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Flow channel shape optimum design for hydroformed metal bipolar plate in PEM fuel cell

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Abstract

Bipolar plate is one of the most important and costliest components of polymer electrolyte membrane (PEM) fuel cells. Micro-hydroforming is a promising process to reduce the manufacturing cost of PEM fuel cell bipolar plates made of metal sheets. As for hydroformed bipolar plates, the main defect is the rupture because of the thinning of metal sheet during the forming process. The flow channel section decides whether high quality hydroformed bipolar plates can be successively achieved or not. Meanwhile, it is also the key factor that is related with the reaction efficiency of the fuel cell stacks. In order to obtain the optimum flow channel section design prior the experimental campaign, some key geometric dimensions (channel depth, channel width, rib width and transition radius) of flow channel section, which are related with both reaction efficiency and formability, are extracted and parameterized as the design variables. By design of experiments (DOE) methods and an adoptive simulated annealing (ASA) optimization method, an optimization model of flow channel section design for hydroformed metal bipolar plate is proposed. Optimization results show that the optimum dimension values for channel depth, channel width, rib width and transition radius are 0.5, 1.0, 1. 6 and 0.5 mm, respectively with the highest reaction efficiency (79%) and the acceptable formability (1.0). Consequently, their use would lead to improved fuel cell efficiency for low cost hydroformed metal bipolar plates.

Keywords: PEM fuel cell; Hydroforming; Flow channel; Reaction efficiency; Formability

1. Introduction

PEM fuel cells have been proposed as a promising power source for many applications, such as transportation systems, stationary cogeneration systems and portable systems, due to their high efficiency, high power density, fast startup, and system robustness [1–3]. But the PEM fuel cells are still too expensive for widespread commercialization. Bipolar plate is one of the most important and costliest components of PEM fuel cells and accounts to more than 80% of the weight and 30% of the total cost in a fuel cell stack [4]. Bipolar plates based on carbon materials have been the main focus of the development activities so far. However, further cost reduction and increases of power density are beneficial for fuel cell technology. Bipolar plates should require several properties to achieve the desired fuel cell stack performance that are electrical conductivity, gas tightness, chemical stability, lightweight and mechanical strength to withstand clamping forces. Also, an optimal bipolar plate should be low-cost and easily manufactured [1,4,5]. Bipolar plates made of micro-hydroformed metal sheets have many above advantages and are promising to replace traditional carbon bipolar plates in PEM fuel cells.Feasibility of the hydroforming process for fabrication of fuel cell bipolar plates has been studied by Koc and Mahabunphachai [6,7].

Flow channel shape design is a very important factor for full fuel cell stacks. A computational three-dimensional half-cell model for predicting the effect of different channels dimensions and shapes was developed by Kumar and Reddy [8]. Simulations were done ranging from 0.5 to 4 mm for different channel width, rib width and channel depth. Optimum values for each of the dimensions (channel width, rib width and channel depth) were obtained. For high hydrogen consumptions (∼80%), the optimum dimension values for channel width, rib width and channel depth were close to 1.5, 0.5 and 1.5 mm, respectively. Watkins

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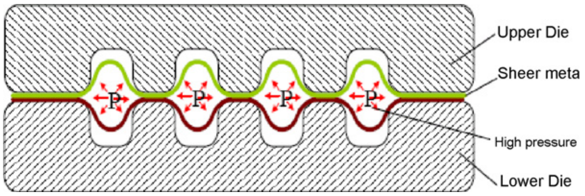

Fig. 1. Sketch of the hydroforming process.

et al. [9] studied the optimal dimension for bipolar channels on cathode side of the fuel cell. They claimed the most preferred ranges to be 1.14–1.4 mm for channel width, 0.89–1.4 mm for rib width and 1.02–2.04 mm for channel depth. However, the flow channel design should consider both the reaction efficiency and the manufacturing method [10]. These optimum dimensions of the channel shape without consideration of manufacturing methods cannot be directly used into the process design for micro-hydroformed bipolar plate because of the defects, such as rupture and wrinkling.

The shape of flow channel not only determines the reaction performance, but also plays an important role on the formability of micro-hydroforming process. In this study, the key dimensions of channel section related with both bipolar plate formability and reaction efficiency are defined. By DOE and response surface method (RMS), the regression models of the reaction efficiency and the formability as the function of these key dimensions are developed. Hence, an optimization model is developed for flow channel design which balances the fuel cell stack performance and formability. At the end, the optimum flow channel section design is obtained.

2. Micro-hydroforming process and formability

2.1. Hydroforming process

Compared with traditional sheet forming technology, sheet hydroforming process has remarkable advantages, such as flexibility, higher drawing ratio, better surface quality, less springback, better dimensional freezing and the capability of forming complicated-shaped sheet metal parts, shorter production cycle, lower cost and easier manufacturing on a construction site [11–13].

