Effect of rubber forming process parameters on channel depth of metallic bipolar plates

Chul-Kyu Jin*

〈Abstract〉

In this study, bipolar plates in fuel cells are formed using rubber forming process. The effects of important parameters in rubber forming such as hardness and thickness of rubber pad, speed and pressure of punch that compress blank, and physical property of materials on the channel depth were analyzed. In the soft material sheet Al1050, deeper channels are formed than in materials STS304 and Ti-G5. Formed channel depth was increased when hardness of rubber pad was lower, thickness of rubber pad was high, and speed and pressure of punch were high. It was found the deepest channel was achieved when forming process condition was set with punch speed and pressure at 30 mm/s and 55 MPa, respectively using rubber pad having hardness Shore A 20 and thickness 60 mm. The channel depths of bipolar plates formed with Al1050, STS304 and Ti-G5 under the above process condition were 0.453, 0.307, and 0.270 mm, respectively. There were no defects such as wrinkle, distortion, and crack found from formed bipolar plates.

Keywords : Rubber forming, Thin plate forming, Metallic bipolar plate, Aluminum alloy, Stainless steel, Titanium

1*Corresponding Author, Assistant professor, School of mechanical engineering, Kyungnam University
(E-mail: cool3243@kyungnam.ac.kr)

1. Introduction

Rubber forming technology is a forming method wherein material is pressed by rubber pad. Rubber pad is attached in the Ram of press and materials to be formed are placed on the Form block. It is a forming method processed according to external shape of formed block and is characterized as imposing almost uniform pressure on entire surface of materials. This process has merits of very simple setting, easy die change, and cost effective for equipment.

A bipolar plate is a product in which concavo-convex shaped channel is inserted as a pattern in the thin sheet. Channel shape has to be distributed evenly on the entire bipolar plate since hydrogen and oxygen required for chemical reaction are moved through channel. Besides, bipolar plate has to be made of material having excellent electric conductivity and thermal conductivity and should possess mechanical strength to some extent. Especially, bipolar plate should be processed as mass production system in any case in order for fuel cell commercialized.

Mahabunphachai et al. [1] prepared a metal bipolar plate using stamping and hydroforming and proposed results about formability and surface roughness. Kwan et al. [2] formed aluminum 1050 bipolar plates with static load of stamping process. Kim et al. [3] fabricated stainless steel 316L bipolar plates with static and dynamic load of tamping process and they found that deeper channels were formed by dynamic load than static load. Hung and Lin [4] made a bipolar plate using High-pressure hydroforming equipment and showed improved formability by 51% than by existing equipment. Hung et al. [5] processed channels in STS316L using micro EDM milling. Lee et al. [6] prepared an electrochemical micro-machining (EMM) process. Liu and Hua [7] have performed forming analysis of channel for rubber pad forming using simulation of FEM. They also prepared a bipolar plate made of STS304. Jin and Kang [8] have prepared an aluminum bipolar plate having precise channel shape using vacuum die casting. Jin et al. [9] made a bipolar plate having high strength, flexible, and precise with cast aluminum alloy, wrought aluminum alloy, pure aluminum using a semi-solid forging process.

Currently, the most suitable method to produce bipolar plate is Stamping. However, since thickness of sheet used in the stamping is quite thin as thin as 0.1 mm, there are problems of irregular flatness due to distortion, wrinkle, and rupture at channel curvature after channel forming done. These problems occurred in stamping using these sheets can be resolved by using rubber forming method. We intended to minimize the defects generated from stamping and to achieve maximum channel depth that can be achieved by stamping while using rubber forming method. During the first stage of experiment, formability of channel in bipolar plate was compared according to physical characteristics of three metal materials viz., Aluminum 1050 (Al1050), Stainless steel 304 (STS304), and Titanium ASTM Grade 5 (Ti-G5) which are drawing limelight as materials for fuel cells. During the second stage of experiment, channel depth of bipolar plate was analyzed by performing forming experiment according to hardness and thickness of rubber pad. During the third stage of experiment, depth of channel in bipolar plate was analyzed by performing forming experiment according to punch speed and pressure that compresses blank and rubber pad. At the last stage of experiment, as a performance test for the fuel cell, current densities under the optimum process parameter conditions at 0.6V was carried out. With four stages of experiments, it was analyzed which material was the most suitable as a material for forming bipolar plate for the fuel cell.

