Iranica Journal of Energy & Environment 4 (2): 91-98, 2013
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
DOI: 10.5829/idosi.ijee.2013.04.02.03

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Forming Metallic Micro-Feature Bipolar Plates for Fuel Cell Using Combined Hydroforming and Stamping Processes

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(Received: August 10, 2012; Accepted in Revised Form: February 12, 2013)

Abstract: Fuel cell constitutes from different components, among which bipolar plates are the important and expensive part. Nowadays, the fabrication methods of bipolar plates are the main challenges in fuel cell technology. Among different methods, the fabrication of bipolar plates from metal forming processes is the best selection. Recently, hydroforming is one of these methods that are used in fabrication of these plates. On the other hand, there are different layouts of flow fields for various usages. These layouts can be categorized, in forming viewpoint, to two distinct groups; one of them is the simple group (e.g. serpentine or parallel flow fields) and the other is the complex group (e.g. pattern and pin type flow fields). This paper investigate on feasibility of a hybrid micro-manufacturing process to fabricate fuel cell metallic bipolar plates that consists of multi-array pin type flow field on a large surface area. First, several forming methods for formation of bipolar plates in the FEM software (ABAQUS 6.10) were simulated. Second, the best method for actual fabrication of metallic bipolar plates without any rupture or defect was hydroformed. The results indicated that the complex flow field metallic bipolar plates can be formed adequately using the combined hydroforming and stamping (sizing) processes.

Key words: Metal sheet forming · Bipolar plates · Hydroforming · Stamping.

INTRODUCTION

Bipolar plate is an important part among the fuel cell components. Selection of the plate material, design the geometry of flow field on this plate and the fabrication method are the main issues in fuel cell knowledge. Nowadays, research about proton exchange membrane fuel cells (PEMFCs) for vehicle applications has been widely developed. In order to produce bipolar plates, different types of materials such as: 1) graphite plates [1, 2], 2) composite plates (Polymer-graphite composite plates [3-5], Carbon/carbon composite plates) [6], 3) metal foam plates, 4) metallic plates (with or without coat) [7-10] have been utilized. Recently, among these materials, metallic bipolar plates, especially stainless steel plates, have received considerable attention due to their low cost, excellent mechanical, electrical and thermal properties and good manufacturability [11, 12]. Moreover, metallic bipolar plates have highest power density in compare to other materials (Fig. 1) [11].

To achieve the best efficiency in various usages, different kinds of flow field are used to design the flow field of bipolar plates. As it is impossible to gain fully homogeneous conditions over the entire active electrode area with respect to temperature, reactant concentrations and humidity, always a compromise has to be made. Heinzel *et al*. [13], investigated various kinds of flow fields. They classified flow fields into four different types (Fig. 2):

- Pin-type flow field
- Parallel channels flow field
- Serpentine flow field
- Interdigitated flow field.

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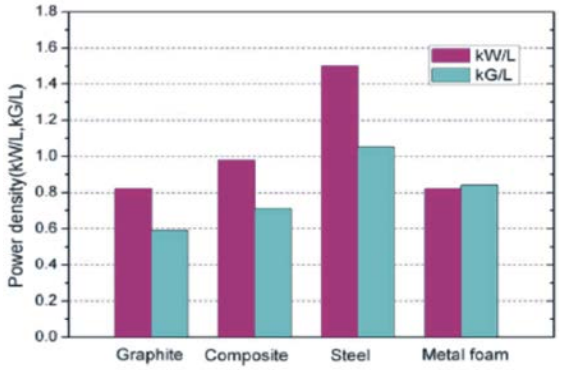

Fig. 1: Comparison of different materials in terms of kW/l and kW/kg [11].

