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ORIGINAL ARTICLE

Investigation of dimensional accuracy in forming of metallic bipolar plates with serpentine flow field

Majid Elyasi [1] · Hossein Talebi Ghadikolaee [1] · Morteza Hosseinzadeh [2]

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Abstract

In this study, the dimensional accuracy of metallic bipolar plates with stainless steel 316 was investigated in diagonal, longitudinal, and transverse direction (directional dimensional accuracy). The results showed that directional dimensional accuracy (uniformity of channel depth) would increase by raising the applied force. In addition, increasing the rubber hardness and rubber thickness leads to higher directional dimensional accuracy. After that, the dimensional accuracy in constant direction (total dimensional accuracy) was investigated. According to the result, central channels have lower channel's depth than lateral channels. Difference between central and lateral channel's depth was decreased when the applied force was increased. Also, total dimensional accuracy increased by increasing hardness and thickness of rubber. Most accurate bipolar plate is fabricated by 450 kN applied force and rubbers with hardness of Shore A 90 and 30 mm thickness. However, dimensional accuracy in conventional rubber forming process was not satisfying. Thus, a new method was used in order to improve the dimensional accuracy of fabricated bipolar plates named semi-stamp rubber forming. The results indicated that using semi-stamp rubber forming instead of conventional rubber forming would lead to 8.35, 3.72, and 3.3% improvement in directional dimensional accuracy and also 1.075% improvement in total dimensional accuracy.

Keywords Fuel cell · Metallic bipolar plates · Metal forming process · Rubber pad forming · Dimensional accuracy

1 Introduction

Renewable energy source would play an important role in the future. Proton exchange membrane fuel cell (PEMFC) is a kind of fuel cell which could be considered as renewable and clean energy source. PEMFC has higher efficiency than other types of fuel cells [1]. Another advantage of PEMFC is the low operation temperature and has safer operation [2]. Fuel cells are two or three times more efficient than heat engines [3]. These mentioned characteristics make PEMFC suitable to be used in vehicles.

The main disadvantages of fuel cells are that they are expensive and the cost of hydrogen production is high. The fuel cell produces energy by converting chemical energy stored in a fuel (hydrogen) through an electrochemical reaction directly into electrical energy [4]. For this purpose, PEMFC's consist of several parts such as diffusion layer, catalyst layer, membrane, and bipolar plates [5]. Among different components of PEMFC, bipolar plates are multifunctional components which constitute over 80 and 30% of weight and cost of fuel cell stack [6]. Separating the individual fuel cells, connecting the cathode side of one cell to another with good conductivity, feeding the reactive gases to the anode side (hydrogen gas) and cathode side (oxygen gas) via flow channels, and removing the heat and reaction products are the functions of bipolar plate in fuel cells [7].

In order to perform tasks, bipolar plates should have high electrical conductivity, high gas impermeability, suitable mechanical performance, chemical stability, thermal conductivity, and corrosion resistance [8]. Bipolar plate's materials are divided into graphite [9], composite [10], and metallic [11] bipolar plates. Among different types of bipolar plates, metallic bipolar plates which are made of aluminum [12], titanium [13], and stainless steel [14] received significant attention. Among these alternatives, stainless steel offers excellent

✉ Majid Elyasi
elyasi@nit.ac.ir; elyasima@yahoo.com

[1] Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, P.O. 484, Babol, Mazandaran, Iran

[2] Department of Mechanical Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Mazandaran, Iran

mechanical properties, electric conductivity, corrosion resistance, and low cost [15].

Bipolar plates have gas flow fields on both sides in order for reactants to flow on catalyst surface, and heat and water management. Ideal design of flow field should lead to a uniform distribution of current density and, thus, produce uniform distributions of temperature and liquid water production. Serpentine flow field is one of the ideal flow field designs which consist of one or more flow field with serpentine direction [16].

Due to the mentioned characteristics of metallic bipolar plate, several researches have been done to investigate various methods in order to form micro channel flow field pattern. Stamping [17], CNC milling [18], hydroforming [19], and electroforming [20] have been investigated to fabricate metallic bipolar plates. One of the main challenges in commercialization of fuel cell is high production cost. Since the bipolar plates consist significant part of fuel cells, decreasing manufacturing cost of metallic plates could have directly affected the decrease of fuel cell production cost.

Besides the mentioned method, rubber pad forming process could be used to fabricate metallic bipolar plates by considering a decrease in manufacturing cost of metallic bipolar plates. This method requires a rigid die which micro channels pattern machined on surface. Other parts of die consist of a rubber pad. Forming equipment of rubber pad which is simpler than other forming process led to a decrease in bipolar plate manufacturing costs.

Characteristics of rubber pad would play an important role on formability and quality of metallic bipolar plates. Due to the capability of rubber pad forming process and important role of flexible rubber pad in this process, some research has been conducted on the effect of rubber and forming process variable on quality of fabricated micro channels.

Lim et al. [12] fabricated aluminum 1050 bipolar plates. Firstly, they studied the effect of channel's cross-sectional area on flowing of the gas in the channels. Also, they investigate the effect of punch speed, applied force, rubber thickness, and hardness on channel depth. As the results of this study, increasing the rubber layer thickness, reduction in hardness, and also increasing the applied force and punch speed lead to an increase in channel depth.

Jin et al. [21] studied the fabrication of titanium bipolar plates. Effect of punch velocity, punch pressure, rubber hardness, and rubber thickness is investigated on channel depth. The result shows that optimum forming conditions were found to be a rubber thickness of 10 mm, rubber hardness equivalent to that of Shore A 20, punch velocity of 30 mm/s, punch pressure of 55 MPa, and punch draft angle of 30 (deg).

Liu et al. [22] investigated concave and convex deformation style in detail with numerical and experimental methods. According to the result, if the ratio of the channel width to the rib width is w/s > 1, the concave style is more appropriate; otherwise, the convex style is preferred.

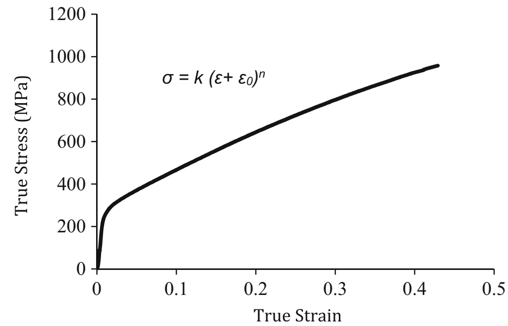

Fig. 1 True stress-strain curve

A 3D finite element model of the process with damage initiation criterion was developed by Kolahdooz et al. [23]. The finite element results show that the thickness distribution in the formed bipolar plate is not uniform. Also, the corners of the micro channels are the regions in which the damage initiation criteria reach maximum values.

Elyasi et al. [24] investigated metallic bipolar plate fabrication with stainless steel 316. The effect of applied force, rubber hardness, and rubber thickness on filling percentage and thickness distribution was investigated. The results showed that filling percentage would increase by rising applied force and rubber thickness, and decrease in rubber hardness. Also, a novel method was developed in order to improve the quality of fabricated bipolar plates. Results indicated that using semi-stamp rubber forming instead of conventional rubber forming would lead to 11.7, 9, and 1.075% improvement in filling percentage, thinning percentage, and uniformity, respectively.

Elyasi et al. [25] examined the effects of concave and convex dies on rubber pad forming process. According to the results, for an equal applied load, the concave die would show more filling depth than the convex one.

Previous researches which investigated fabrication of micro channels by rubber pad forming process focused on effect of process parameter on micro channel's depth. Channel depth is an important parameter due to their effect on performance of fuel cell [26].

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

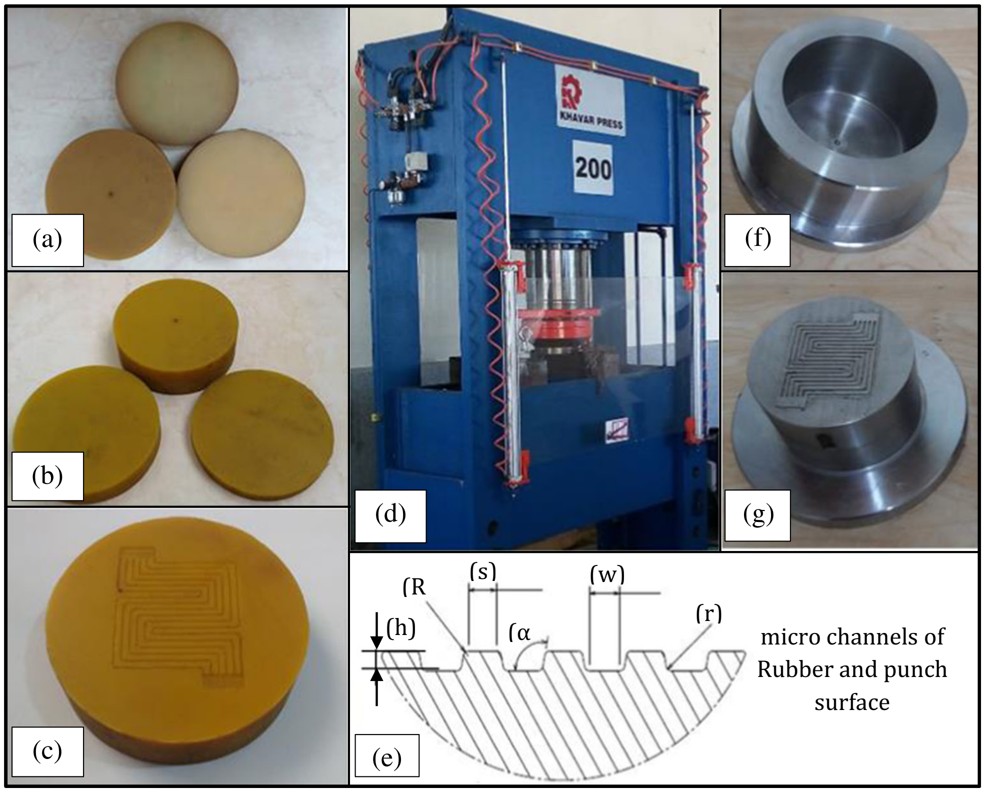

Fig. 2 **a** Rubber with different hardness; **b** rubber thickness; **c** machined rubber; **d** 200 ton hydraulic press; **e** micro channel parameter; **f** rubber container; **g** punch