Fig. 1 shows the sketch of hydroforming process. During the forming process, metal sheets are put between the upper die and the lower die which form the close cavity (shown in Fig. 1). High-pressure medium is pushed into the cavity between the sheets. Thus the final shape of parts can be obtained with the increasing of hydro-pressure. Some new hydroforming processes have entered this area, such as viscous pressure forming technology, warm sheet hydroforming, and the hydroforming of sheet metal pairs. By this hydroforming process, the bipolar plate can be formed where the close cavity is the flow channel.

2.2. Formability definition for micro-hydroforming process

In conventional sheet hydroforming process simulations, metal sheets are assumed as plane stress shell to save simulation cost. However, in micro-sheet forming process, sheet thickness and forming feature size are of the same magnitude. Hence, it cannot be simplified as shell and the most widely used formability criterion based on the Keeler's forming limit diagram (FLD) either cannot be used in micro-sheet forming process [12].

In this study, a criterion based on sheet thickness is developed to represent the risk of rupture and wrinkling. In this sheet thickness criterion, the sheet thinning means the possible rupture of workpiece and the thickening means wrinkle. It can be expressed as Eq. (1):

$$f = \frac{t_0 \psi(\delta, \varphi)}{\Delta t} \tag{1}$$

Δt is the thickness variation during the micro-sheet forming process; t_0 the original sheet thickness; $\psi(\delta,\varphi)$ a standard function decided by material, in which δ and φ are shrinkage ratio and elongation ratio obtained from micro-sheet tensile experiments [14]. For sheet material used in this study, the value of average elongation ratio φ is 46% and the shrinkage ratio δ of broken section is 61%. In conservative sheet thickness criterion, the even thinning of sheet cannot exceed 46% in order to obtain high quality forming parts. If the sheet thickness reduction reaches 61%, the workpiece will rupture [14]. Here, f is a variable to evaluate the formability. Consequently, large negative value of f means wrinkle because of the excessive increase of sheet thickness. Small $f(0 < f < 1)$ means the possibility of rupture. Meanwhile, larger $f(f > 1)$ means the safer process. In theory, no rapture will come up when the value is larger than 1.

3. Objective and methodology

From the above analysis, it is known that wrinkle and rupture are the most common defects in hydroformed sheet metal bipolar plates. However, the section shape plays an important role on the formability. Furthermore, the optimum shape prescribed by Kumar and Reddy, in which only reaction performance is considered, cannot be totally achieved by the hydroforming process. This flow channel section shape design will make sheet become very thin or even rupture due to large uneven deformation during micro-hydroforming process. Therefore both the formability and efficiency should be considered.

The main problem concerned in this paper is how to balance these two sides. That is to improve quality of bipolar plates and keep high efficiency of fuel cell stacks simultaneously by favorable geometrical shape design, which can be properly achieved by micro-hydroforming process.

By taking reaction efficiency as the optimization objective, micro-hydroformability as the constraint, key dimensions of flow channel section as the deign variables, ASA as the optimization method, an optimization model is proposed in this study to optimize the flow channel section design. The methodology of flow channel section optimization design for hydroformed metal plates is shown in Fig. 2.

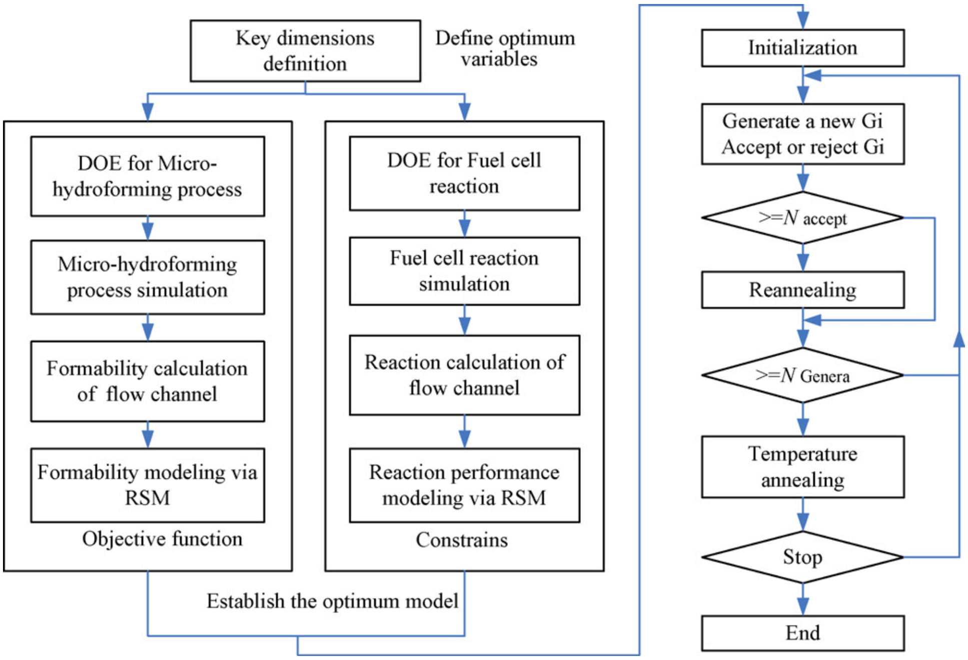

Fig. 2. Methodology of the optimization design for the flow channel section.