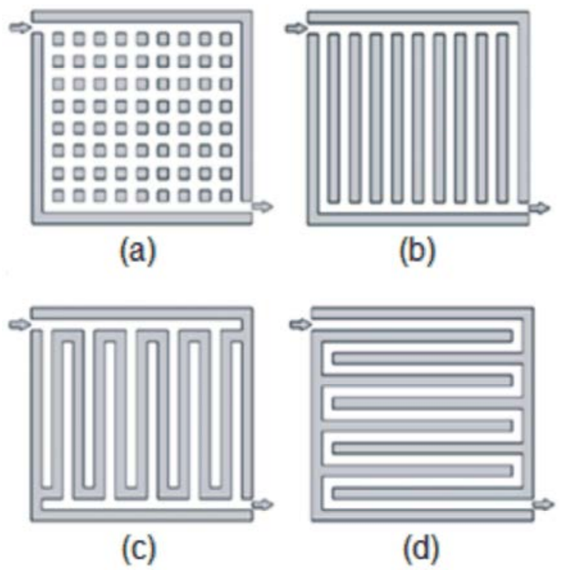

Fig. 2: Schematic drawing of a) pin-type flow field, b) parallel channels flow field, c) serpentine flow field and d) interdigitated flow field [13].

Fabrication methods of bipolar plates can refer following candidates: (1) machined graphite plates, (2) molded polymer-carbon composite, (3) molded carbon-carbon material, (4) electro machining and photo etched metal plates (with and without coatings) and (5) formed metallic plates (with and without coatings). Different methods of fabricated bipolar plates are shown in Fig. 3.

In recent years, in the field of metallic bipolar plate forming, limited researches have done on serpentine flow field design. For instance, Liua *et al*. [15] studied the feasibility of rubber pad forming in forming of metallic bipolar plates and forming parameters of this method. Their have showed that convex die is suitable for narrow channel while concave die is suitable for wide channel.

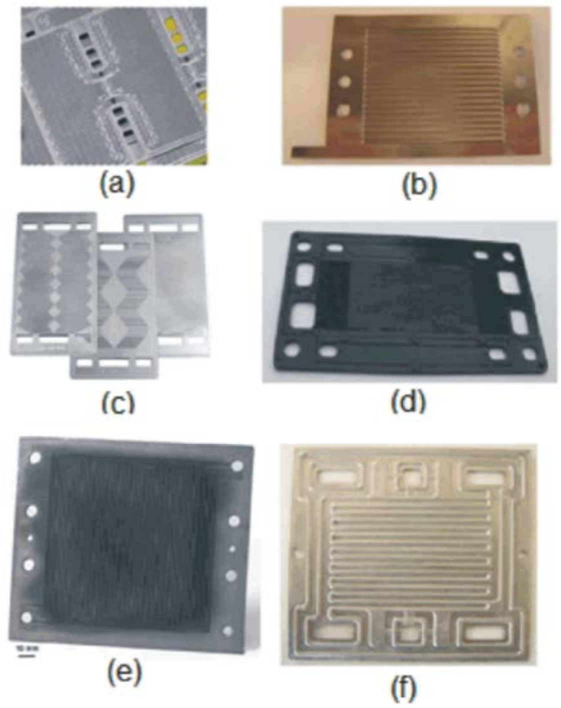

Fig. 3: Single bipolar plate of (a) machined graphite (Graftech Co.), (b) stamped stainless steel sheet (GenCell Corp.), (c) photo etched stainless steel/titanium plate (Tech-etch, Inc.), (d) molded polymer-carbon composite , (e) molded carbon-carbon material and (f) sheet metal forming (rubber pad forming) of stainless steel [11,14].

A group of collaborators consisting of American Trim, the Ohio State University and General Motors [16] have developed a commercially viable prototype production process to manufacture metallic fuel cell bipolar plates in which electromagnetic coils and forming dies were integrated. Furthermore, Koc and Sasawat [12, 14, 17] investigated forming of metallic bipolar plates with hydroforming process. Although, many researchers have been carried on forming of different types of flow fields; but they are limited to the forming of serpentine pattern.

All these researches were carried on the serpentine flow fields and did not discover any report about forming of metallic bipolar plates with pin-type flow fields. Because forming this type of bipolar plate flow fields (pin-type) is more complex than other flow fields. Therefore, performing an investigation on forming this case is very important.