Also, uniformity of channel depth in different channels of fabricated bipolar plate in various directions (dimensional accuracy) is another important parameter which was not investigated in previous study. They just investigate the effect of process parameters on value of channel depth in order to form channels with higher depth. But, effect of process parameter (rubber hardness, rubber thickness, and applied force) on uniformity of channel depth was not considered in previous study. The effect of channel depth non-uniformity shows the major impact on pressure drop and uniformity in distributions inside PEMFC [27]. As a result, dimensional accuracy could have a major effect on efficiency of PEMFC. The goal of this research was to improve dimensional accuracy (uniformity of channel depth) of bipolar plates in different directions and different channels in same direction, due to the importance of dimensional accuracy of micro channels on quality of bipolar plates and performance of PEMFC. To this goal, the effect of rubber characteristics and applied force on dimensional accuracy (channel depth uniformity) in longitudinal, transverse, and diagonal direction and also dimensional accuracy of depth in channels which are in the same direction (longitudinal) was investigated. In the next step, the effect of novel method (semi-stamp rubber forming which was developed by Elyasi et al. [24]) on dimensional accuracy in different directions and dimensional accuracy of different channel's depth in longitudinal direction was investigated in order to improve directional and total dimensional accuracy of bipolar plates compared to conventional rubber pad forming process. According to the result, the new method would have a significant effect on increasing the dimensional accuracy of metallic bipolar plates.

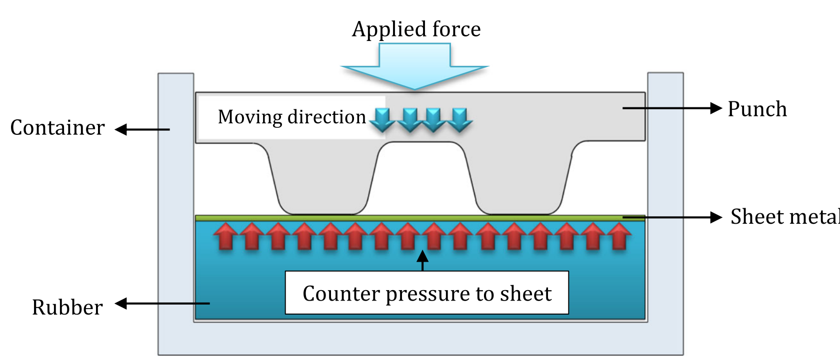

Fig. 3 Rubber pad forming process

Table 2 Geometrical dimensions of micro channels

Geometric parameter	Value
Channel 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)

2 Experimental

In this study, conventional rubber pad forming process and semi-stamp forming process were used to manufacture metallic bipolar plates with stainless steel 316. The thickness of primary blank was 0.1 mm. Parallel serpentine flow field pattern was selected because their performance in PEMFC led to lower pressure drop than other types of flow field [28]. Uniaxial tensile tests were used in order to identify mechanical behavior of sheet metal. Figure 1 shows the stress-strain curve which resulted from uniaxial tensile test. Strain hardening law was used to estimate the stress-strain curve which resulted from uniaxial tensile test (Fig. 1). Mechanical properties and value of strain hardening law's parameters for SS316 are shown in Table 1.

Figure 2 shows experimental equipment's which are needed to fabricate metallic bipolar plate by the rubber pad forming process. Two hundred ton hydraulic press was used to apply force on die set in order to supply the required pressure. Die internal pressure is needed to deform primary sheet between the rubbers and the punch's micro channels (Fig. 3). Rubber forming die consists of a punch, a rubber container, and some rubber pads. In this study, punch plays upper die role and container considered as matrix (Fig. 3). As mentioned before, serpentine flow field was selected as flow field pattern on metallic bipolar plate. In order to aim this propose, intended pattern with specific dimension [12, 21, 29] was machined on punch surface by CNC milling machine to form primary black into machined pattern on rigid die. Container and punch are showed in Fig. 2f and g, respectively. As shown in Fig. 2e, geometrical dimension of micro channels consists of channel width (w), rib width (s), external fillet radius (R), internal fillet radius (r), draft angle (α), and channel depth (h). Table 2 shows the value of geometrical dimension of micro channels

Rubber pads are another important part of rubber forming process. Displacement of punch to downward leads to rubber pads deformed proportional to applied force. As a result, sheet metal flows into punch cavity due to deformation of rubber pads. Finally, sheet metal would deform to machined pattern on rigid die. Thus, the effect of rubber characteristics on quality of metallic bipolar plates is significant.

Uniform elastic deformation of rubber pads is needed in order to produce bipolar plates with uniform channel depth and high quality. Due to the importance of rubber in rubber pad forming process, different rubber pads with a diameter of 107 mm (equal to the container diameter), a shore hardness of A40, A65, and A90 which were tested to examine the effect of rubber hardness on uniformity of channel depth in different positions of fabricated bipolar plates. Three thickness ranges of 10, 20, and 30 mm were used to investigate the effect of rubber thickness on intended output. After that, semi-stamp rubber forming process (a novel method which was developed by Elyasi et al. [23]) was used to improve the dimensional accuracy of fabricated metallic bipolar plate. Figure 4 shows a schematic form of rubber deformation in conventional rubber forming process and semi-stamp rubber forming process. When metal forming process in conventional method starts, the rubber would have an elastic deformation due to moving upper die (punch) to downward, and then apply force on rubber. The elastic deformation of the rubber near the central channel is lower than lateral channels (Fig. 4a). Therefore, there would be a difference between channels' depth of fabricated bipolar plates by conventional process in the same condition. Due to this problem, samples which were formed by

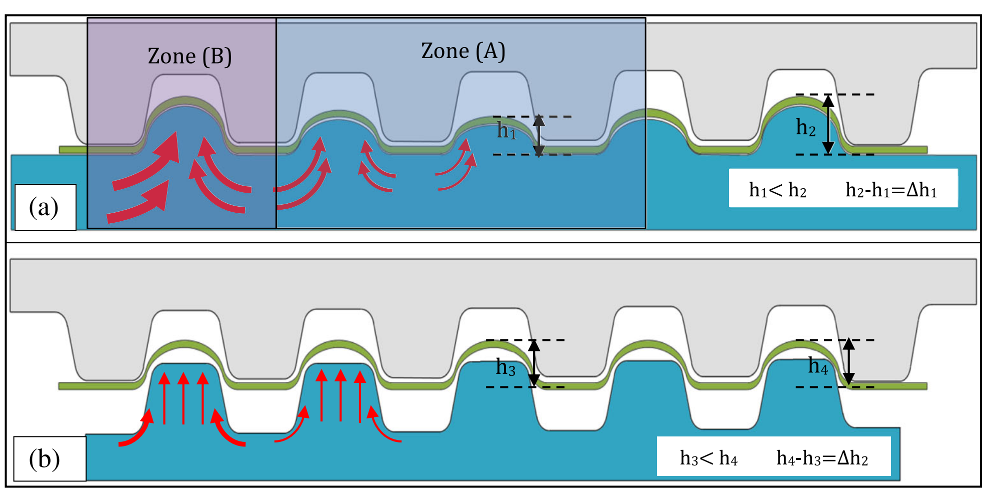

Fig. 4 **a** Schematic rubber deformation in conventional rubber forming; **b** schematic rubber deformation in semi-stamp rubber forming

Table 3 Process parameters in rubber forming of bipolar plates

Process parameter	Value
Force (kN)	300, 350, 450
Punch velocity (mm/s)	5
Rubber hardness (Shore A)	40, 65, 90
Rubber thickness (mm)	10, 20,30

conventional process showed low dimensional accuracy. It is expected that, process variable such as applied force, rubber hardness, and thickness has influence on uniform or ununiformed deformation of rubber pad and finally would be effective on dimensional accuracy of metallic bipolar plates. However, in semi-stamp rubber forming, machining of rubber led to more uniform deformation and penetration of rubber into punch cavity (Fig. 4b). As a result, the difference between central and lateral channel depth could decrease. This would help to increase dimensional accuracy in fabricated bipolar plates by semi-stamp rubber forming process. To investigate the effect of rubber characteristics and forming load and compare conventional and semi-stamp rubber forming, all tests were done at the same press speed (5 mm/s) for an accurate comparison. The range of different process parameters is shown in Table 3.

After forming process, fabricated samples were cut in longitudinal, transverse, and diagonal direction using wire cut machine to investigate and measure different channel's depth in various directions. Due to the rough surface of samples after wire cut, they mounted with epoxy resin. After that, surfaces were sanded and polished to see their profile under optical microscope [23, 24].

