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Investigation of Die Clearance in Rubber Pad Forming of Metallic Bipolar Plates

M. Elyasi[1*], F. Ahmadi Khatir[1], M. Hosseinzadeh[2]

[1] Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran
[2] Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran

ABSTRACT: In this research, rubber pad forming process of metallic bipolar plates made of stainless steel 316L with a thickness of 0.1 mm has been studied. In addition, a rubber pad made of polyurethane with the hardness number of shore A 85 and a thickness of 25mm is used in order to apply pressure to the plate to form the sheets. In order to study the effect of die clearance on depth filling, two die sets with different clearances were made. The results showed that when clearance is applied between punch die and matrix, the amount of uniformity becomes more in the depth of stuffed channel. But, the rubber pad is destroyed after some forming operation and plastic deformation occurs in it. Also, in the die set with the lower clearance, the amount of rubber pad life has been increased and the amount of flow channel depth gets greater. In the research results, it was determined that when the channel depth is small and a rubber pad is used with a higher hardness, the die set with a clearance has more favorable results due to uniformity in the flow channels' depth. However, by increasing the depth of bipolar plate channels, using die sets with lower clearance are better due to the increasing the rubber pad life.

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1- Introduction

Nowadays, fuel cells are thought to be a suitable replacement for internal combustion engines. Other advantages of fuel cell technology are its compatibility with the environment due to the lack of sound pollution, and producing heat and electricity simultaneously. Bipolar plates are among the most important parts of a fuel cell, which are responsible for gathering the external flow of the cathode and anode. The cooling fluid also flows in bipolar plates, and the distribution of reactive gases is done by rainwater or grooves created on the surface of these plates [1].

Among the fuel cell components which contain a sum of ME, bipolar plates, collectors, end plates, seals, screws and nuts and pneumatic connectors, the bipolar plates are the most important parts of these sections, because they contain something about 70 percent of weight, and 11 to 45 percent of a collection [2, 3]. The most important role of these plates in the fuel cell collection is the monotonous distribution of fuel and oxygen in the effective surface of the fuel cell, releasing something created by reactions and also leading and transferring flow into connectors [2]. According to Fig. 1, each bipolar plate includes flow channels and anode-cathode surfaces. Anode-cathode surfaces have more thickness and smooth surfaces in comparison of flow channels. Because of the contact of MEA, this surface is under corrosion [4]. Metals are one of best selection to produce bipolar plates. Using metals could bring advantages such as good electrical conductivity, good machinability, not containing surface porosity because of low cost, good mechanical properties, and can keep reactors apart from each other. The biggest problem with metals is their high density and weakness against corrosion. To protect from corrosion, bipolar plates are coated with a carbon base, polymer, and graphite materials. In order to reduce the production cost of these plates, we should use a simple and cheap method [5]. To decrease the production cost of bipolar plates, rubber pad forming was used. The tools and process cost in rubber pad forming process is lower than other bipolar plates manufacturing processes, such as hydroforming and stamping. Fig. 2 shows the sequence of rubber pad forming for a bipolar plate production. In stage one, the sheet is placed between two die jaws; the rubber inside the container and between the lower shell, playing the role of a matrix; and convex or concave dies in the upper jaw, playing the role of a plunger. In stage two, the force of a hydraulic stamp is exerted to form the sheet. In this stage, the flexibility of rubber causes the sheet to fill channel cavities. In stage three, the formed sheets are extracted from the die.

According to the importance of production process of bipolar plates, many types of researchers have performed studies in this field. Liu et al. [6] studied the effect of forming patterns on producing bipolar metallic plates (SS304) using rubber pad forming process. They created both convex and concave dies for a single channel of bipolar plates. The influence of these two patterns on filling force and thickness distribution of channels were also investigated. The study analyzed the ratio of channel width (*w*) to channel rib (*s*) through two-dimensional simulations. The results showed that if the ratio was greater than unity, the concave method would be more efficient, otherwise the convex pattern would be better. Son et al. [7] formed aluminum plates through rubber pad forming process. To conduct the study, some parameters, such as speed, punch pressure in flow channel depths, a die with a convex pattern and rubbers with different rigidity were

Corresponding author, E-mail: elyasi@nit.ac.ir

utilized. The results illustrated that increasing speed and pressure would lead to more filling depth in flow channels. The maximum decrease in sheet thickness would cause rises in punch pressure and speed. Jin et al. [8] examined the rubber pad forming of titanium bipolar plates. They also examined processing parameters, such as ram speed, punch pressure, and wall angle. The results indicated that for 60 mm thickness of rubber, ram speed 30 mm/s, punch pressure 55 MPa and 20 degree wall angle, were obtained as an optimal figure. Osia et al. [9] studied pin type bipolar plate by hydroforming process. They stated that stamping process is necessary after hydroforming of each deformed bipolar plates. Elyasi et al. [10, 11] examined the effects of concave and convex dies on rubber pad forming process. In their research, stainless steel sheet 316L with a thickness of 0.1 mm and a rubber layer with a hardness of 85 Shore A was used to form samples. According to the results, for an equal applied load, the concave die would show more filling depth than the convex one. In addition, by increasing forming force to a maximum value, filling depth would become stable in the concave die, and increasing the force would cause damage in rubber.

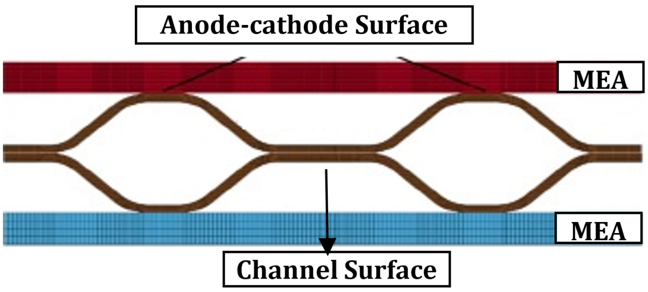

Fig. 1. Structure of a bipolar plate

The effect of die clearance in convex and concave dies has been studied in the present study. The aim of this research is to produce an industrial scale and industrial form of metallic bipolar plates with serpentine grooves using rubber pad forming process. It focuses on the effect of die patterns on the final shape of workpieces. In other words, the effects of both convex and concave patterns on the distribution of thickness and uniformity of ribs are studied.