Table 1 The physical and material properties of SS304, TiG5 and Al1050

Parameter	Unit	STS304	TiG5	Al1050
Density	g/cm^3	8.0	4.43	2.70
Brinell Hardness	HB	123	294	43
Tensile Strength	MPa	505	895	160
Elongation at Break	%	40	10	7
Electrical Resistance	Ω-cm	$72x10^{-6}$	$171x10^{-6}$	$2.9x10^{-6}$
Thermal Conductivity	W/mK	16.2	17.0	227

2. Experiment

2.1 Materials

Aluminum, Stainless steel, Titanium which have excellent electric conductivity, thermal conductivity, and corrosion resistance are drawing limelight as the most suitable materials for metal bipolar plate for fuel cell. The sheets formed from these three materials having thickness 0.1 mm were used for experiment. Blank was prepared by cutting the materials towards width (rolling direction) and length direction at 100 mm each. Heat treated Aluminum alloy with purity 96% among pure aluminum alloy Al1050-H18 was used for experiment and channel was formed after removing heat treated characteristics of materials. STS304 among austenitic series having excellent corrosion resistance by containing 8.03% Ni, 18.07% Cr, and 0.14% Mo was used for forming experiment. Also, Ti-G5 was adopted for experiment. This is an alloy into which 5.5% Aluminum and 3.5% Vanadium were added so that ductility was reduced and strength was prominently improved. Table 1 shows physical properties of three tested materials. In case of Al1050, density is lower by three times than that of STS304 and by 1.6 than that of Ti-G5. Also, it is judged that A11050 is the most suitable material for bipolar plate in fuel cell since electric conductivity and thermal conductivity are far higher than those of STS304 and Ti-G5. However, the tensile strength and elongation rate of raw material Al1050 from which heat treatment was removed were 76 MPa and 39% indicating very a lower tensile strength than those of STS304 and Ti-G5. Besides, Al1050 is very thin with thickness 0.1 mm, formed bipolar plate can be easily deformed even with a small external force.

2.2 Experiment method and condition of rubber forming process

A 200 ton hydraulic press was used to form channel in metal sheet during rubber forming process. The rubber forming equipment installed in 200 ton hydraulic press was presented in Fig. 1 (a). After connecting ram of hydraulic press and upper die with joint, punch was assembled on the upper die. Container was fixed on the press bed so that punch can be inserted inside of container precisely when punch was descended. Rubber pad was made in such way that it can be fixed inside of container with almost no tolerance to prevent rubber expelled out from container after compressed when rubber pad was compressed by punch. The punch with channel shape and cross-sectional drawings of punch cavity are presented in Fig. 1 (b). Dimension of punch was 150 x 150 mm in width and length and 100 mm in thickness. Pattern dimension as active area of channel was 50 x 50 mm in width and length. As can be seen from cross-sectional drawing of punch, depth of punch groove corresponding to channel of metal sheet in which channel is formed was 0.4 mm and width of groove was 0.8 mm. The width of protruding part of punch corresponding to rib was 1.2 mm. If width of punch groove or protruding part is narrow, channel depth can be formed smaller due to small elongation per unit area of sheet material. It was reported that channel depth should be at least more than 0.3 mm and width ratio of channel width and rib width should be 1.5. Punch groove and protruding area were designed based on these theories and testing backgrounds. Also draft angle of channel width was arranged at 30º so that blank can be filled inside of punch cavity by repulsive force so that elastic deformation of rubber pad can be evenly transmitted to overall area of blank. Besides, curvature of 0.2 mm was given to edge that connects channel to rib to prevent rupture of material during compressing the blank.

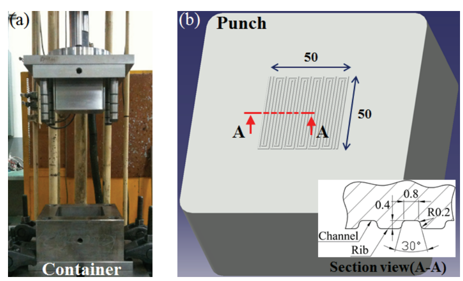


Fig. 1 (a) experimental apparatus of rubber forming and (b) design of the punch with channels (unit: mm).