In this research, a novel manufacturing process for forming of metallic bipolar plate with pin-type flow field design was proposed. Two methods of hydroforming

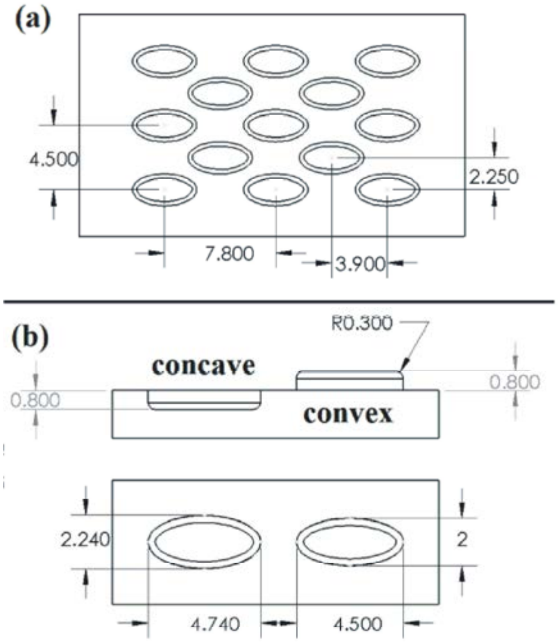

Fig. 4: Dimensions of convex and concave pattern dies.

Table 1: Chemical compositions of the SS304 sheet (wt.%).

Fe	Co	Mo	Ni	Cr	Mn	C
Balance	0.08	0.19	8.85	18.1	1.29	0.064
	Al	V	Cu	Si	S	P
	0.001	0.096	0.27	0.31	0.005	0.03

process were studied with the FEM software (ABAQUS 6.10) and validated by experimental tests. These two methods are:

- Hydroforming with concave die
- Hydroforming with convex die

After simulation of the process, the most appropriate method of hydroforming process was selected which lead to the best thickness distribution and shape of desired flow field design.

Experimental Setup and Methodology: Multi-array pin type flow field that was studied in this research is shown in Fig. 4. Figure 4a is the flow field pattern and Figure 4b is the convex and concave pins. The size of the concave pattern is about twice the sheet thickness larger than that of the convex pattern. Forming of the pin type pattern is difficult because of the complexity and accuracy of the shape as well as the short distance between the patterns.

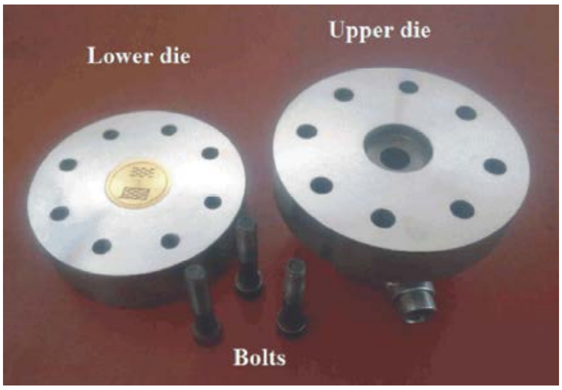

Fig. 5: Photograph of the forming die for the experiments.

Fig. 6: Photograph of the forming equipment for the experiments.

Sheet metal used in this study is stainless steel 304 with thickness 110ìm. Chemical compositions of the SS304 sheet (wt.%) is shown in Table 1.

Fig. 5 shows the die set used in this paper. It consists of upper die, lower die, die insert and some bolts. The die insert was made from brass and the two dies were made from steel SPK. The patterns were machined on the die insert with a CNC machine.

Fig. 6 shows the equipment for forming of metallic bipolar plates. It consists of a 40 tons hydraulic press and a pressure unit.

Table 2: Mechanical properties of the SS304 metal sheet[7]

E (Gpa)	194
Y	0.3
σ_y (MPa)	344
K (MPa)	1436
N	0.586
ε_0	0.054

The true stress strain curve is approximated by $\bar{\sigma} = K\left(\varepsilon_0 + \bar{\varepsilon}^p\right)^n$. E: Young's modulus; υ: Poisson's ratio; σ_y and : yield stress.