In the present research, the influence of the die clearance amount has been examined in both convex and concave dies. In convex die, the flow channel is changeless while the anode-cathode bipolar plate is forming. Whereas, the anode-cathode plate is changeless and the current is forming in the convex die. A set of dies is used in order to investigate the forming of bipolar plates in both of the dies. At first, a model of die with 2 mm clearance between the punch and die was made based on the simulating results for the fewer numbers of channels. After that, the effects of this set on the depth of the filled channels uniformity amount were examined. Due to the simulating results, the set of the die was made completely, and the status of the sheet was examined with clearance in the die set. Moreover, the die clearance was decreased as less as possible, the percentage of the final plates filling and thinning were measured, and the life of the rubber pad was compared with the clearance set.

2- Experimental Procedure

The drawing of the serpentine bipolar plate and its dimensions used in this study are shown in Fig. 3. The little space between

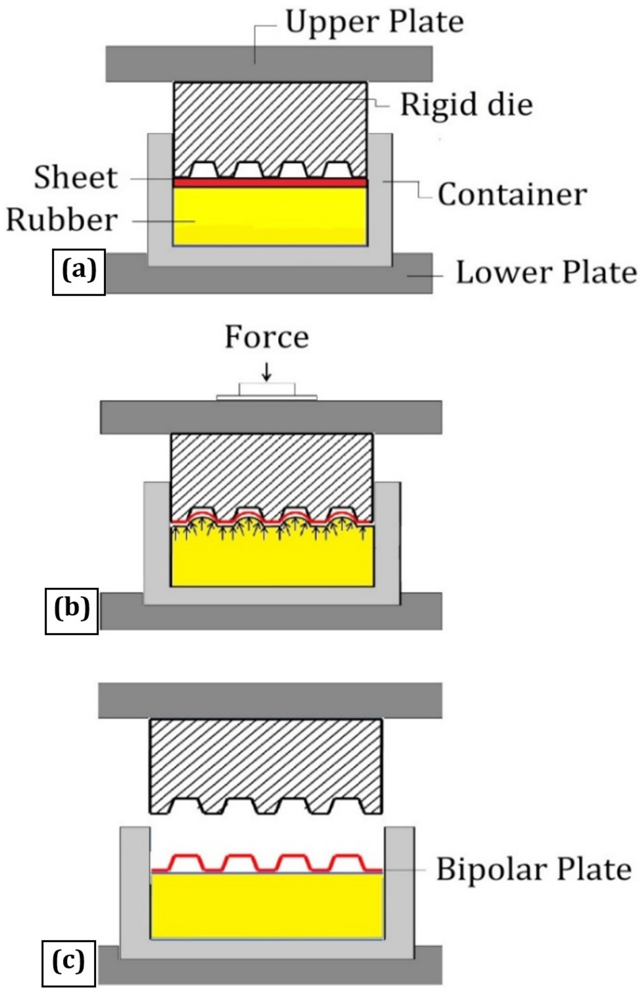

Fig. 2. Schematic diagram of rubber pad forming process, (a) stage one, (b) stage two, and (c) stage three

channels and serpentine geometry leads to a most complicated state for forming process. First, some four channels inserts were made in order to examine the channels crosscheck effects on each other and in order to investigate the effect of clearance. After investigating the channels forming for reaching the admissible clearance, a concave die with a high accuracy was made by CNC exactly similar to the primary pattern dimension. The created dies are shown in Fig. 4. The thickness of bipolar sheet material created by SS316LL is 0.1 mm because this material has the most resistance to corrosion among the kinds of steels and it is formed easier. The results of spectrometry test for this sheet are shown in reference [8]. After forming these sheets, in order to investigate the amount of filling and the channels thickness distribution, the formed sheet will be cut in the longitudinal direction. Since the surface of these sheets was burned by the result of cutting, the mounting operation was done to be able to polish and use emery on the surface of the sample sheets. This leads to having some samples devoid of flash and it can be seen clearly by microscope. The brief steps of the sample preparation is shown in Fig. 5.

Fig. 6 shows a hydraulic press machine with 200 tons capacity made by Khavar Press Company which is used to apply a force to the die set. In order to record the machine output, some automatic facilities are set on the machine, thus it is possible to receive the outputs as printed curves or a text file with the suffix of TXT. All of the machine's operations can be controlled by the connected computerized unit as it provides the possibility of adjusting the accurate progress rate and observing the accurate force of the press in each moment.

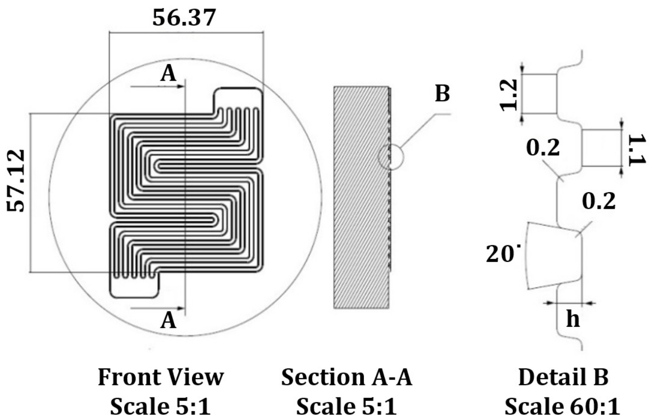

Fig. 3. The frame of paralleled worming grooves of a bipolar plate and its dimensions and sizes

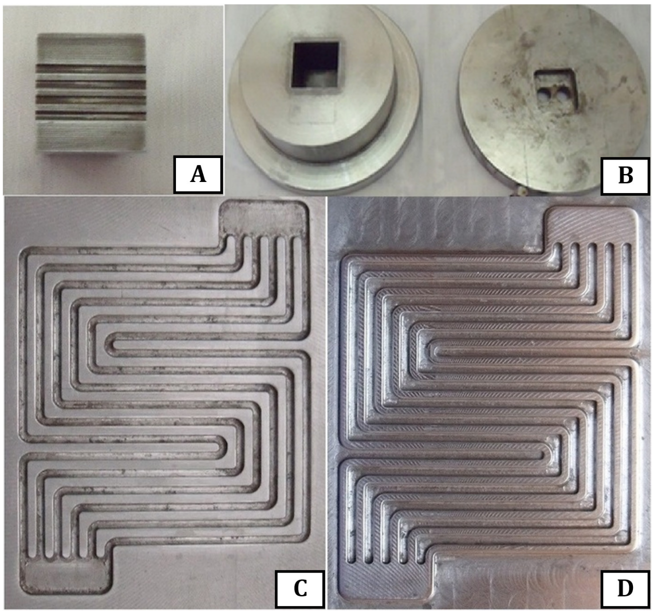

Fig. 4. Dies used in this study. A) Insert four channels, B) Insert template of four channels, C) Complete the concave die, D) complete the convex die.

