of graphite composite bipolar plates. J Power Sources 154:467–471
9. Hung JC, Yang TC, Li KC (2011) Studies on the fabrication of metallic bipolar plates—using micro electrical discharge machining milling. J Power Sources 196:2070–2074
10. Dur E, Cora ÖN, Koç M (2011) Effect of manufacturing conditions on the corrosion resistance behavior of metallic bipolar plates in proton exchange membrane fuel cells. J Power Sources 196: 1235–1241
11. Belali-Owsia M, Bakhshi-Jooybari M, Hosseinipour SJ, Gorji AH (2015) A new process of forming metallic bipolar plates for PEM

fuel cell with pin-type pattern. Int J Adv Manuf Technol 77:1281–1293

12. Koç M, Mahabunphachai S (2007) Feasibility investigations on a novel micro-manufacturing process for fabrication of fuel cell bipolar plates: internal pressure-assisted embossing of micro-channels with in-die mechanical bonding. J Power Sources 172: 725–733
13. Hu Q, Zhang D, Fu H, Huang K (2014) Investigation of stamping process of metallic bipolar plates in PEM fuel cell-numerical simulation and experiments. Int J Hydrog Energy 39:3770–3776
14. Lee SJ, Chen YP, Huang CH (2005) Electroforming of metallic bipolar plates with micro-featured flow field. J Power Sources 145:369–375
15. Liu Y, Hua L (2010) Fabrication of metallic bipolar plate for proton exchange membrane fuel cell by rubber pad forming. J Power Sources 195:3529–3535
16. Lim SS, Kim YT, Kang CG (2013) Fabrication of aluminum 1050 micro-channel proton exchange membrane fuel cell bipolar plate using rubber-pad-forming process. Int J Adv Manuf Technol 65:231–238
17. Jin CK, Jeong MG, Kang CG (2014) Fabrication of titanium bipolar plates by rubber forming and performance of single cell using TiN-coated titanium bipolar plates. Int J Hydrog Energy 39:21480–21488
18. Jeong MG, Jin CK, Hwang GW, Kang CG (2014) Formability evaluation of stainless steel bipolar plate considering draft angle of die and process parameters by rubber forming. Journal of Precision Engineering and Manufacturing 15:913–919
19. Elyasi M, Khatir FA, Hosseinzadeh M (2016) Manufacturing metallic bipolar plate fuel cells through rubber pad forming process. Int J Adv Manuf Technol. doi:10.1007/s00170-016-9297-6
20. Manso AP, Marzo FF, Barranco J, Garikano X, Garmendia Mujika M (2012) Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell: a review. Int J Hydrog Energy 37:15256–15287
21. Taccani R, Zuliani N (2011) Effect of flow field design on performances of high temperature PEM fuel cells: experimental analysis. Int J Hydrog Energy 36:282–287