3 Result and discussion

In order to understand the effect of process parameters on quality and uniformity of fabricated metallic bipolar plates and compare conventional and semi-stamp rubber forming, the channel's depth uniformity in different positions of metallic bipolar plate was investigated. In order to quantify the result of channel's depth uniformity, some criteria should be introduced and defined. f_{DD}, f_{LD}, and f_{TD} were used to calculate average filling percentage in various directions (Eq. 1–4). Diagonal dimensional accuracy error (DDAE), longitudinal dimensional accuracy error (LDAE), transverse dimensional accuracy error (TRDAE), and total dimensional accuracy error (TDAE) were used to investigate the uniformity or non-uniformity of channels' depth and compare the effect of process parameters on dimensionless parameters (Eqs. 3–8):

$$\textit{Filling percentage} = f_i = (\textit{channel depth of formed plate}/\textit{channel depth of}\ \text{die}) \quad (1)$$

$$f_{DD} = \frac{\sum_{i=1}^{5}((h_{DDi})/0.75)}{n_d} = \frac{\sum_{i=1}^{5} f_{DDi}}{n_d} \quad (2)$$

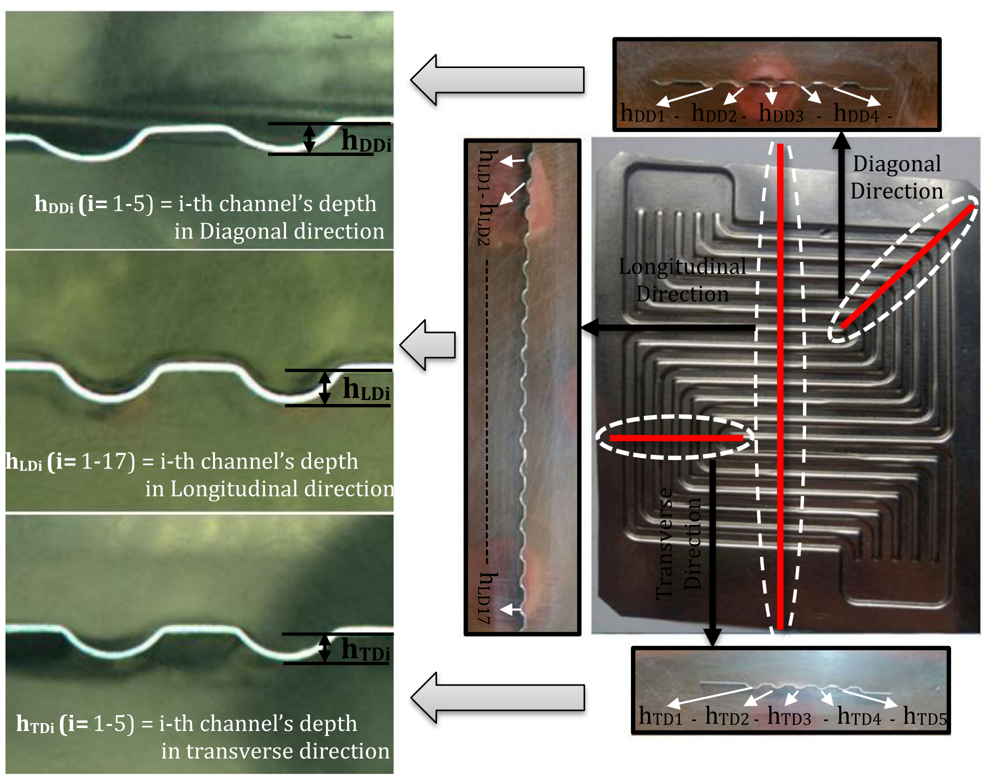

Fig. 5 Fabricated metallic bipolar plate and micro channels in different direction

$$f_{LD} = \frac{\sum_{i=1}^{17} ((h_{LDi})/0.75)}{n_d} = \frac{\sum_{i=1}^{17} f_{LDi}}{n_d} \quad (3)$$

$$f_{TD} = \frac{\sum_{i=1}^{5} ((h_{TDi})/0.75)}{n_d} = \frac{\sum_{i=1}^{5} f_{TDi}}{n_d} \quad (4)$$

$$DDAE = \frac{f_{DD} - \left(\frac{f_{DD}+f_{LD}+f_{TD}}{3}\right)}{\frac{f_{DD}+f_{LD}+f_{TD}}{3}} = \frac{f_{DD}-f_{AT}}{f_{AT}} \quad (5)$$

$$LDAE = \frac{f_{LD} - \left(\frac{f_{DD}+f_{LD}+f_{TD}}{3}\right)}{\frac{f_{DD}+f_{LD}+f_{TD}}{3}} = \frac{f_{LD}-f_{AT}}{f_{AT}} \quad (6)$$

$$TRDAE = \frac{f_{TD} - \left(\frac{f_{DD}+f_{LD}+f_{TD}}{3}\right)}{\frac{f_{DD}+f_{LD}+f_{TD}}{3}} = \frac{f_{TD}-f_{AT}}{f_{AT}} \quad (7)$$

$$TDAE = max\left(\frac{f_{DDi}-f_{DD}}{f_{DD}}\right), (i = 1\text{–}17) \quad (8)$$

Where f_i is the filling percentage of micro channels, and f_{DD}, f_{LD}, and f_{TD} are averages filling percentage of channels in diagonal, longitudinal, and transverse directions. f_{DDi}, f_{LDi}, f_{TDi} and h_{DDi}, h_{LDi}, h_{TDi} (Fig. 5) are filling percentage and depth of simple channels, respectively. f_{AT} is average value of f_{DD}, f_{LD}, and f_{TD} (total average of channels' depth). As mentioned before, diagonal dimensional accuracy error (DDAE), longitudinal dimensional accuracy error (LDAE), and transverse dimensional accuracy error (TRDAE) and total dimensional accuracy error (TDAE) were used to compare dimensional accuracy in various positions and investigate the effect of process parameter on uniformity of metallic bipolar plate's channel depth. As can be seen from Eqs. 5, 6, 7, and 8, more uniform channel depth led to lower value in DDAE, LDAE, TRDAE, and TDAE. In other word, we should minimize these parameters in order to fabricate high quality metallic bipolar plate.

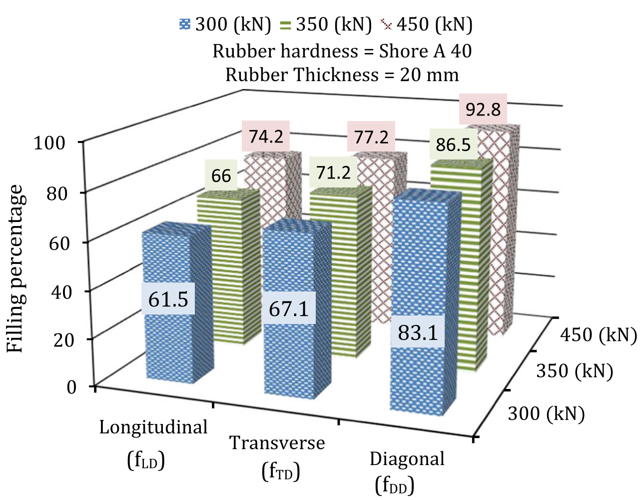

Fig. 6 Directional channel depth by using rubber with hardness of Shore A 40

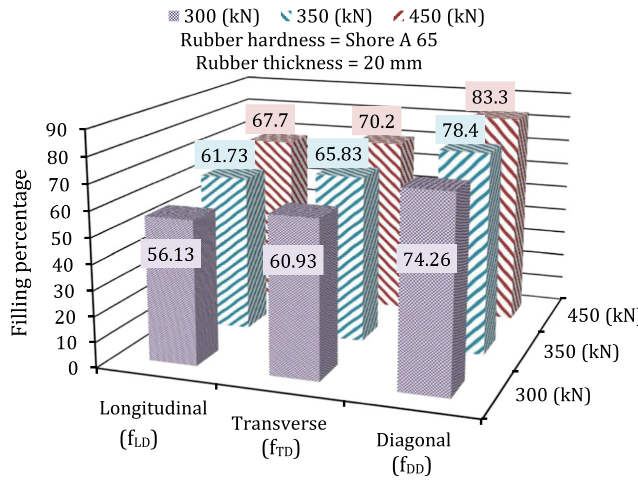

Fig. 7 Directional channel depth by using rubber with hardness of Shore A 65

3.1 Effect of force and rubber hardness dimensional accuracy

In this study, the effect of rubber hardness and force on directional and total dimensional accuracy was investigated. Figures 6, 7, and 8 show filling percentage of bipolar plate's micro channels along longitudinal, diagonal, and transverse directions (f_{DD}, f_{LD}, f_{TD}). Samples were fabricated by rubber with shore hardness of A40, 65, and 90. Thickness of rubber was set to 20 mm. Applied force varied from 300 to 450 kN. As can be seen, there is difference between average channel