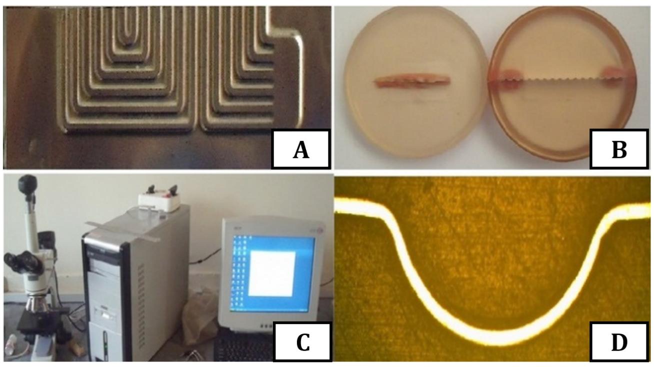

Fig. 5. Preparing stages of formed samples, A) sheet cutting in longitudinal sectional directions, B) mounting samples to see the profile under microscope, C) microscope for seeing mounted profile with X4 magnifying, D) image of channel plate with X4 magnifying

Fig. 6. Applied hydraulic stamping device for acting force on the die with capacity of 200 ton

In this research, two sets of dies are made. The difference between them is in the amount of the applied clearance between the punch and the matrix. This difference is shown clearly in Figs. 7 and 8. The effect of these sets on forming the sheets is studied.
To measure the amount of the formed sheets filling , (Fig. 9), filling space criterion is used and by measuring the profile filled space the amount of filling percentage was calculated based on Eq. (1). To measure thinning ratio of the produced sheet, Eq. (2) has been used. In this equation, the amount of the thinning ratio percentage is calculated by measuring the thinnest point of the sheet and comparing the primary thickness.

3- Simulation Procedure

In order to simulate the process, ABAQUS software is used. Because of plane strain process, the recent research was modeled in the 2D state.
To determine the mechanical quality of the steel sheet 316L, some elastic test samples are prepared and adjusted to the standard in Fig.10 and the results of the elastic test reached as a stress-strain curve in Fig.11. To define the features of the sheet into software, the isotropic sheet is supposed and the plastic behavior is estimated based on Eq. (3). The mechanical properties of the sheet are shown in Table 1. Moreover, to specify the features of the rubber layer, the samples of pressure tests are provided based on the standards of Fig. 12. Since the rubber layer is nonlinear and incompressible, Mooney- Rivlin model is used to describe rubber property, which was introduced to the software point by point as it is in Fig. 13.
In order to decrease the process analysis time, the die set and the preserver container were simulated as analytical rigid parts, but for the sheet and the rubber layer with 0.03 and 0.06, CPE4R element for sheet and rubber were simulated, respectively.
The aim of simulation process is to investigate the effects of the die clearance amount on the channels deepness uniformity. Moreover, a die with the less number of channels is used to decrease the process analysis time.

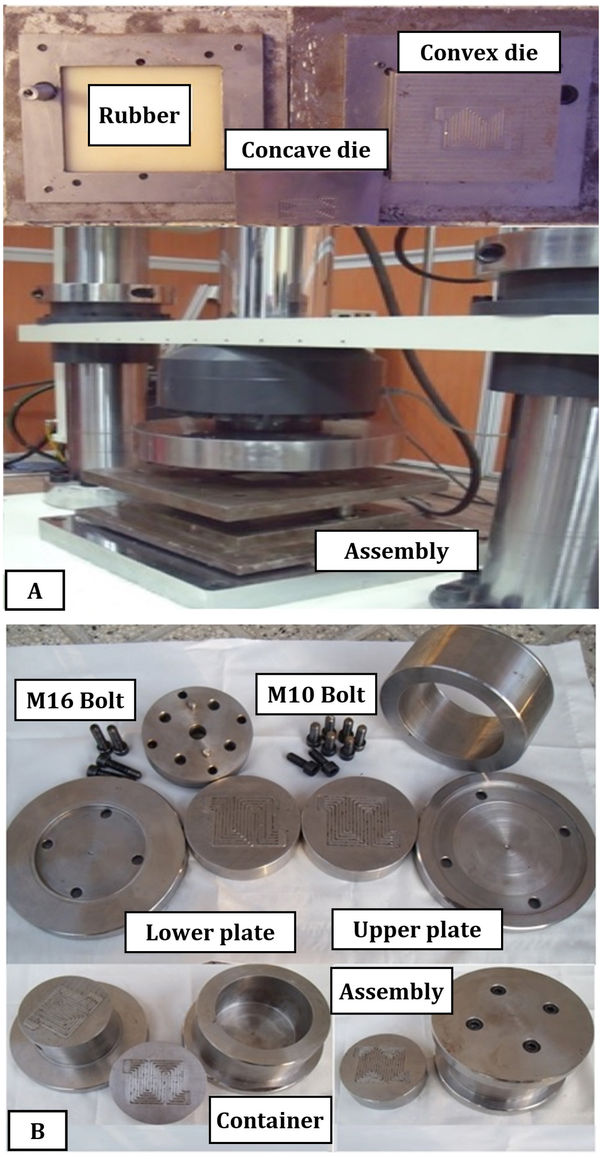

Fig. 7. Set of dies used to forming the plates, A) set template with 2 mm clearance between the punch and matrix, B) die with 0.01 mm clearance

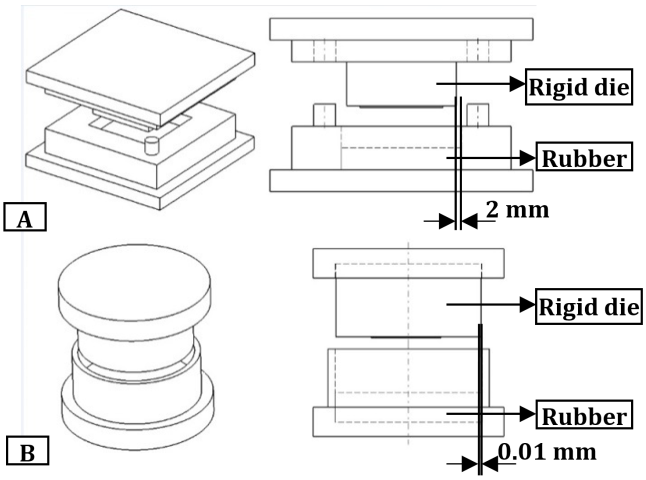

Fig. 8. The difference between the two sets of templates, A) Set template with a clearance of 2 mm, B) Set template with a clearance of 0.01 mm