Fig. 7: Schematic of a) convex and b) concave die in ABAQUS software.

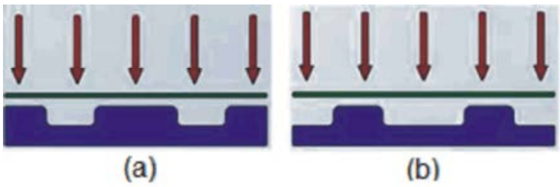

Fig. 8: Sketch of hydroforming: (a) concave die, (b) convex die.

Numerical simulation

Finite element modeling: For simulation of the process, ABAQUS 6.10 was utilized. The mechanical properties of stainless steel 304 sheet are shown in Table 2.

In the simulation, the behavior of sheet metal was assumed to be isotropic and modeled as a 3D deformable shell. Also, the die set was modeled as 3D discrete rigid elements. As shown in Fig. 7, the geometry of the die consists of one ellipse with four quarters of adjacent ellipses.

The friction coefficient between the sheet and die for hydroforming process was supposed 0.1 and that for stamping process 0.15. The boundary condition of the sheet was fixed at edges along lateral and longitudinal and free along height. For meshing of elements, Quad-dominated mesh with mesh size 0.0001 was used. After introducing the parameters, two different methods of hydroforming process were modeled in the simulation software; that are shown in Fig. 8. These methods are:

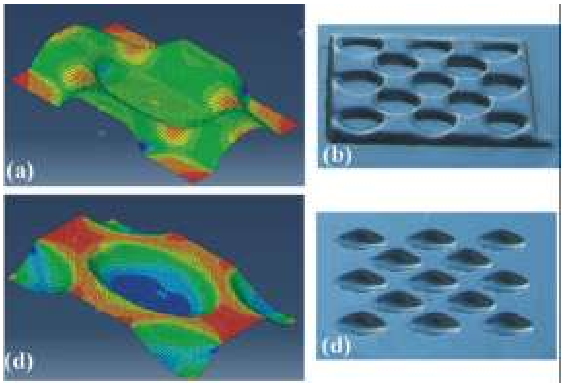

Fig. 9: Validation of FEM results with experimental samples.

- Hydroforming with concave die
- Hydroforming with convex die

Following the forming process, for achieving the best geometry accuracy of bipolar plates, a final step of stamping was used to size the bipolar net shape. Therefore, in this work four cases were studied. After simulation of the process, thickness distribution and filling percent of the metallic bipolar plates formed have been studied.

Validation of FEM Model: In order to determine the accuracy of the FE model, the results of FE model were verified using experimental tests. Accordingly, based on the pattern, samples with 13 patterns for the two cases of convex and concave dies were formed (Fig. 9). As shown in the figure, filling depth of patterns obtained from the simulations is generally in agreement with that of the experiments.

In order to examine the validation more closely, the convex pattern have been selected. For investigation of filling percent, d/D or l/L ratio (Fig. 10) was defined (Eq. 1) [15].

$$filling\ percent = \frac{d}{D} \times 100 = \frac{l}{L} \times 100 \quad (1)$$

Liu *et al* [15] used the above ratio to determine the filling percent for of bipolar plates with grove profiles. In convex pattern, the depth of the formed pattern was measured and compared with the simulation results (Fig. 11). The depth is 0.558 mm for experimental and 0.566 mm for simulation results.