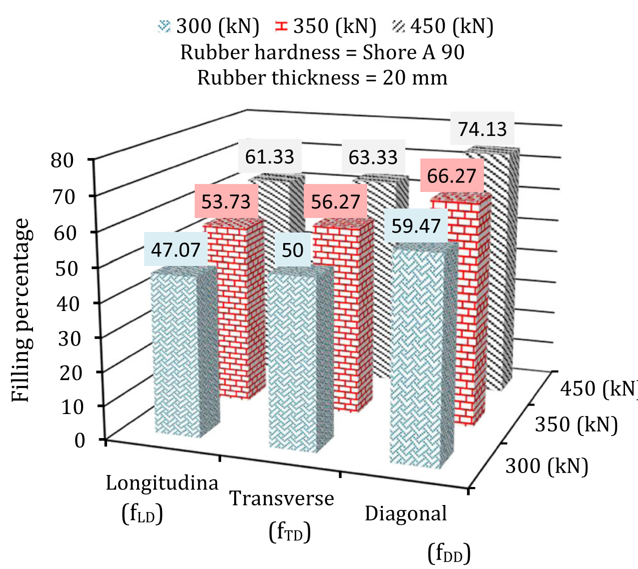

Fig. 8 Directional channel depth by using rubber with hardness of Shore A 90

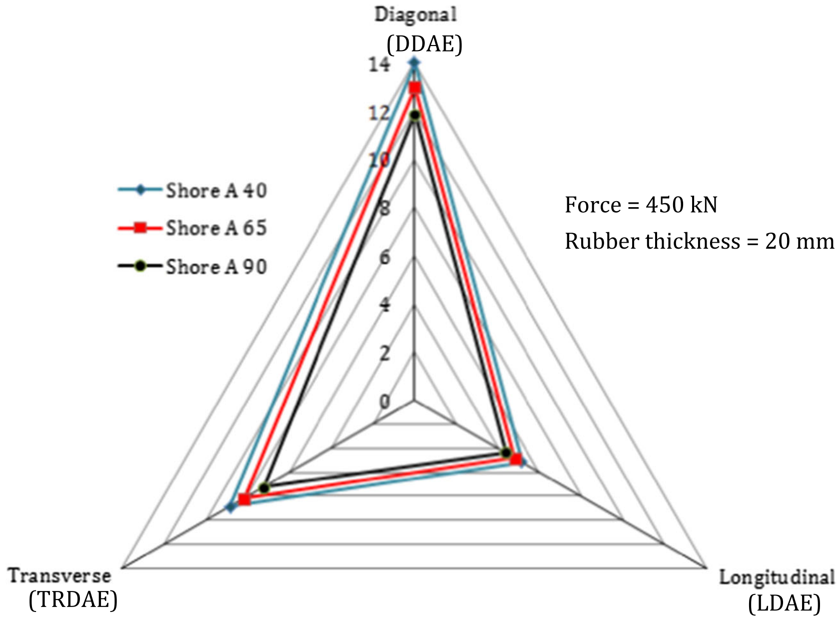

Fig. 9 Effect of rubber hardness on directional dimensional accuracy

depth in various directions (f_{DD}, f_{LD}, f_{TD}). In lower hardness of rubber (Shore A 40), difference between average channel depth in diagonal and longitudinal direction would decrease by increasing the force. According to Fig. 6, 21.6% difference between diagonal and longitudinal direction at 300 kN force would decrease to 18.6% at 450 kN force. Comparing result in Figs. 6, 7, and 8 shows that hardness of rubber would have a positive effect on uniformity of channel depth. By assuming constant force (450 kN), Figures 6, 7, and 8 show increase of rubber hardness led to 5.8% decrease in difference of channels' depth between longitudinal and diagonal direction (18.6% difference between diagonal and longitudinal direction would decrease to 12.8%). DDAE, LDAE, and TRDAE parameters were calculated by using average filling percentage in different directions, in order to detail investigation of the effect rubber hardness on channel depth uniformity. According to the result, DDAE would decrease from 14 to 11.88% by using rubber with Shore A 90 instead of rubber with Shore A 40 (thickness of rubber and applied force were set to 20 mm and 450 kN, Fig. 9). This issue refers to the positive effect of increasing rubber hardness on uniformity of channels' depth. As Fig. 9 shows, LDAE and TRDAE were investigated in samples which were fabricated at 450 kN force by using rubbers with thickness of 20 mm and different rubbers with hardness of shore A 40, 65, and 90. According to the result, both LDAE and TRDAE value shows descending trend by increasing hardness of rubber. As can be seen from Fig. 9, LDAE and TRDAE would decrease from 8.84 and 5.15% to 8.18 and 4.79%, respectively. All mentioned result insists that increasing the hardness of rubber would lead to improving channels' depth uniformity in different directions.

Samples that were fabricated at 300, 350, and 450 kN by rubber pad forming process were used to study effect of force on total dimensional accuracy of bipolar plates. To compare the effect of force on total dimensional accuracy, all samples were formed using the rubber with hardness of Shore A 90 and thickness of 30 mm. Forming depth was measured in nine

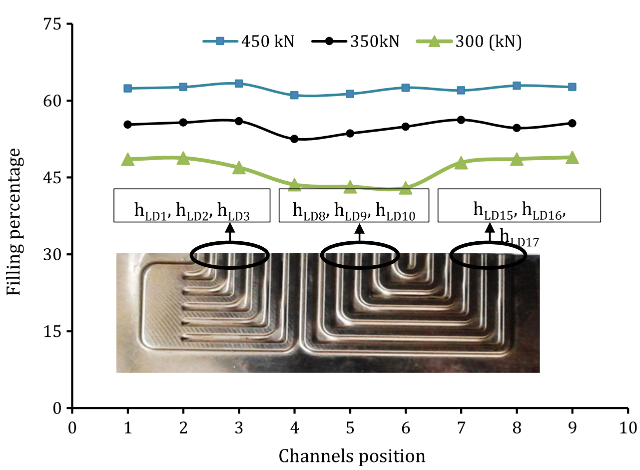

Fig. 10 Effect of force on longitudinal channel filling percentage

Table 4 Effect of force on TDAE value of bipolar plates

Channel position	300 kN	450 kN
h_{LD1}	4.161	0.119
h_{LD2}	5.580	0.547
h_{LD3}	0.708	1.616
h_{LD8}	6.456	2.020
h_{LD9}	7.314	1.592
h_{LD10}	6.986	0.333
h_{LD15}	3.634	0.523
h_{LD16}	4.268	0.975
h_{LD17}	4.998	0.547

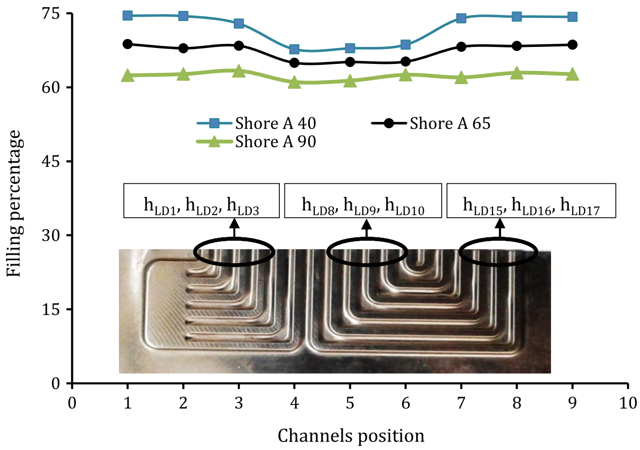

Fig. 11 Effect of rubber hardness on longitudinal channel filling percentage

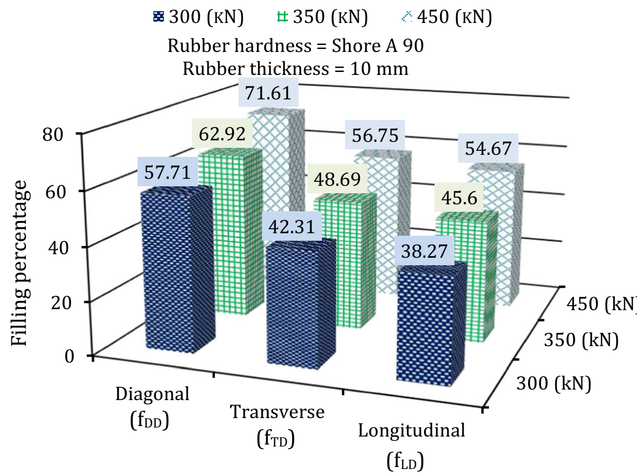

Fig. 12 Directional channel depth by using rubber with thickness of 10 mm

positions, i.e., h_{LD1}, h_{LD2}, h_{LD3} in the left side, h_{LD8}, h_{LD9}, h_{LD10} in the middle of bipolar plates, and h_{LD15}, h_{LD16}, h_{LD17} in the right side, Fig. 5. Equation (8) was used to quantitatively evaluate total dimensional accuracy of channel depths, representing variations of channel depth (h_{LD1}, h_{LD2}–h_{LD17}) based on average values. Figure 10 shows the filling percentage of different channels in longitudinal direction. As can be seen, there is difference in filling percentage of central and lateral channels. Lateral channels have more filling percentage than central one. Also, trend of the diagram in Fig. 10 shows difference between central and lateral channel depth would decrease by rising force. In the next step, TDDE was calculated using Eq. 8, and shown in Table 4. As can be seen, maximum value of TDDE decreased from 7.314 to 2.020% by increasing forming force from 300 to 450 kN. Decreases in TDAE value showed that total dimensional accuracy of samples would increase by raising the force. Also, effect of hardness of rubber on TDAE was investigated, Fig. 11. To study effect of rubber hardness on total dimensional accuracy of bipolar plates, different rubbers with hardness of Shore A 40, 55, 65, and 90 were investigated. All samples were formed at 450 kN and rubber with thickness of 30 mm. As can be seen, difference between channel depth decreased by increasing rubber hardness. In order to quantitatively evaluate total dimensional accuracy, value of TDAE in different forming conditions (change rubber hardness from Shore A 40 to 90) was calculated and represented in Table 5. As can be seen, maximum value of TDAE decreased from 15.432 to 2.020% by increasing hardness of rubber from Shore A 40 to Shore A 90. This issue represents that hardness of rubber could contribute to uniformity of channel depth. The effect of rubber hardness on TDAE of the samples was studied and it was shown that increasing rubber hardness would lead to improvement in TDAE and uniformity of channel depth (13.412% improvement by using rubber with hardness of Shore A 90 instead of Shore A 40).