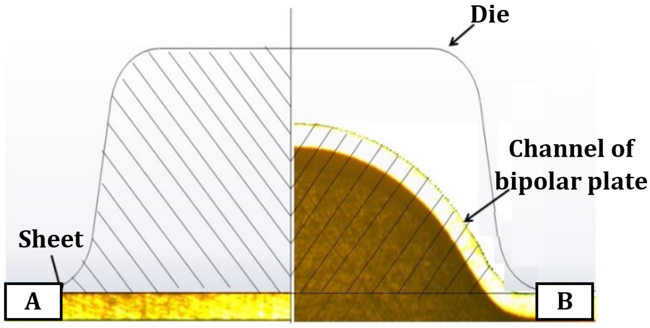

Fig. 9. The measure of filling percentage, A) Before forming, B) after forming

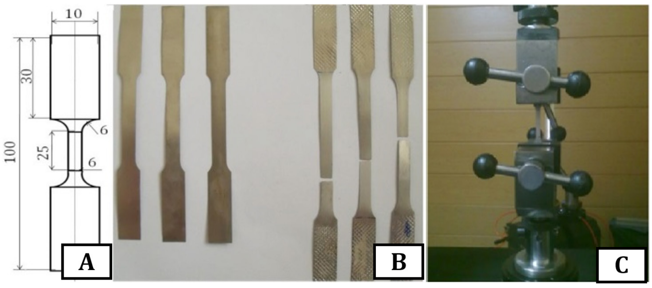

Fig. 10. Tensile test of sheet steel plate austenitic 316 A) size of the sample, B) samples taken, C) tensile testing machine

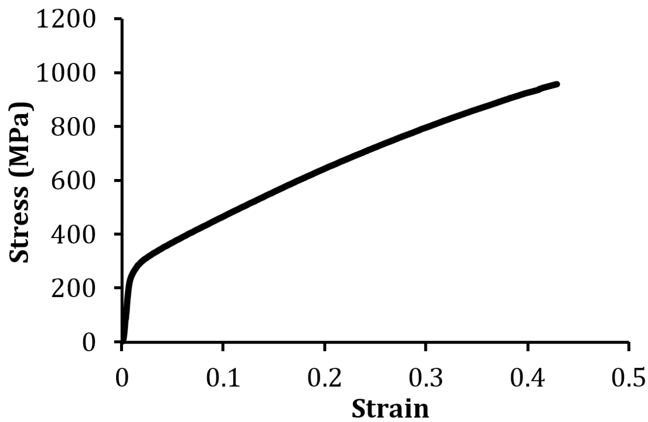

Fig. 11. True stress-strain curve of 316 austenitic stainless steel

Fig. 12. Samples of rubber pressure test and the applied device

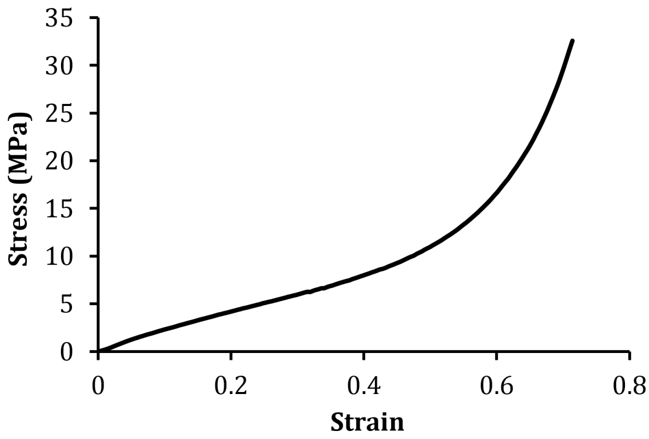

Fig. 13. Tension diagram according to Polyurethane rubber with hardness shore A 85

$$\text{Filling percentage}=\frac{\text{filled area of formed channel}}{\text{total area of die channel}} * 100 \qquad (1)$$

$$\text{Thinning percentage}=\frac{t_0-t_f}{t_0} * 100 \qquad (2)$$

$$\sigma=K(\varepsilon_0+\varepsilon)^n \qquad (3)$$

Table 1. Mechanical properties of stainless steel 316 sheet

Mechanical properties	Value
Young's modulus (E, GPa)	200
Poisson's ratio (v)	0.3
Yield stress (σ_y, MPa)	296
K, MPa	1512
n	0.53
ε_0	0.04

4- Results and Discussions

At first, four channels of a bipolar sheet were studied experimentally and simulated in order to investigate the interaction of channels on each other. Then, the effect of the die clearance amount on the filling channel depth uniformity is evaluated by the help of simulating results and after that, a die set is created despite the existence of the clearance between punch and matrix and the results are investigated in a die with clearance.

4- 1- The accuracy of the simulating results

To confirm the simulating results, some samples in the forces of 25, 35, and 45 kN are shown experimentally. Fig. 14 compares the channels filling depth in both experimental and simulating status. As shown in the figure, the maximum difference between the experimental and simulating is 5% that clarifies a good congruity between them. After the assurance of the simulating results, the effects of the die clearance were examined simulated on the filling channel depth uniformity.

4- 2- The effect of die clearance amount on the uniformity of channels depth

Fig. 15 compares the effect of the die clearance on the uniformity of channel depth in the similar filling depth. As illustrated in this figure, when clearance is applied between the die punch and matrix, the uniformity of the depth of the channel would be better. Thus, in 2 mm clearance status, the difference of channel filling depth to the non-clearance status from channel 1 to 4 is so less.