The rubber forming experiment wherein

channel is formed by compressing metal blank and rubber pad after placing metal blank onto rubber pad is presented in Fig. 2. The experiment sequence was as follows. After inserting rubber pad inside the lower container, metal blank was placed on the rubber pad. Descending speed and pressure of punch were set in hydraulic press and then blank as well as rubber pad were compressed at the same time by descending punch. Metal blank in which channel was formed was taken out and then experiment was repeated after inserting blank again.

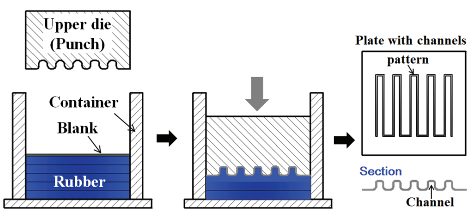


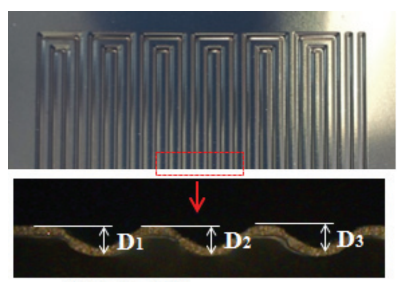
Fig. 2 Rubber forming for forming channels on metallic blank

Channel depth was analyzed according to physical properties of materials, thickness and hardness of rubber pad, and descending speed and pressure changes of punch. Table 2 shows testing parameters of rubber forming process. The materials used in the experiment were three types viz., Aluminum 1050, Stainless steel 304, and Titanium G5 having thickness 0.1 mm. As a rubber pad, six numbers of rubber pads having thickness 10 mm were applied by stacking them from one number until six in numbers during experiment. Four types of hardness Shore A 20, 25, 30 and 35 of rubber pad were tested. While punch speed was changed from 5 mm/s till 30 mm/s by increasing speed at 5 mm/s each time making six variations. Also, punch pressure total five variations from 15 MPa until 55 MPa increased by 10 MPa at each time were implemented.

Table 2 The experiment conditions of the rubber forming process

Properties	Unit	Value
Rubber hardness (Hr)	Shore A	20, 25, 30, 35
Rubber thickness (tr)	mm	10, 20, 30, 40, 50, 60
Punch velocity (Vp)	mm/s	5, 10, 15, 20, 25, 30
Punch pressure (Pp)	MPa	15, 25, 35, 45, 55

Fig. 3 shows the measurement method of channel depth of formed bipolar plate.



$$D = \frac{D_1 + D_2 + D_3}{3}$$

Fig. 3 Measurement of formed channel depth

The central portion of formed metal bipolar plate was cut and cross-sectional shape at center portion was measured using digital microscope. The three channel depths (D_1, D_2, and D_3) of bipolar plate were measured using image analysis and average depth was adopted as channel depth (D_c).

3. Results of experiment

For rubber forming method, installation time of testing equipment is quite short and so as is the forming time for bipolar plate. The duration of installing equipment in the press is within around five minutes. The insertion time of rubber pad into container is around three second, compression time of rubber pad and blank by punch is two second, and blank inserting time after taking out formed bipolar plate is within five seconds. Therefore, the required time to make one bipolar plate is very short around within ten second, thus it is regarded as suitable for mass production system to produce bipolar plates.

The bipolar plates made of Al1050, STS304, and Ti-G5 in which channels were formed are presented in Fig. 4. Though the difference of channel depth in three bipolar plates cannot be distinguished by eyes, it can be confirmed that channel pattern was clearer in bipolar plate made of Al1050. From three types of bipolar plates, it was clear that formed bipolar plates were not only free from crack and wrinkle but also shows flatness without distortion of sheet materials.

3.1 Depth of channel formed according to rubber hardness

The effect of rubber pad's hardness on the formed channel depth was analyzed. Four types of rubber pads (thickness 60 mm) with hardness Shore A 20, Shore A 25, Shore A 30, and Shore A 35 were used. Punch speed and pressure was set at 30 mm/s and 55 MPa, respectively. Rubber pad was changed during each trial.