These phenomena could be due to the fact that rubbers with higher hardness have more uniform elastic deformation than rubbers with lower hardness. In other words, changing in forming condition (central or lateral channel and changes in channel's width) has lower effect on elastic deformation of rubbers with higher hardness. Finally, the difference between

Table 5 Effect of rubber hardness on TDAE value of bipolar plates

Channel position	Shore A 40	Shore A 90
h_{LD1}	15.432	0.119
h_{LD2}	15.308	0.547
h_{LD3}	12.953	1.616
h_{LD8}	4.896	2.020
h_{LD9}	5.175	1.592
h_{LD10}	6.290	0.333
h_{LD15}	14.596	0.523
h_{LD16}	15.138	0.975
h_{LD17}	15.045	0.547

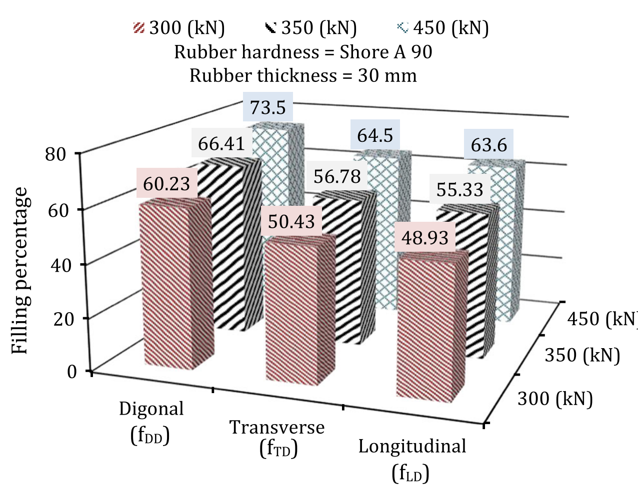

Fig. 13 Directional channel depth by using rubber with thickness of 10 mm

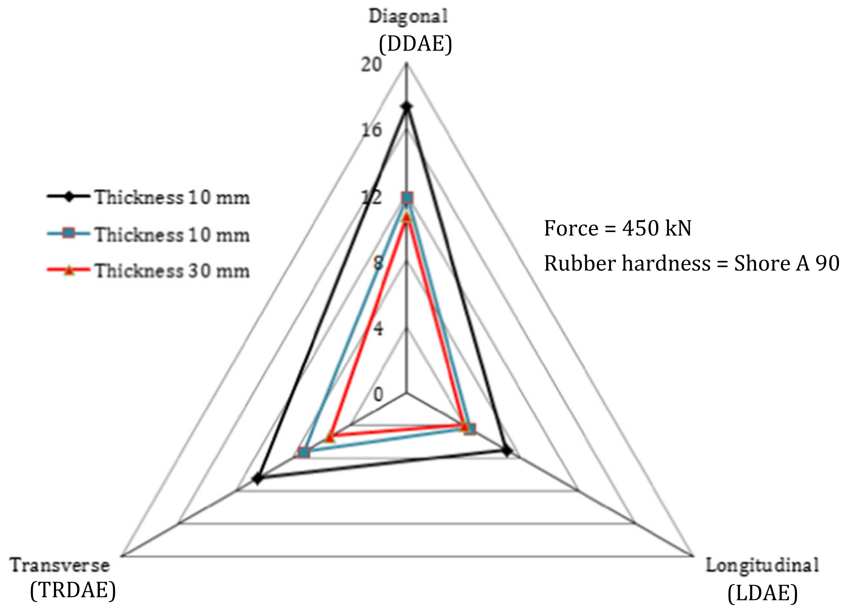

Fig. 14 Effect of rubber thickness on directional dimensional accuracy

penetration of rubber in central and lateral channels which were machined on punch (Fig. 5a) could decrease.

3.2 Effect of rubber thickness on directional dimensional accuracy

Rubber thickness is considered as effective parameter on uniformity of channel depth; the effect of rubber thickness pad was investigated on average filling percentage in different directions (Figs. 12 and 13). Punch velocity and hardness of the rubber pad were set to 5 mm/s and Shore A90, respectively. Different rubbers with thickness of 10, 20, and 30 mm were investigated. As can be seen in Figs. 12 and 13, difference between directional average filling percentage decreases by rises in rubber thickness. As Figs. 12 and 13 show, maximum deviation between average filling percentage in longitudinal (f_{LD}) and diagonal (f_{DD}) direction was 16.94% (samples were

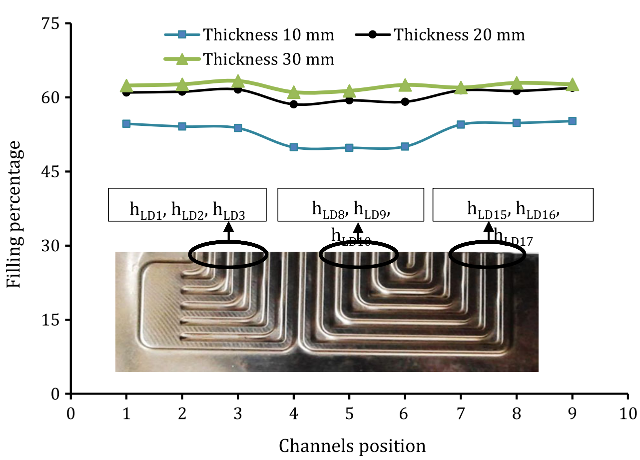

Fig. 15 Effect of rubber thickness on longitudinal channel filling percentage

fabricated by 450 kN force and rubber pad with thickness of 10 mm). According to the result, difference between f_{LD} and f_{DD} reduces to 11.3% by increasing rubber thickness to 30 mm.

In the next step, in order to a more detailed investigation of the effect of rubber thickness on uniformity of channel depth, directional dimensional accuracy was studied in samples which fabricated by 450 kN force and rubber pad with Shore A 90 hardness. DDAE, LDAE, and TRDAE parameters were used to quantitative investigation of effect of rubber's thickness on channel's depth uniformity. Increase in thickness of rubbers would cause decreasing DDAE, LDAE, and TRDAE. This represents that deviation of difference between average value of channel depth in each direction) f_{DD}, f_{LD}, f_{TD}) and total average of channel depth in all direction (f_{AT}) would decrease. According to the result in (Fig. 14), DDAE, LDAE, and TDAE would decrease from 17.38, 10.39, and 6.98% to 10.71, 5.35, and 4.02%, respectively (by increasing rubber hardness from Shore A40 to A90). This shows that

Table 6 Effect of rubber thickness on TDAE value of bipolar plates

Channels position	10 mm	20 mm	30 mm
h_{LD1}	3.171	0.643	0.119
h_{LD2}	2.114	0.891	0.547
h_{LD3}	1.547	1.663	1.616
h_{LD8}	5.832	3.316	2.020
h_{LD9}	6.002	1.996	1.592
h_{LD10}	5.530	2.491	0.333
h_{LD15}	2.869	1.319	0.523
h_{LD16}	3.454	1.138	0.975
h_{LD17}	4.190	2.114	0.547

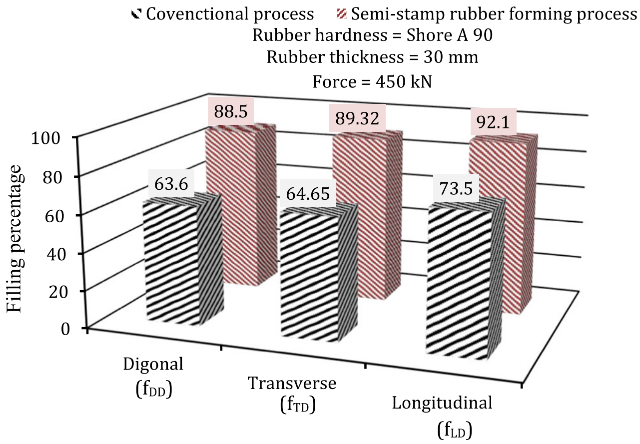

Fig. 16 Directional channel depth by using conventional and semi-stamp process

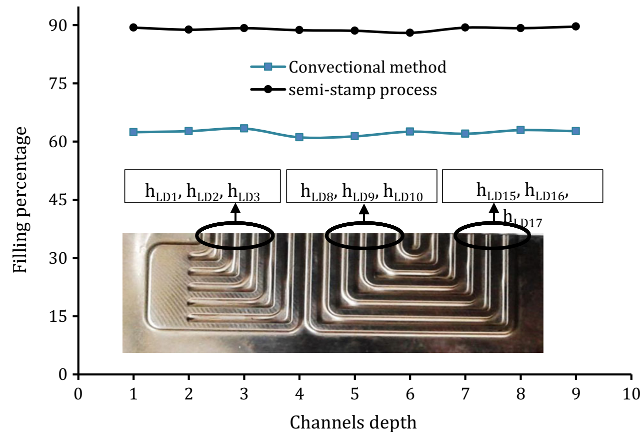

Fig. 18 Effect of semi-stamp rubber forming process on longitudinal channel filling percentage

increase in thickness of rubber led to fabrication of more uniform bipolar plates which could increase efficiency of fuel cell. As can be seen in Fig. 14, the intensity of the effect of rubber thickness would decrease in rage of 20 to 30 mm. Investigation of changing trend of DDAE by increasing rubber thickness from 10 to 20 mm shows that DDAE would decrease from 17.39 to 11.8%. This represents almost 5.59% improvement in dimensional accuracy in diagonal direction. However, by increasing rubber thickness from 20 to 30 mm, DDAE would decrease from 11.8 to 10.71%. This shows just 1.09% improvement in dimensional accuracy in diagonal direction. The changing rate of TRDAE and LDAE has the same trend in this condition (increase rubber thickness from 20 to 30 mm). As a result, it is expected that increasing rubber thickness over than 30 mm would not have a significant effect on directional dimensional accuracy.