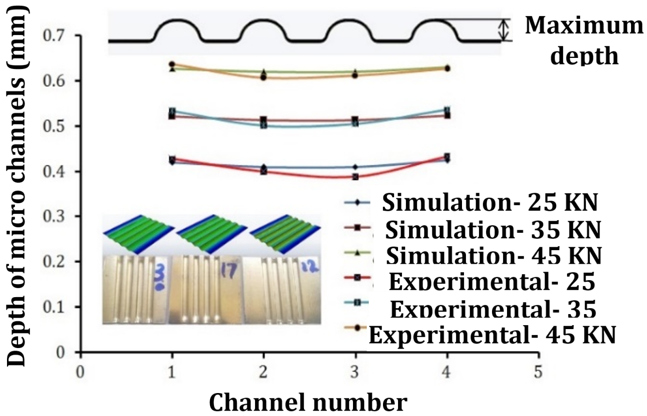

Fig. 14. Uniformity of depth filling in convex pattern die under different loads

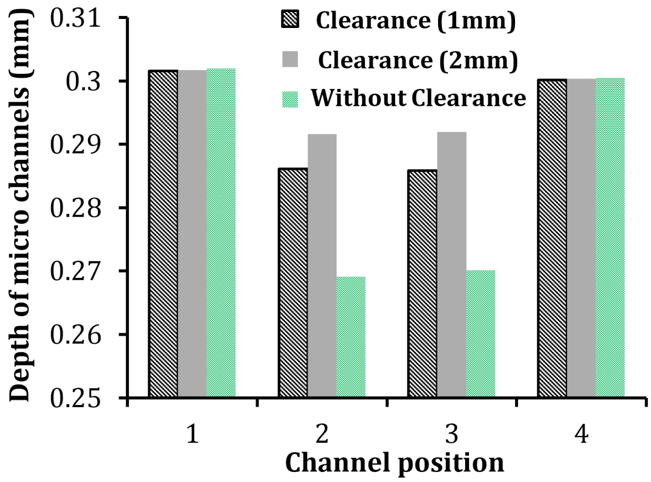

Fig. 15. The impact of die clearance of the uniformity of the channel depth

To show the amounts, the error percentage formula is used based on Eq. (4). In this equation, hm is the average of the measured channels and hk shows the depth of the channel in each phase. Parameter e also shows the error percentage of channel depth no uniformity. The error percentage for the three statuses of being without clearance, clearance 1mm, and clearance 2mm is shown in Table 3.

$$e=\frac{|h_m-h_k|}{h_m}\times 100 \qquad (4)$$

Table 2. Percentage error of the uniformity of the channel depth in the die of a clearance and without clearance

Channel position	Without clearance	Clearance (1mm)	Clearance (2mm)
1	5.80	2.77	1.79
2	5.72	2.48	1.61
3	5.35	2.57	1.50
4	5.27	2.28	1.33

After studying simulation results, a die set with 2 mm clearance was made between the punch and matrix and the effect of this set on forming a bipolar sheet was completely studied.
Having similar channel depth in a bipolar sheet is one of the advantages of bipolar sheets that means all channels should have similar channel filling depth or they should be located in a specific tolerance area. Otherwise, the sheet operation in fuel set would have a problem; hence, the set efficiency and operation decrease.
After forming, the bipolar sheet is cut and measured in nine different positions which contains three channels (h1, h2, and h3) on the left, three channels (h4, h5, and h6) in the center, and three channels (h7, h8, and h9) on the right (Fig. 16).

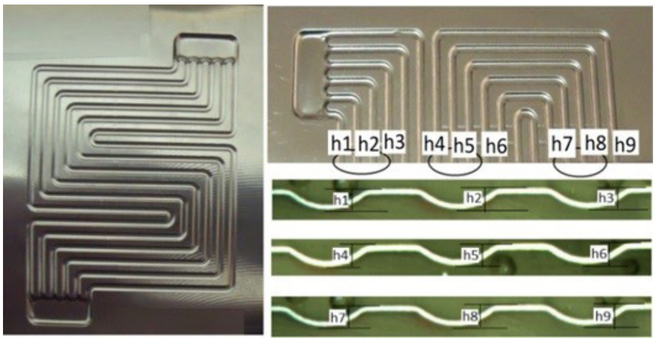

Fig. 16. Longitudinal section to evaluate the uniformity of the channel depth

Fig. 17 is depicted to show the channel depth uniformity in the convex pattern for different forces. The error percentage of channel depth uniformity that is attained by Eq. (4) is shown in Table 3.

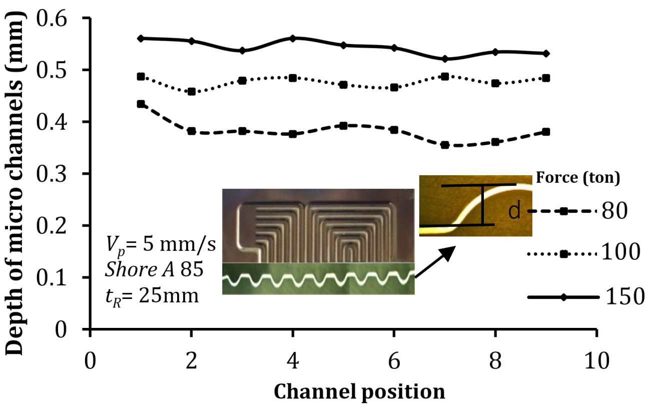

Fig. 17. Channel filling depths in different situations in longitudinal cutting in the convex die.

By comparing the data in Fig. 17 and Table 3 it is obvious that the pattern of the produced channel uniformity depth is convex and the average of the error percentage is about 2 %. Moreover, the other elements that cause this measure difference are the results of the measuring and preparing errors. Because of the sheets thinness, sanding and polishing the surface should be done with a high delicacy, however, the operator error percentage is so high during this process, thus the differences of filling depth channels can be admissible.
The amount of channel depth uniformity for a concave pattern in maximum forces is shown in Fig. 18. Increasing the force more than 100 ton does not have any effect on increasing the flow channel depth. It just increases the pressure on the rubber layer and destroys it. Because of the channel little space in a concave pattern, the rubber layer is unable to lead the sheet into the channels, thus it flows out from the clearance, which exists between the punch and matrix. As a result, increasing the forming force, and as observed in Fig. 19, makes a change in the rubber form. The error percentage of channel depth non-uniformity in the concave pattern is shown in Table 4. The measured error percentage average for the concave pattern is calculated about 3 %. After investigating the sheet forming in the die set with a clearance between the punch and matrix, it was specified that the uniformity of the channel depth is accurate in this set. The dimensional accuracy intensification and the channels depth uniformity are because of changing the form of the rubber layer, which is more uniform, and the focus of the rubber movement in the sides decreases. Therefore, the existence of clearance causes the rubber layer out from the clearance distance and makes a channel filling depth uniformity.
The only problem regarding the die with clearance is the destruction of the rubber layer after some forming operations. The filling amount is also fixed for the concave pattern, and increasing the force just causes more change in the rubber layer, accordingly, it changes the form of the rubber layer.
In order to increase the rubber layer life and decrease the cost of the final workpiece- because of the rubber layer high cost- and also increase the channel depth, the reformed die set is made. The amount of clearness decreased into the minimum possible amount and the height of the container became more