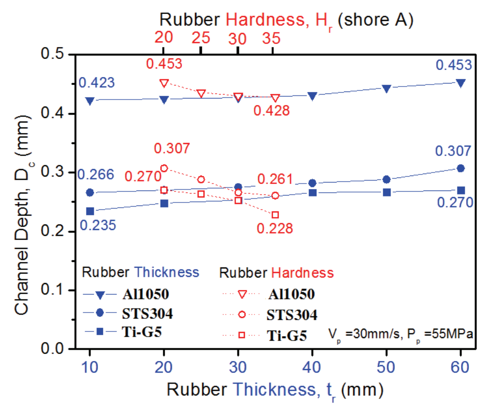


Fig. 5 Depth of channel formed by different thickness and hardness of rubber pad

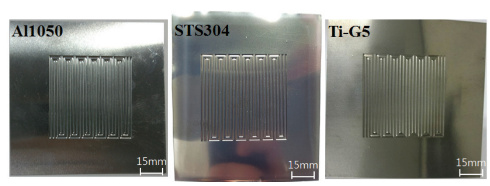


Fig. 4 Metallic bipolar plates formed by rubber forming

Red dot lines in Fig. 5 shows formed channel depth according to hardness of rubber pad. As hardness of rubber pad was increased, formed depth of channel was decreased. The results showed that with rubber pad having hardness Shore A 20, maximum forming depth was achieved from all three materials. The highest channel depth was achieved in Al1050 with all types of pad hardness, while the lowest channel depth was found from Ti-G5. It was thus, confirmed that the softer the materials, the deeper was the channel depth. In the material Al1050, channel was deeper by 0.146 mm than that of STS304 and by 0.183 mm than that of Ti-G5.

The reason why deeper channel could be achieved as hardness of rubber pad was decreased might be because as hardness of rubber pad became reduced, elastic deformation was occurred more easily, consequent repulsive force to blank became larger. Fig. 6 shows stress-strain curve obtained from uniaxial tensile test for four types of rubber pads. The test specimens were dumbbell shape #3 of JISK-6251 and characteristics of rubber were examined using Universal Testing Machine (UTM) Autograph AG-X to predict stress-strain changes according to Shore hardness of rubber pad.

It indicates that as Shore hardness of rubber was increased, more loads were required. In case of shore A 20, though elongation was the least, the required force for deformation became the least. Therefore, in case of rubber pad having Shore A 20, since it is softer material as compared with other three types of rubber pads, rubber can be filled into all the parts of punch cavity during forming. Besides, since the compressed amount during compression by punch was the highest, the resulting repulsive force also was the largest which could produce the deepest channel.

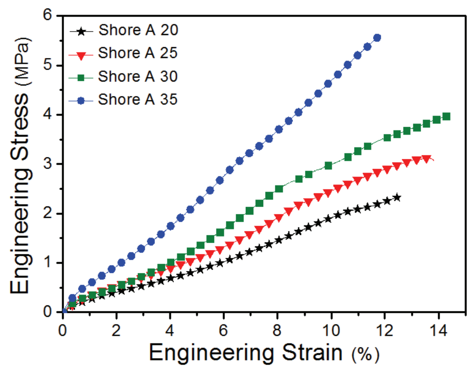


Fig. 6 Curve of engineering stress-strain for different rubber pads

3.2 Depth of channel formed by various rubber thicknesses

The effect of rubber pad thickness on the channel depth was analyzed. Experiment was carried out by stacking rubber pad having thickness 10 mm and hardness Shore A 20 one by one onto the container until total stacked rubber pad thickness 60 mm was achieved. Punch speed and pressure were set at 30 mm/s and 55 MPa.