In order to investigate rubber's thickness effect on uniformity of channel depth in specific direction (TDAE), filling percentage of various channels in longitudinal direction was calculated in samples that were fabricated by rubbers with thickness of 10, 20, and 30 mm. To investigate the effect of rubber hardness, value of force and rubber hardness was set to 450 kN and Shore A 90, respectively. As can be seen from Fig. 15, increases in rubber thickness led to reduce difference between filling percentage of channels in longitudinal direction. It seems that intensity of the effect of rubber thickness on uniformity of filling percentage of channels in range of 10 to 20 mm is more significant than range of 20 to 30 mm. In order to detail investigation of rubber thickness effect, TDAE was calculated in samples that were fabricated by rubber pads with different thicknesses (Table 6). According to the result, TDAE would decrease by increasing rubber thickness. This shows more uniformity in filling percentage of channels in samples that were fabricated by rubber pads with higher thickness.

Fig. 17 Effect of semi-stamp rubber forming process on directional dimensional accuracy

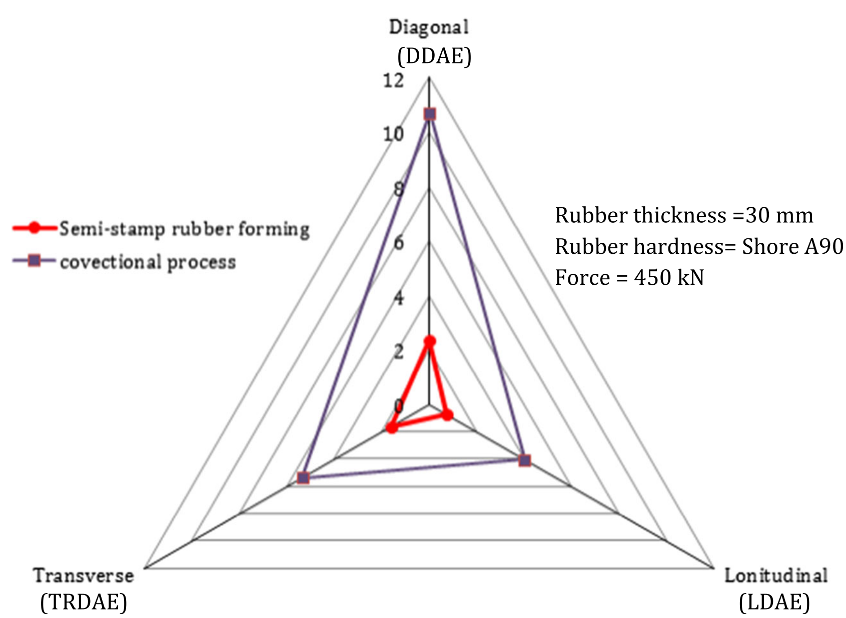

Table 7 Total dimensional accuracy error in semi-stamp rubber vs conventional process

Channels position	Conventional process	Semi-stamp process
h_{LD1}	0.119	0.370
h_{LD2}	0.547	0.163
h_{LD3}	1.616	0.237
h_{LD8}	2.020	0.296
h_{LD9}	1.592	0.430
h_{LD10}	0.333	0.963
h_{LD15}	0.523	0.370
h_{LD16}	0.975	0.237
h_{LD17}	0.547	0.637

Maximum value of TDAE by using rubber with thickness of 10 mm was 6.002%. Maximum value of TDAE decreases to 3.316% by using rubbers with thickness of 20 mm instead of 10 mm. This shows 2.686% improvement in channel uniformity. 1.296% improvement would be achieved by using rubbers with thickness of 30 mm instead of 20 mm. This shows that intensity of rubber's thickness effect on channel uniformity would decrease in higher levels, besides their positive effect on channel uniformity.

As mentioned in previous sections, non-uniform elastic deformation of rubber in rubber pad forming process causes difference between depths of bipolar plate's channels. This condition (uniformity of elastic deformation) gets worse due to decrease in thickness of rubber in central channels. This could be due to the fact that during rubber pad forming process, volume of rubber which deformed in central zone (zone A, Fig. 5) should divide and penetrate into several channels on punch, and also, there is more constraint in central zone which prevents from convenient deformation and penetration of rubbers. In other hand, penetration of deformed rubber in lateral channels (zone B in Fig. 5) is more than the central zone due to feeding from left side (Fig. 5). This issue led to the difference between central and lateral channel depth and ununiformed channel depth in samples which were fabricated by lower thickness of rubber.

Table 8 Comparison of dimensional accuracy in semi-stamp and conventional forming process

Dimensional accuracy parameters	Semi-stamp rubber forming process	Conventional forming process
DDAE	10.71	2.36
LDAE	5.35	1.63
TRDAE	4.02	0.72
Max(TDAE)	2.020	0.963

3.3 Effect of semi-tamp rubber forming process on dimensional accuracy

According to the previous result, highest quality in dimensional accuracy (does not consider filling percentage) was observed in sample that was fabricated by rubbers with 30 mm thickness and hardness of Shore A 90. Value of parameters such as DDAE, LDAE, TRDAE, and maximum value of TDAE in best sample that was fabricated by conventional forming process was 10.71, 5.35, 4.02, and 2.020%, respectively. However, directional and total dimensional accuracy in conventional rubber forming process was not satisfying. Thus, effect of semi-stamp rubber forming process (Fig. 4b) on directional and total dimensional accuracy of bipolar plates was investigated in the following. For this purpose, samples were fabricated in same condition (rubber hardness and thickness in both process were set to Shore A 90 and 30 mm and samples formed by 450 kN force). Result of average channel's filling percentage in various directions (f_{LD}, f_{DD}, f_{TD}) is shown in Fig. 16. As it is clear, difference between filling percentage in different direction decreases significantly by using semi-stamp rubber forming process. According to the result (Fig. 16), difference between f_{DD} and f_{LD} was 9.9% in samples with highest uniformity of channel's depth in conventional rubber forming process. The difference between f_{DD} and f_{LD} decreases to 3.6% by using semi-stamp rubber forming process. This shows positive effect of novel method on uniformity if filling percentage in different directions.

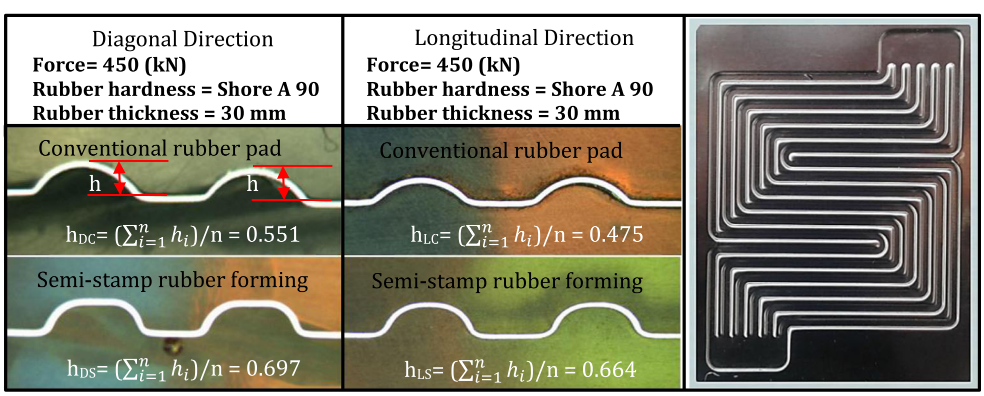

Fig. 19 Fabricated bipolar plates, diagonal, and longitudinal channel cross section in semi-stamp and rubber forming process