Table 3. Error percentage of uniformity in channel depths in the convex die

Channel position	80	100	150
1	13.4	2.14	3.17
2	0.34	3.92	2.20
3	0.34	0.48	1.19
4	1.71	1.62	3.17
5	5.4	1.17	0.75
6	0.34	2.27	0.21
7	7.20	2.15	4.10
8	5.84	0.61	1.66
9	0.69	1.59	2.15

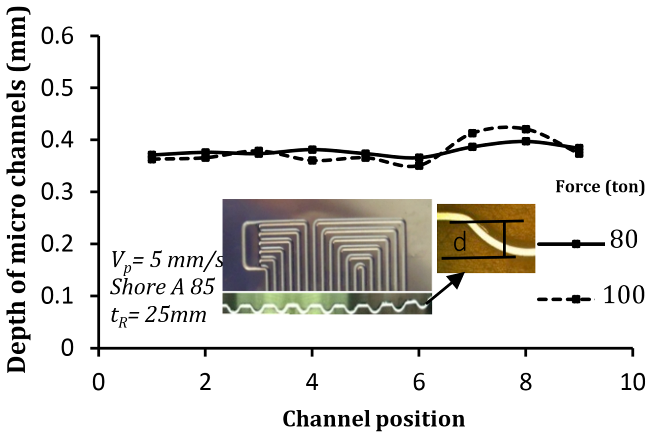

Fig. 18. Channel filling depths in different situations in longitudinal cutting in the concave die.

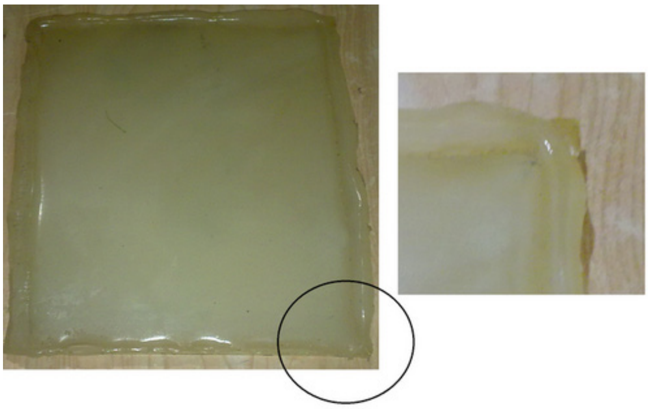

Fig. 19. Plastic deformation and destruction of the rubber pad after several actions forming

Table 4. Error percentage of uniformity in channel depths in the concave die

Channel position	80	100
1	2.08	3.66
2	0.7	2.96
3	1.38	0.52
4	0.7	4.36
5	1.38	2.96
6	3.47	6.96
7	2.08	9.59
8	4.86	11.69
9	1.38	0.87

than the height of the rubber layer. As a result, the rubber layers do not have any way but filling the channel's holes.
Filling depth profile of the convex sample in two maximum forces is shown in Fig. 20. It is obvious that increasing the force will cause tearing in channel sheet flow. By calculating the filled area of formed channel to total area of die channel, the percentage of filling was calculated with a high accuracy. Table 5 shows the geometrical features of the produced final sheet.

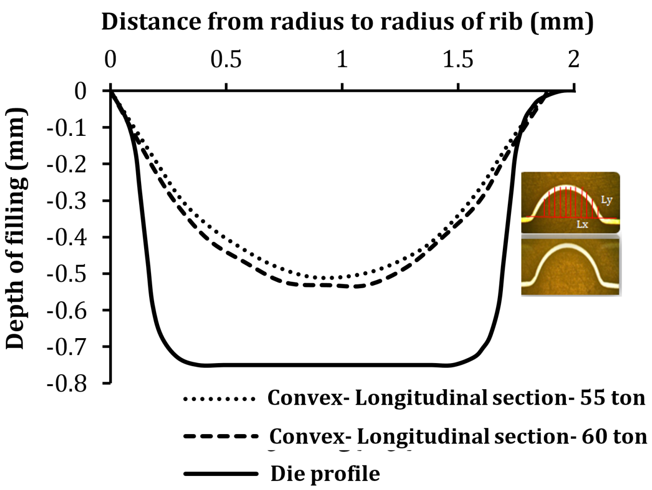

Fig. 20. Filling Profile samples of the convex die in the longitudinal direction.

Table 5. Final geometrical produced plates

Geometric parameters	Convex plates (%)	Concave plate (%)
Filling percentage	60	49
Thinning percentage	26	32

To study the way of the sheet thickness distribution in two anode-cathode surfaces and flow channel in two convex and concave patterns, the thickness was measured in three zones of the sheet based on Fig. 21. As it is shown, zone A shows flow channel, zone B shows the angle radius and the wall angle, and zone C shows the anode-cathode surface. The fewer changes in thickness occur in zone A because the sheet is bounded between the die and the rubber layer, thus due to the increasing friction forces, it is difficult for the sheet to flow. The less thickness changes occur in zone A because the sheet is bounded between the die and the rubber layer. This is because of friction that the flow of material harder into the die.

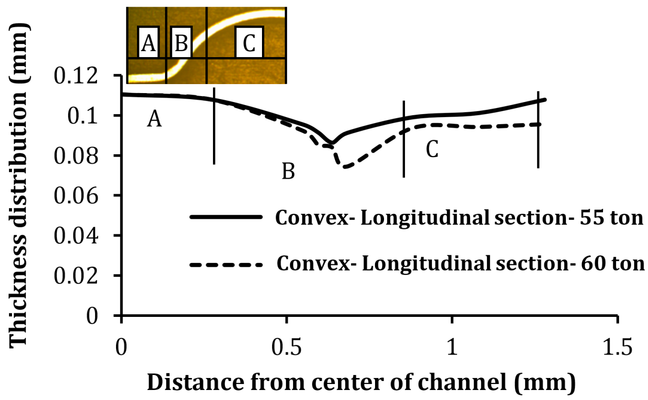

Fig. 21. Measuring sheet thickness in three regions of a channel in the convex die at longitudinal section

The most thinness in the sheet occurs in zone B that is because of the sheet tension for filling the die hole. The least amount of the sheet thickness in this zone is measured 0.074 mm, which is achieved by a 60 tons force. Distributing the sheet thickness has an increasing process from zone B to C, which is because of decreasing tension in this zone.
The filling depth profile in maximum force is shown in Fig. 22. The force of 55 tons is the maximum force that the sheet can endure.The shown profile in the figure is the maximum filling depth that a sheet can endure without tearing. Fig. 23 shows the concave sample thickness distribution in two forces of 55 tons and 60 tons. In a 55 tons force, the least thickness has been occurred in zone B and is calculated to be 0.069 mm. Byincreasing the force to 60 tons, tearing on the wall and the bottom of the channel occur. When the force increases, the applied force from the rubber to the sheet increases. Since C is forming in the concave die, because the flow channel width is smaller than the width of anode-cathode channel, the sheet reaches to the boundary of rupture before filling the channel's hole.