The blue solid lines in the graph as shown

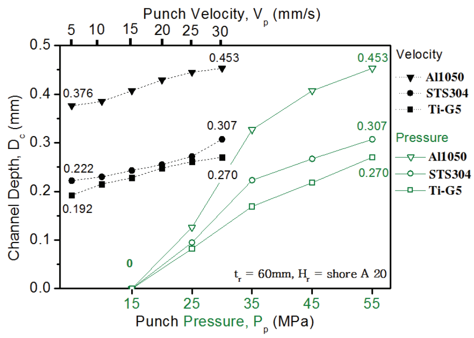


Fig. 7 Depth of channel formed by different velocities and pressures of punch

in Fig. 5 represent channel depth for three types of formed materials according to rubber thickness changes. As thickness of rubber pad became increased, the depth of formed channel in the bipolar plate became increased. The loss of load in the punch imposed on the rubber pad during forming was reduced as thickness of rubber pad was increased. Therefore, large repulsive force from rubber pad could be imposed to blank. While, as thickness of rubber pad was decreased, large amount of loss towards outside might be occurred while punch load was transmitted to rubber pad. Therefore, only small repulsive force might have been generated.

Same as the results of hardness test for rubber pad, the deepest channel was achieved in material A11050 with all the rubber thickness variations. Whereas, the shallowest channel depth was obtained from material Ti-G5. When the thickness of rubber pad was 60 mm, maximum channel depth was achieved from all three types of materials with 0.453 mm for A11050, 0.307 mm for STS304, and 0.270 mm for Ti-G5.

3.3 Depth of channel formed by various punch velocities

The effect of descending speed of punch that compresses blank and rubber pad on the forming depth of channel was analyzed. The six types of descending speeds of punch were varied from 5 mm/s until 30 mm/s increased by 5 mm/s each time. The rubber having hardness Shore A 20 and thickness 60 mm was used and punch pressure was set at 55 MPa.

Black dot lines in graph in Fig. 7 show formed channel depth for three types or materials according to changes of descending speed of punch. As punch speed was increased, channel depth was proportionally increased. The maximum channel depths for all three materials were achieved with fastest punch speed at 30 mm/s. On the contrary, the shallowest channel depth was observed at the slowest punch speed 5 mm/s.

The reason of forming depth of channel increased as punch descending speed was increased might be because as compression speed on the rubber pad became faster, the elastic deformation speed of rubber pad was increased, thereby all the instant repulsive force of rubber pad was transmitted to blank before it was lost to outside.

3.4 Depth of channel formed by various punch pressures

The effect of punch pressure on the blank and rubber pad on the forming depth of channel was analyzed. The five variations of punch pressures from 15 MPa until 55 MPa increased by 10 MPa at each time were applied. The rubber pad same as that one used during punch speed experiment was adopted and punch descending speed was set at 30 mm/s.

The green solid lines in the graph in Fig. 7 show formed channel depth for three types of materials according to punch pressure changes. As punch pressure was increased, the channel depth was also increased in proportion to the punch pressure. The deepest channel depth was achieved from material Al1050 under all the punch pressure conditions same as three experiment conditions. While, the shallowest channel depth was found from material Ti-G5. No channel was formed from all three materials tested when punch speed was at 15 MPa. Also, with increases in punch pressure, channel depth was increase in a large scale in A11050 than those of other two materials. Besides, when channel depth graph was compared according to hardness and thickness of rubber pad and punch speed, the gradient of graph for channel depth for punch pressure is steep. That is, punch pressure affect more on the increases in channel forming than that achieved by thickness and hardness of rubber pad and punch speed.

3.5 Uniformity of channels formed by optimal conditions

The testing condition by which the deepest channel could be achieved was inserting rubber pad having thickness 60 mm and hardness Shore A 20 into container and carrying out forming with punch speed at 30 mm/s and punch pressure at 55 MPa. The formed channel depths for materials Al1050, STS304, and Ti-G5 by implementing the above testing conditions were 0.453 mm, 0.307 mm, 0.270 mm, respectively. Cross-sectional shapes for three types of materials are presented in Fig. 8.

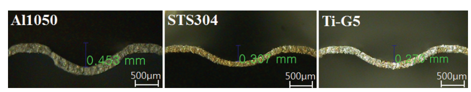


Fig. 8 Shape of channels formed by optimal forming condition

Channel depths were measured for nine numbers of portions at center of three types of metal bipolar plates prepared under the optimum test condition in order to judge whether formed channel depths were uniform in overall. Fig. 9 shows channel depths for nine portions of three types of metal bipolar plates prepared under the optimum forming condition. In case of material Al1050, the difference between deepest and shallowest channel depth was 0.007 mm, 0.002 mm for STS304, and 0.004 mm for Ti-G5. Though the deepest channel was observed from bipolar plate made of Al1050, the uniformity of channel was achieved from bipolar plate made of STS304.