$$filling\ percent(EXP) = \frac{0.558}{0.8} \times 100 = 69.75 \quad (2)$$

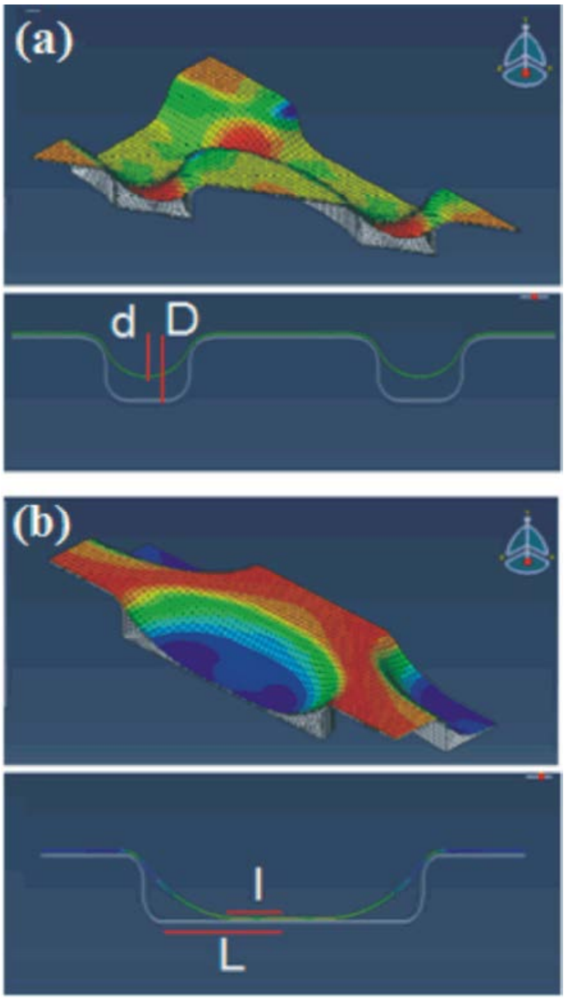

Fig. 10: Definition of filling percent, a) convex die, b) concave die.

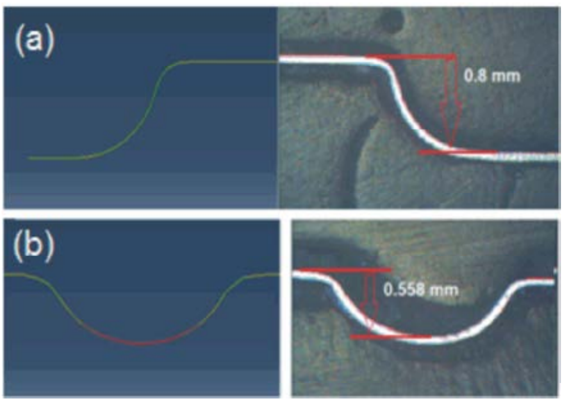

Fig. 11: Comparison of the depth of the formed pattern in convex case obtained from experiment and simulation, a) lateral direction b) crisscross direction.

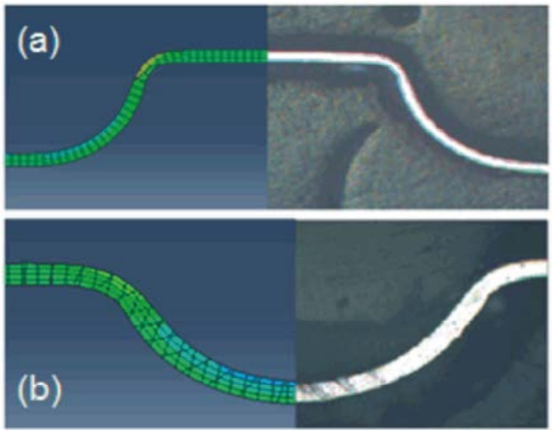

Fig. 12: Comparison of the sheet thickness of the formed pattern in convex case obtained from experiment and simulation, a) lateral direction b) crisscross direction.

$$filling\ percent\ (SIM) = \frac{0.566}{0.8} \times 100 = 70.75 \qquad (3)$$

The above equations show that filling percent of simulation (70.75%) is very close to that of the experimental one (69.75%). Also, to validate the thickness distribution of simulation results in lateral and crisscross directions, the sheet was modeled. As shown in Fig. 12, FEM results have good agreement with experimental ones.