4- 3- Comparing the die filling depth with clearance and without clearance

Figs. 24 and 25 compare filling depth profile of the convex and concave pattern in the maximum filling depth for both dies with clearance and without clearance. Based on Fig.

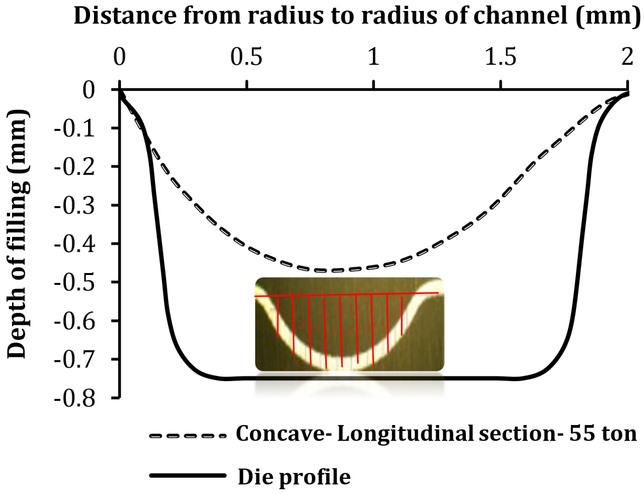

Fig. 22. Filling Profile samples of the concave die in longitudinal direction

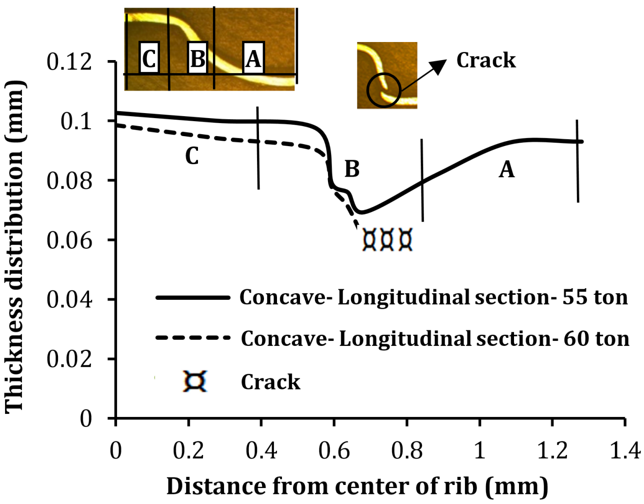

Fig. 23. Measuring sheet thickness in three regions of a channel in the concave die at longitudinal section

24, the difference of filling percentage in convex pattern between the die with clearance and without clearance is so low, which is about 1 %. The former results show that the channels filling depth in the concave pattern with clearance are limited. Because by increasing the force in the concave pattern the filling depth is changeless, increasing the force causes the rubber layer destruction and rupture. Since flow channel of a bipolar sheet in a concave pattern is forming, the flow channel depth is less than the anode-cathode surface width; the rubber layer does not have the capacity to lead the sheet into the channel hole and applying more force just causes more changes in the form of the rubber layer. But in the improved die, the clearness decreases to a minimum amount, hence the rubber layer does not have any way but filling the channel's hole.

By attending to Fig. 25, it is clear that in the improved die the filling amount percentage in the concave pattern increases 9 % than the die with 2 mm clearance.

4- 4- The produced sheets features

Figs. 26 and 27 show the best produced sheets from the improved concave and convex die, which have the most

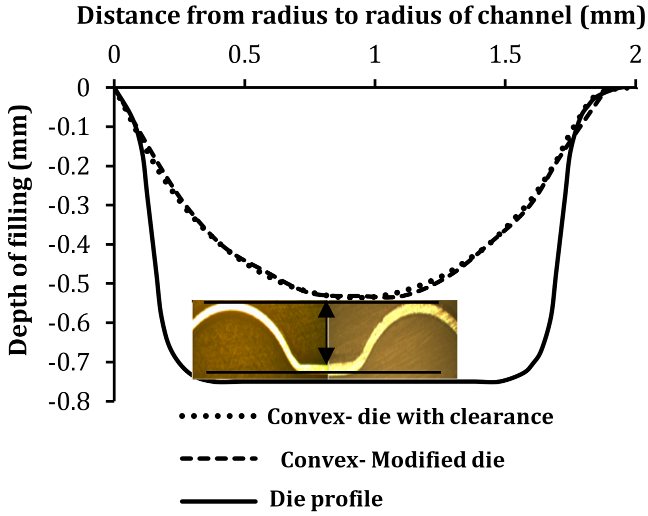

Fig. 24. Compare Profiles filling in a convex pattern in two form of die, first die with clearance and second die without clearance in a maximum depth of filling for both of them.

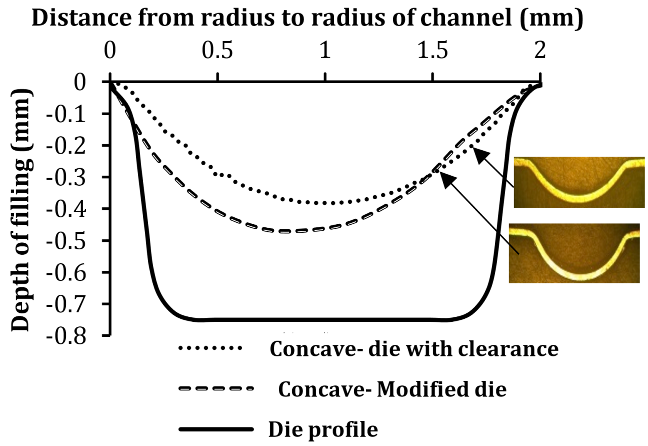

Fig. 25. Compare Profiles filling in a concave pattern in two form of die, first die with clearance and second die without clearance in a maximum depth of filling for both of them.

filling percentage and the least thinness. Table 5 also shows the measured geometrical features of the final sheets.