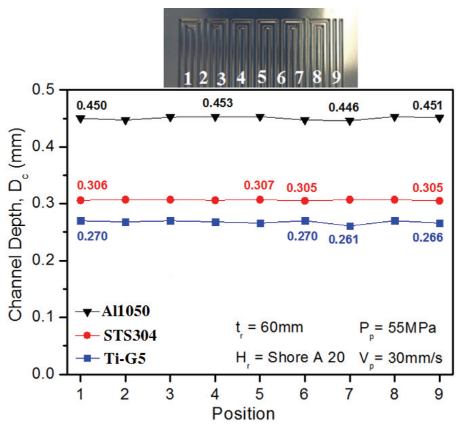


Fig. 9 Depth in different positions of channel formed by optimal forming condition

3.6 Performance of a single fuel cell

Prepared three types of metal bipolar plates (Al1050, STS304, and Ti-G5) were assembled into single cell to examine the performance of metal bipolar plates after implemented in the fuel cell. Single cell includes bipolar plates between hydrogen electrode and oxygen electrode, Holder, Current Collector that makes current flow into bipolar plate, and End sheet. Also, Membrane Electrode Assembly (MEA) was combined between

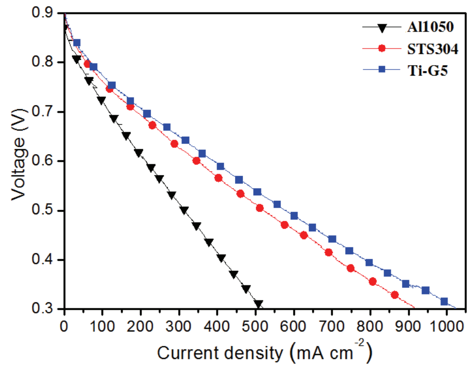


Fig. 10 I-V curve for the single cells using different formed bipolar plates

bipolar plates located between hydrogen electrode and oxygen electrode.

Humidified hydrogen and oxygen gases at flow rate 300 ccm were supplied to Anode and Cathode while maintaining temperature of humidifier at 70 ° C. Therefore, Single cell drive temperature was maintained at 70 ° C. Performance test for single cell was carried out for each bipolar plate made of Al1050, STS304, and Ti-G5.

The performance of fuel cell was expressed as current density for voltage 0.6 V. Therefore, current densities under voltage condition 0.6V for three types of metal bipolar plates were measured through I-V curve. Fig. 10 shows I-V curve of fuel cells into which three types of metal bipolar plates were implemented. The current density for Al1050 bipolar plate was observed as 205 mA/cm^2, 345 mA/cm^2 for STS304, and 396 mA/cm^2 for Ti-G5 under voltage 0.6 V. The highest current density was observed from Ti-G5 showing the reverse order of channel depth achieved with lowest current density from Al1050. Al1050 not only had excellent electric conductivity than those of STS304 and Ti-G5 but also had deeper channels, but its current density was the lowest. It is because aluminum surface is easily oxidized under aggressive acidic fuel cell environment, the conductivity in the surface is abruptly dropped by passivating oxide film. Therefore, as voltage is decreased, current density is decreased in a large scale by Ohmic loss. Stainless steel, though corrosion resistant property is improved thanks to the passive film on formed on the surface (preventing serious corrosion), this film can act electric insulating materials to reduce electric conductivity to some extent. It might be because titanium oxide film(TiO_2) has far excellent performance than oxide film of aluminum and stainless steel, thus exhibiting excellent corrosion resistance than stainless steel and aluminum thereby higher current density was generated.

4. Conclusions

Four types of forming conditions, i.e., thickness and hardness of rubber pad, punch speed and pressure all affected on the channel depth of bipolar plate during rubber forming. Especially, punch pressure was more effective on the channel forming depth of bipolar plate. The effects of hardness and thickness of rubber pad, speed and pressure of punch, and physical properties of metal sheet materials on the forming depth of channel were analyzed and the results are summarized as below.