RESULTS AND DISCUSSION

In this paper, two subjects were investigated. One of these is the filling percent of pattern profile and the other is thickness distribution of sheet metal. Both of these two subjects, for the two convex and concave patterns were examined for the longitudinal, lateral and crisscross sections. These sections are shown in Fig. 13.

Filling Percent: The filling percent of the three different sections for each of the two convex and concave patterns were studied. Then, the lowest filling percent for each pattern was specified as the critical zone of forming. In Fig. 14 the geometry of die and the deformed mesh for the two patterns are shown. As can be seen, the critical zone for hydroforming with convex pattern is at the center of the channel (Fig. 14c) and that for the concave die is at the corner of ellipse profile (Fig. 14e). These results were obtained at pressure of 750 bars. For concave pattern, the filling percent is 47.5%, while for convex pattern, it is 70.8%. For full filling of these areas, a final stamping is required for sizing the profile.

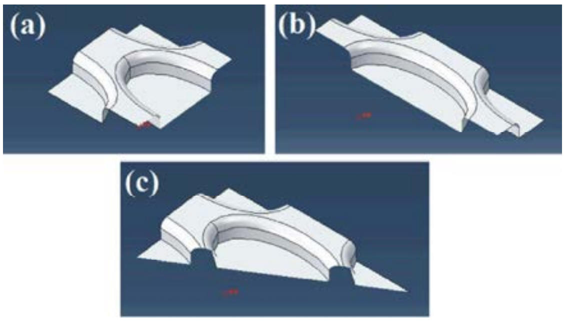

Fig. 13: Three sections investigated for thickness distribution; a) lateral, b) longitudinal, c) crisscross sections.

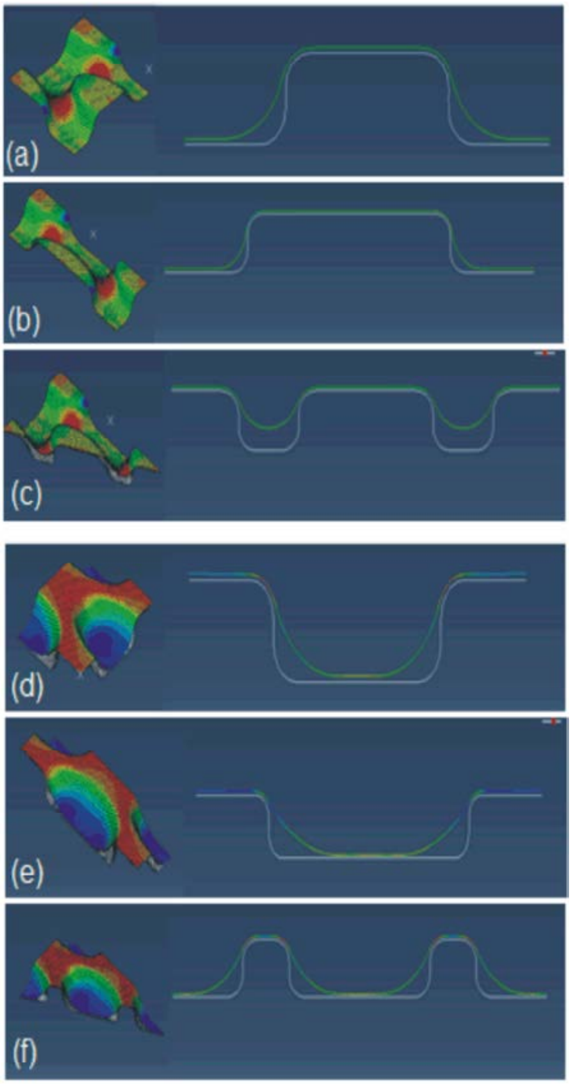

Fig. 14: Sections of filling profiles in lateral, longitudinal and crisscross direction; a, b, c) convex status; d, e, f) concave status