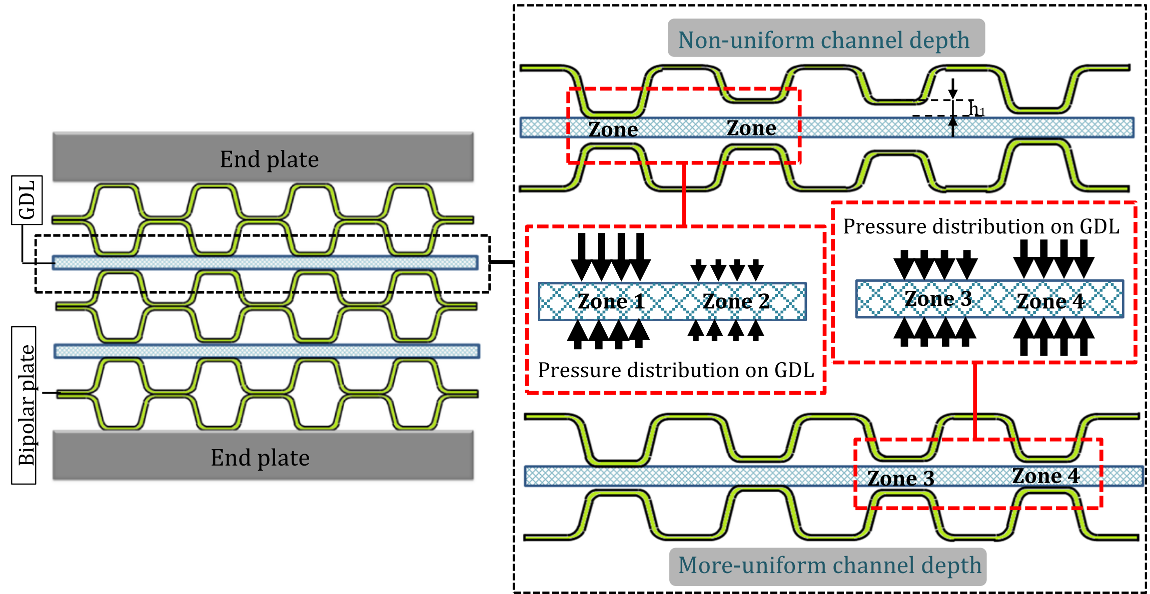

Fig. 20 Variation of contact pressure at different zone

Equations 5, 6, and 7 were used to quantitatively evaluate directional dimensional accuracy of bipolar plates that were fabricated by conventional and semi-stamp rubber forming process. Figure 17 shows calculated value of DDAE, LDAE, and TRDAE in conventional and semi-stamp forming process. As can be seen, using semi-stamp rubber forming process has a significant effect uniformity of channel depth in different directions. DDAE, LDAE, and TRDAE would decrease from 10.71, 5.35, and 4.02% in conventional process to 2.36, 1.63, and 0.72% in semi-stamp rubber forming process, respectively. This shows 8.35, 3.72, and 3.3% improvement in directional dimensional accuracy.

Finally, the effect of semi-stamp process on total dimensional accuracy was investigated in this study. Figure 18 shows filling percentage of various channels in longitudinal direction. According to Fig. 18, uniformity of filling percentage would increase by using semi-stamp rubber forming process (difference between central and lateral channel depth would decrease). Also, investigation of TDAE value which was calculated by Eq. 8 shows 1.057% improvement in total directional accuracy by using semi-stamp process instead of conventional rubber forming process (maximum value of TDAE would decrease from 2.020 to 0.963% by using novel process, Table 7). Positive effect of semi-stamp process on dimensional accuracy of bipolar plates is due to the fact that machining micro channel pattern on rubber (Fig. 1c) led to more uniform penetration into punch cavity (Fig. 4a). As a result bipolar plate would have uniform channel's depth and difference between various channels in the same and different directions would decrease ($\Delta h_2 \leq \Delta h_1$ in Fig. 4).

3.4 Produced bipolar plates

The goal of this study was to fabricate metallic bipolar plates through rubber pad forming process with maximum uniformity in channel depth and dimensional accuracy. Conventional rubber pad forming process and semi-stamp rubber forming were investigated to produce bipolar plates. According to the

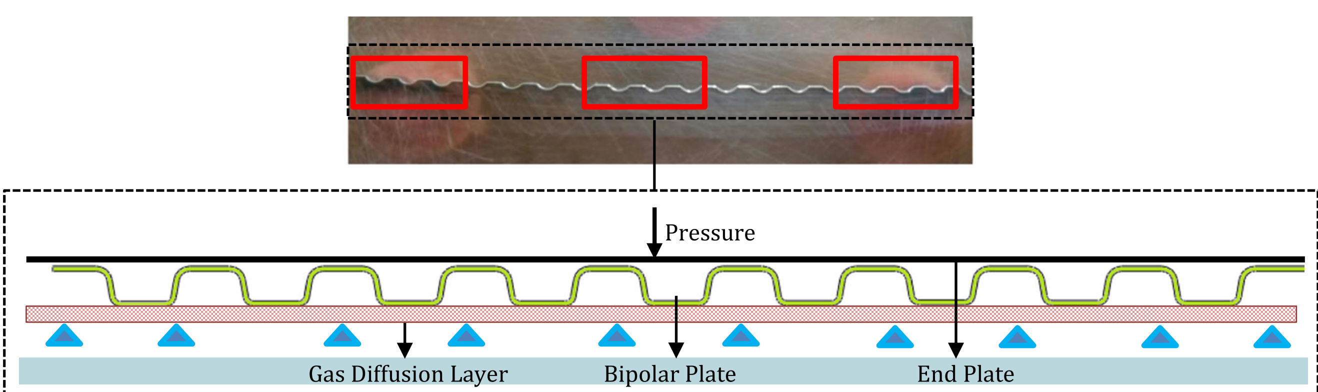

Fig. 21 Bipolar plate/GDL/end plate assembly

Table 9 Properties of bipolar plate and GDL

Component	Material	Young's modulus (GPa)	Poisson's ratio	Thickness (mm)
Bipolar plate	SS 316	200	0.3	0.1
GDL	Carbon paper	6.1	0.09	0.1

result of this study, fabricated samples by semi-stamp rubber forming showed considerable improvement in uniformity of channel depth and dimensional accuracy than the conventional method, it could be concluded that semi-stamp rubber forming method would be more suitable to fabricate uniform bipolar plate. Figure 19 shows the fabricated bipolar plates, diagonal, and longitudinal channel cross section in samples that were fabricated by conventional and semi-stamp rubber forming process. As can be seen, semi-stamp rubber forming that was developed in this research was capable of producing bipolar plates with more uniform channel depth than the conventional method. Dimensional accuracy characteristics of best samples which were fabricated by both conventional and semi-stamp rubber forming process are shown in Table 8.

3.5 Pressure distribution on gas diffusion layer

Uniform distribution of contact pressure on gas diffusion layers (GDL) is one of the most important factors in performance and efficiency of PEMFCs. Inappropriate contact pressure would lead to excessive compression on GDL and distortion in membrane electrode assembly, which would effect on gas flow, and internal leakage. Dimensional errors (the difference between channel depths) could lead to inappropriate pressure distribution on GDL and finally caused a reduction in efficiency of PEMFCs. The dimensional error is an unavoidable phenomenon during manufacturing of bipolar plate with various processes. As shown in Fig. 20, after assembly of PEMFCs, contact between the bipolar plate and GDL is non-uniform and this leads to variation in contact pressure at different zone (zone 1 and zone 2 in Fig. 20). More uniform pressure distribution is achievable by increasing dimensional accuracy (zone 3 and zone 4 in Fig. 20). To achieve this aim, the effect of process parameters such as applied force, the hardness of rubber, and thickness of rubber was investigated on the uniformity of channel depth and dimensional accuracy in various directions, in the previous section. Also, the effect of the novel method (semi-stamp rubber forming process, which was developed by authors) on dimensional accuracy was studied to produce the bipolar plate with more uniform channel depth. Pressure distribution on GDL was studied by using the worst and the best samples in conventional forming process and the best sample which was produced by semi-stamp forming process (from the point view of pressure distribution), in order to investigate the effect of the previous result on quality of produced bipolar plates.

The commercial code of ABAQUS is used to build the FEA model as follows. Nine channels in longitudinal direction were considered (Fig. 21). The model consists of the 2D section of the end plate, bipolar plate, and GDL. Clamping load was considered equal to 0.5 MPa. The properties of materials (bipolar plate and GDL) used for finite element simulation are listed in Table 9 [24, 30]. Since the end plate is much thicker and more rigid than the BPP, it can be treated as a rigid body in the model to save the computing time. Thus, a rigid line is created on the top of the BPP to simulate the assembling press instead of the end plate. Figure 21 shows the schematic of FEA model of bipolar plate/GDL/end plate assembly.

Three samples which were fabricated by different forming condition were selected in order to investigate the effect of dimensional accuracy on pressure distribution uniformity. Forming condition on these three samples was shown in Table 10.

At first, pressure distribution was investigated by using channel depth of sample A. Depth of nine channels in sample A was considered to study the distribution of pressure on GDL. Figure 22 shows the pressure distribution on GDL. As can be seen, pressure distribution is completely non-uniform in this condition (Fig. 22). According to the result, contact pressure between bipolar plate and GDL in the lateral zone is more than the central area. In other words, there is almost no contact between central channels and bipolar plates. Localized contact pressure in lateral channels increased up to 4 MPa which could lead to failure in GDL. Also, the very low contact pressure between central channel and GDL caused leakage between the channels and increase in contact electrical resistance and finally lead to decrease in efficiency of PEMFCs.