1) The deeper channel was formed in relatively soft material Al1050 than those in STS304 and Ti-G5 under all the forming conditions tested.
2) The lower the hardness of rubber pad, the more beneficial was for the deformation of rubber and deep channel in the bipolar plate achieved with larger repulsive force.
3) The thicker the rubber pad, the deeper was channel in the bipolar plate due to not losing load imposed by punch toward outside and converted into repulsive force to attribute deeper channel forming.
4) If punch speed that compresses rubber pad was fast, elastic deformation of rubber pad was fast thereby it was transmitted to entire surface of blank to make channel depth increased.
5) Punch pressure was the key factor increasing repulsive force more than that of hardness and thickness of rubber pad and punch speed.
6) The optimum condition for rubber forming process was hardness of rubber pad at Shore A 20, thickness of rubber pad at 60 mm, and punch speed and pressure at 30 mm/s and 55 MPa, respectively. The channel depths in the bipolar plates prepared under the above conditions for materials Al1050, STS304,

and Ti-G5 were 0.453 mm, 0.307 mm, and 0.270 mm, respectively.

7) The I-V curve indicating performance of fuel cell showed that current density under 0.6V condition was mA/cm2, 345 mA/cm2 for STS304, and 396 mA/cm2 for Ti-G5 under voltage 0.6 V. The highest current density was observed from the bipolar plate made of material Ti-G5 thus to say that it was suitable as materials for bipolar plate. However, there were problems of high material cost and low formability. In case of material STS304, though it showed a little lower current density than that of Ti-G5, the cost and formability are satisfactory.

Acknowlegement

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea Government (No.2017-017242).

Reference

[1] S. Mahabunphachai, Ö. N. Cora, M. Koç, “Effect of manufacturing processes on formability and surface topography of proton exchange membrane fuel cell metallic bipolar plates”, J Power Sources, Vol. 195, pp. 5269-5277, (2010).

[2] H. J. Kwon, Y. P. Jeon, and C. G. Kang, “Effect of progressive forming process and processing variables on the formability of aluminium bipolar plate with microchannel“, Int J Adv Manuf Technol, Vol. 64, pp. 681–694, (2013).

[3] M. J. Kim, C. K. Jin, and C. G. Kang, “Comparison of formabilities of stainless steel 316L bipolar plates using static and dynamic load stamping“, Int J Adv Manuf Technol, Vol. 75, pp. 651–657, (2014).

[4] J. C. Hung, and C. C. Lin, “Fabrication of micro-flow channels for metallic bipolar plates by a high-pressure hydroforming apparatus”, J Power Sources, Vol. 206, pp. 179-184, (2012).

[5] J. C. Hung, T. C. Yang, and K. C. Li, “Studies on the fabrication of metallic bipolar plates- Using micro electrical discharge machining milling”, J Power Sources, Vol. 196, pp. :2070-2074, (2011).

[6] S. J. Lee, C. Y. Lee, K. T. Yang, F. H. Kuan, and P. H. Lai, “Simulation and fabrication of micro-scaled flow channels for metallic bipolar plates by the electrochemical micro-machining process”, J Power Sources, Vol. 185, pp. 1115-1121, (2008).

[7] Y. Liu, and L. Hua, “Fabrication of metallic bipolar plate for proton exchange membrane fuel cells by rubber pad forming”, J Power Sources, Vol. 195, pp. 3529-3535, (2010).

[8] C. K. Jin, and C. G. Kang, “Fabrication process analysis and experimental verification for aluminum bipolar plates in fuel cells by vacuum die-casting”, J Power Sources, Vol. 196, pp. 8241-8249, (2011).

[9] C. K. Jin, M. G. Jung, and C. G. Kang, “Fabrication of Aluminum Bipolar Plates by Semi-solid Forging Process and Performance Test of TiN Coated Aluminum Bipolar Plates”, Fuel Cells, Vol. 14, pp. 551-560, (2013).

(Manuscript received Match 9, 2017; revised Match 27, 2017; accepted June 9, 2017.)