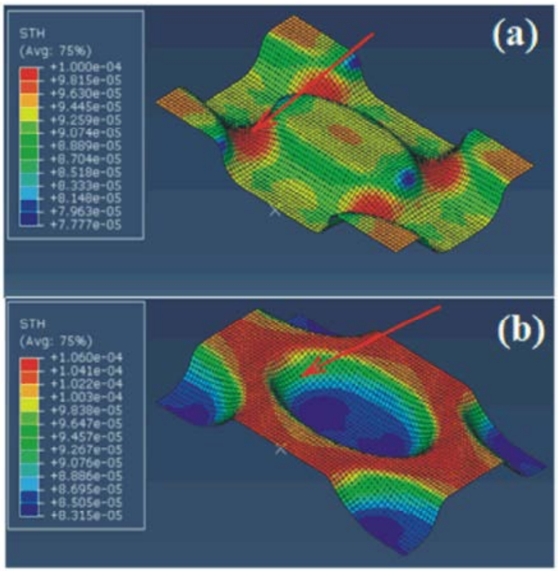

Fig. 15: The FEM geometry and thickness distribution, a) convex pattern, b) concave pattern

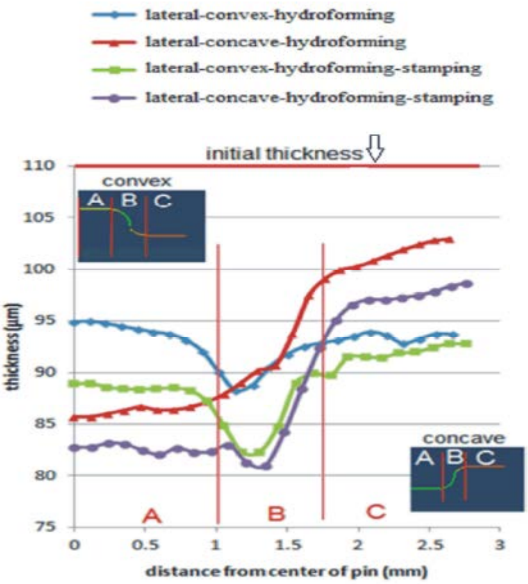

Fig. 16: Thickness variation of the formed parts in lateral sections.

Fig. 15 illustrates the deformed geometry and the thickness distribution for the two convex and concave patterns. In this figure, the arrows show the zones that should be stamped in the final stage of stamping die. As it can be seen, for the convex pattern the zone that should be stamped has the thickest thickness, while for the concave pattern has not. This shows the preference of using the convex pattern.

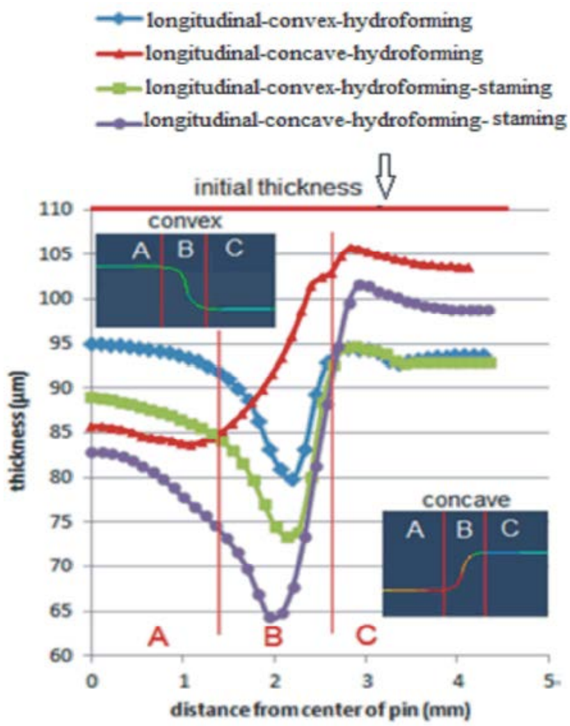

Fig. 17: Thickness variation of the formed parts in longitudinal sections.