Table 10 Forming condition of sample A, B, and C

Name	Forming process	Rubber hardness (Shore A)	Rubber thickness (mm)	Force (kN)
Sample A	Conventional rubber forming	40	30	450
Sample B	Conventional rubber forming	90	30	450
Sample C	Semi-stamp rubber forming	90	30	450

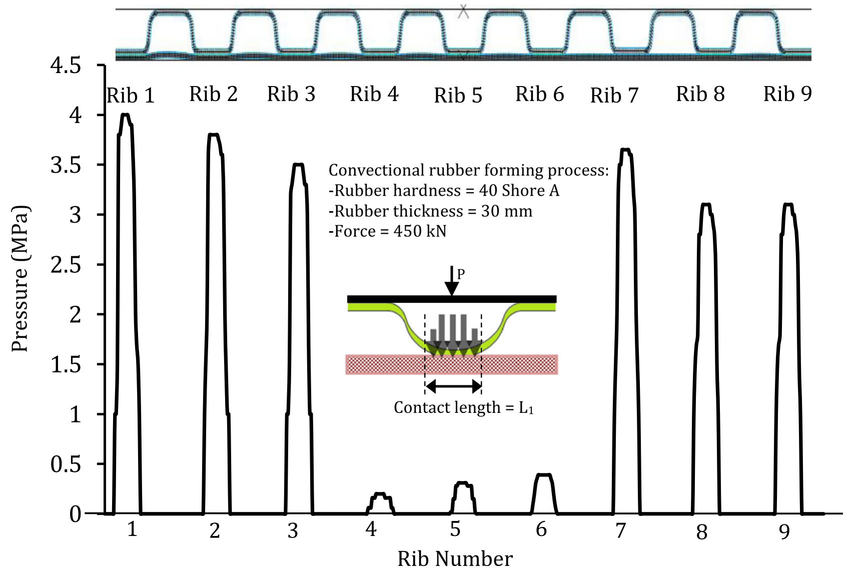

Fig. 22 Pressure distribution of sample A on GDL

Figure 23 shows contact pressure distribution of sample B on GDL. According to the previous result, dimensional accuracy of sample B was the best one in conventional rubber forming process. The pressure distribution on GDL improved significantly. The difference between the maximum and minimum value of localized contact pressure in central and lateral channels decreased from 3.8 MPa in sample A to 0.6 MPa in sample B. This would lead to increase in efficiency of PEMFCs. It should be mentioned, although the filling percentage of channels in sample A is more than sample B, but the uniformity of pressure distribution on GDL is lower than sample B due to lower dimensional accuracy, which is not appropriate. This issue represents the importance of dimensional accuracy.

In the following, pressure distribution on GDL was investigated by using channel depth of sample C which was fabricated by semi-stamp rubber forming process (Fig. 24). According to the result, most uniform pressure distribution was achieved in this condition. The difference between the maximum and minimum value of localized contact pressure in central and lateral channels was 0.51 MPa in sample C. This shows 2.29 and 0.9 MPa improvement than sample A and sample B, respectively. Also, it should be mentioned that maximum localized pressure value in sample A was 4 MPa which decreases to 2.48 and 1.52 MPa in sample B and C. The importance of this issues increases when the local pressure exceeds the pressure limit (pressure which leads to failure in GLD) on GDL. According to the result, uniformity of pressure distribution increases by rises in dimensional accuracy. Also, the maximum localized pressure between bipolar plates and GDL would decrease with rising dimensional accuracy. Both mentioned items (pressure distribution and maximum

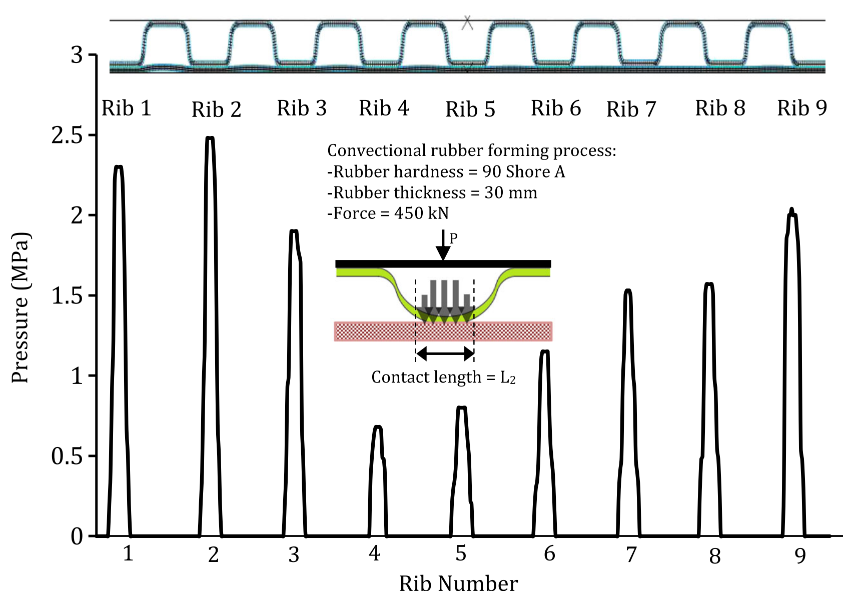

Fig. 23 Pressure distribution of sample B on GDL

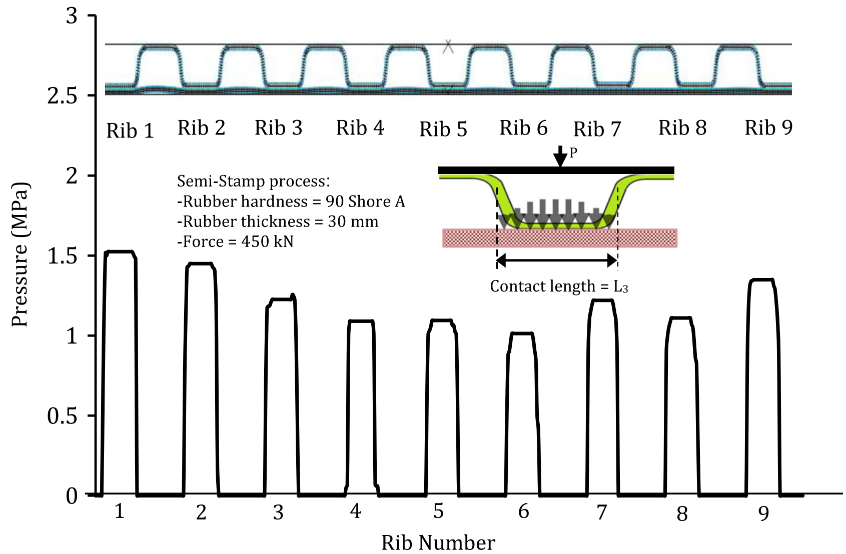

Fig. 24 Pressure distribution of sample C on GDL

localized pressure) would have an effect on performance on PEMFCs.

4 Conclusions

Uniformity of channel depth in metallic bipolar plates with serpentine flow field micro channels was investigated by rubber pad forming process. Stainless steel 316 with thickness of 0.1 mm was used.

Effect of process parameters such as rubber hardness, rubber thickness, and applied force was investigated on uniformity of channel depth. According to the result, channel uniformity was not desirable in conventional rubber pad process, a semi-stamp rubber forming was developed, and the effect of this method on uniformity of channel depth and dimensional accuracy was investigated. The following results were obtained:

1) In lower hardness of rubber by increasing the force, difference between average channel depth in diagonal and longitudinal direction decreases.
2) Increasing the hardness of rubber would lead to improving channel's depth uniformity and directional dimensional accuracy. DDAE would decrease from 14 to 11.88% by using rubber with Shore A 90 instead of rubber with Shore A 40. Also, LDAE and TRDAE would decrease from 8.84 and 5.15 to 8.18 and 4.79, respectively.
3) Increase in applied force has positive effect on total dimensional accuracy. Maximum value of TDAE decreased from 7.314 to 2.020% by increasing forming force from 300 to 450 kN. This shows 5.294% improvement in total dimensional accuracy.
4) Channel depth uniformity and total dimensional accuracy and rubber hardness directly depended on each other. Maximum value of TDAE decreased from 15.432 to 2.020% by increasing hardness of rubber from Shore A 40 to Shore A 90. This shows 13.412% improvement in total dimensional accuracy and generally increasing rubber hardness would lead to improvement in TDAE and uniformity of channel depth.
5) Increase in thickness of rubber led to fabrication of more uniform bipolar plates. Increase rubber's thickness from 10 to 30 mm causes 6.61, 5.04, and 2.96% improvement in DDAE, LDAE, and TRDAE value.
6) Increases in rubber thickness led to reducing difference between filling percentage of channels in longitudinal direction. Using rubbers with thickness of 30 mm instead of 10 mm led to 3.982% improvement in channel depth uniformity.
7) Intensity of the effect of rubber thickness on uniformity of filling percentage of channels in range of 10 to 20 mm is more significant than range of 20 to 30 mm.
8) Difference between filling percentage in different directions decreases significantly by using semi-stamp rubber forming process. DDAE, LDAE, and TRDAE would decrease from 10.71, 5.35, and 4.02% in most uniform sample that was fabricated by conventional process, to 2.36, 1.63, and 0.72% in semi-stamp rubber forming process, respectively.
9) Uniformity of filling percentage in longitudinal direction would increase by using semi-stamp rubber forming process. Also, investigation of TDAE value shows 1.057% improvement in total directional accuracy by using semi-stamp process instead of conventional rubber forming process.
10) Dimensional accuracy would have the significant effect on the uniformity of pressure distribution. Uniformity of

pressure distribution increases by rises in dimensional accuracy. Also, the maximum value of pressure on GDL would decrease with rising dimensional accuracy.

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