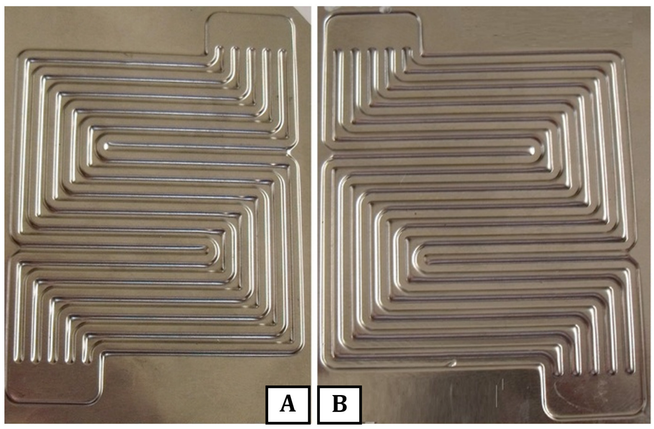

Fig. 26. A sample of a metal bipolar plate fabricated by rubber pad forming with convex die, (A) front of the bipolar plate and (B) back of the bipolar plate.

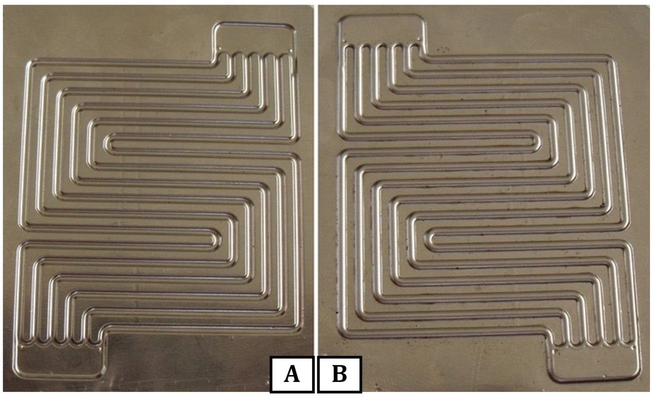

Fig. 27. A sample of a metal bipolar plate fabricated by rubber pad forming with concave die, (A) front of the bipolar plate and (B) back of the bipolar plate.

5- Conclusion

In this research, by using SS316L in forming bipolar rubber sheets with form changing the concave and convex pattern, it is shown that in the convex pattern the anode-cathode pattern is forming and in concave pattern flow channel surface forms. The die sets that can be used in rubber forming process is the die with clearance between the punch and matrix and also the die set with the least clearance. At first, the effect of the clearance amount on channel depth uniformity was simulated and investigated in a die with the less number of channels. Then, two sets were made for the complete bipolar sheet and the following results were achieved:

a. When clearance is applied to punch and matrix die, it causes channel depth uniformity, however, it destroys the rubber layer after some forming operations.

b. In forming process with the rubber layer, the life of the rubber layer increases and the forming operation will be done easier if the punch can move in the matrix easily and the rubber container height is more than the rubber layer, in which the forming process can be done.

c. The filling percentage difference in convex pattern is insignificant for both of the die sets with clearance and without it; however, the rubber layer life in the die set with clearance is too low that will lose its efficiency after some rubber layer forming operations.

d. The filling percentage for the two die sets with clearance and without clearance for the concave pattern is 9 %. Therefore, in the die set with clearance increasing the force does not have any effect on the channel filling depth and it just causes a high change in the form of the rubber layer. However, in the die set without clearance, the filling depth amount and the rubber layer life increase.

e. If the channel depth is low and the rubber layer hardness is high because it has more resistance against changing the rubber form, using the die set with clearance is preferable since there is more uniformity in channel depth. However, when the flow channels depth increases, the die set without clearness has more ideal results and the rubber layer life increases.

References

[1] S.C. Singhal, K. Kendall, High-temperature solid oxide fuel cells, fundamentals, *design and applications*, Elsevier, 2003.

[2] L. Ma, S. Warthesen, D. Shores, Evaluation of materials for bipolar plates in PEMFCs, *Journal of New Materials for Electrochemical Systems*, 3(3) (2000) 221-228

[3] H. Wang, J. Turner, Reviewing metallic PEMFC bipolar plates, *Fuel Cells*, 10(4) (2010) 510-519

[4] S. Mahabunphachai, A Hybrid Hydroforming and Mechanical Bonding Process for Fuel Cell Biopolar Plates, (2008)

[5] V. Mehta, J.S. Cooper, Review and analysis of PEM fuel cell design and manufacturing, *Journal of Power Sources*, 114(1) (2003) 32-53

[6] Y. Liu, L. Hua, J. Lan, X. Wei, Studies of the deformation styles of the rubber-pad forming process used for manufacturing metallic bipolar plates, *Journal of Power Sources*, 195(24) (2010) 8177-8184.

[7] C.Y. Son, Y.P. Jeon, Y.T. Kim, C.G. Kang, Evaluation of the formability of a bipolar plate manufactured from aluminum alloy Al 1050 using the rubber pad forming process, Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 226(5) (2012) 909-918

[8] C.K. Jin, M.G. Jeong, C.G. Kang, Fabrication of titanium bipolar plates by rubber forming and performance of single cell using TiN-coated titanium bipolar plates, *International Journal of Hydrogen Energy*, 39(36) (2014) 21480-21488

[9] M.B.Osia, M.B.Jooybari, S.J.Hosseinipour, A.Gorji, The Experimental and Simulation Investigation of Process and Geometrical Parameters for Hydroforming of Pin-type Metallic Bipolar plates, *Modares Mechanical Engineering*, 15(7) (2015) 215-226

[10] M. Elyasi, F.A. khatir, M. Hosseinzadeh, Experimental study of the die patterns in rubber pad forming process for production of metallic bipolar plates, *Modares Mechanical Engineering*, 15(9) (2015) 179-186

[11] M. Elyasi, F.A. khatir, M. Hosseinzadeh, Lubricant effect on depth fling of metallic bipolar plates with concave and convex patterns in rubber pad forming process, *Modares Mechanical Engineering*, 15(12) (2015) 450-460

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