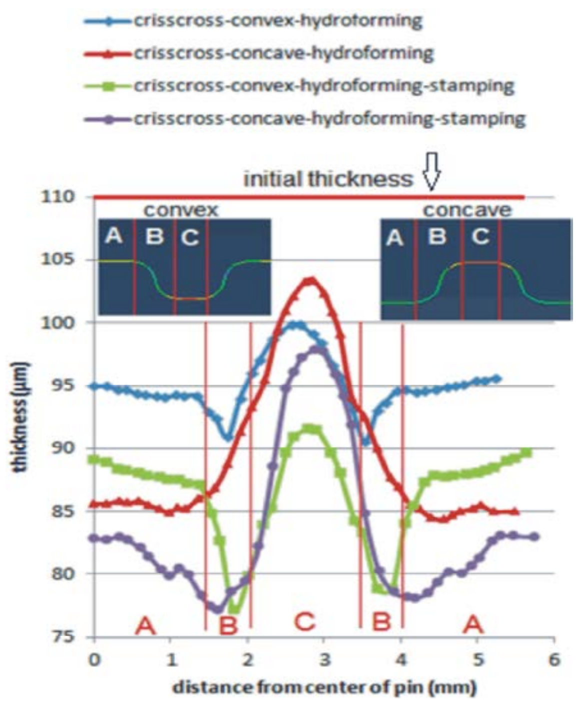

Fig. 18: Thickness variation of the formed parts in crisscross sections.

Thickness Distribution: In Figs. 16-18 the thickness distribution of the formed sheets, before and after final stamping for the two patterns are shown. One of the important points of bipolar plates is the uniformity of the sheet thickness. Moreover, because of chemical reaction that occurs in surfaces in contact with MEA, these surfaces should have appropriate thickness to increase the working life.

As shown in Fig. 16, in lateral direction, the sheet formed with convex profile (before and after stamping) has generally a better thickness distribution compared to that formed with concave profile. But, a different behavior can be observed in wall of pattern (region B) for concave case before stamping (the same behavior has occurred for longitudinal direction in Fig. 17). These behaviors are because of less filling the profile as shown in Fig. 14d and Fig. 14e, while the thickness distribution of this regions for concave pattern after stamping are thinner than that of the convex pattern. This is because of stretching of the region. Furthermore, as stated previously, the convex pattern has better filling percent

In Fig. 18 (crisscross direction), two ends of these curves shows top side of the pins (region A) and middle zone is the bottom of bipolar plate (region C). As shown in Fig. 18, in this direction too, sheet formed with convex pattern has more uniform thickness distribution than concave pattern. But in region C, thickness of sheet formed which is formed using concave pattern (before and after stamping) is higher than sheet formed by using convex pattern. This area related to top side of bipolar plates is shown in Fig. 14f. This difference is because of low deformation of these areas in concave pattern. Finally, convex pattern have better thickness distribution in this direction.

Also, after study the thickness distribution in these three directions, seen that the important areas of bipolar plate (region A that contact with MEA) that formed using convex pattern has higher thickness than concave pattern. So metallic bipolar plates that formed by using convex pattern have longer working life (because of uniform thickness distribution and higher thickness in region A) than metallic bipolar plates that formed by using concave pattern.

CONCLUSION

In this paper, two methods of hydroforming process (concave and convex pattern) were investigated for forming of metallic bipolar plates with pin type pattern (complex pattern). At first, these methods were simulated by FE model (ABAQUS 6.10). Then, experiments were formed for verification of FE model. After verification of FE results, these two methods were investigated for selecting the best forming method of metallic bipolar plates. In this investigation, filling percent and distribution of sheet metal thickness were studied after forming. Also, a final stamping step is necessary for sizing the formed profile because of lack of filling the profile by hydroforming. Moreover, after stamping, distribution of sheet metal thickness was investigated. In both cases (after and before stamping) it can be seen that convex pattern was better than concave pattern. According to this result, metallic bipolar plate that hydroformed with convex die has better filling percent and thickness distribution. So, metallic bipolar plates that formed with this method have better operation (because of better filling of pattern profiles) and longer working life (because of uniform thickness distribution). By using the combined hydroforming and stamping processes, appropriate and accurate metallic bipolar plates were successfully formed.

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