4. Optimization of flow channel section design for hydroformed metal bipolar plate

4.1. Design variables of channel section

The bipolar plate contains many micro-grooves where the rupture may occur because of the large, uneven deformation. Fig. 3 shows the key dimensions of the section of flow channels and the rigid die. For fuel cell bipolar plate channels, the fuel channel width w, coolant flow channel width D, channel depth h and transition radius R and sheet thickness t are concerned.

In this study, 0.2 mm thickness metal sheets are used. Fig. 3 shows the key dimensions in the rig die and the flow channel section. Some of them are the design variables as follows:

- Lower radius: $r = 0.3$ mm,
- Draw angle: $\alpha = 10^\circ$,
- Die radius: R,
- Draw depth (flow channel depth): h,
- Fuel channel width: w,
- Rib width: s.

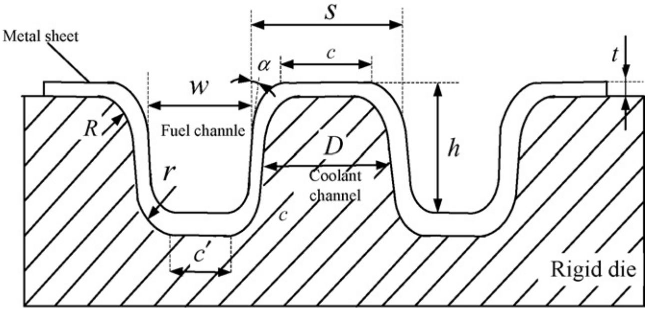

Fig. 3. Dimensions and geometry of the flow channel section.

The width of coolant channels and fuel flow channels can be calculated by these dimensions with considering the sheet thickness. Considering better contact condition to reduce the contact resistance and easy stack assembly, the following Eq. (2) should be satisfied:

$$\begin{cases} s = 2(R + t) + c \\ w = 2(r - t) + c' \\ c \geq 0.5 \\ c' \geq 0.5 \end{cases} \tag{2}$$

where c and c' are the contact length for joint assembly and are defined more than 0.5 mm in this paper.

4.2. Performance model for various flow channels

The performance of PEM fuel cell stack is related with the flow channel design. The reaction efficiency can be obtained by the model proposed by Kumar and Reddy [8]. The simulation results are calculated by the commercial software CFX and the results are listed in Table 1.

Response surface methodology (RSM) [15] is a useful tool in process design and product improvement. RSM is a collection of experimental design and optimization techniques that enables the experimenter to obtain the relationship between the response and the independent variables. It is typically used for mapping a response surface over a particular region of interest, optimizing the response, or for selecting operating conditions to achieve target specifications or customer requirements.

In this paper, RSM is applied to establish the reaction efficiency model for various flow channel section shapes. And the approximate model for reaction performance can be expressed by response surface as the function of the design variables

Table 1
Reaction efficiency (%) with various dimension of flow channel

Depth of flow channel, *h* (mm)	Width of land, s (mm)	Width of flow channel, W (mm)			
		0.5	1	1.5	2
0.5	0.5	78.5	80	82	80
	1	78.3	80	80	80
	1.5	77.8	80	80	80
	2	76.6	78.5	79.2	79
1.0	0.5	79	80	83	80.7
	1	80	81.5	82.6	81.5
	1.5	79.4	80.8	82	81.2
	2	77.7	78.8	80	80.2
1.5	0.5	81.5	82	84	82.3
	1	81.8	83.3	83.8	83.1
	1.5	81.2	83	83.3	83.1
	2	79.9	81.1	82.6	82.1
2.0	0.5	79.7	80.7	84	80.9
	1	80	82.1	82.9	81.8
	1.5	79.5	81	82.3	82
	2	78.5	79.8	81.1	80.8

defined above. In RSM, supposing there are n_v variables and regression function is *f*, *f* can be expressed by a second-order polynomial model as Eq. (3):

$$f = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i<j} \sum_{j=1}^{n} \beta_{ij} x_i x_j \tag{3}$$

where x_i and x_j are design variables. β_0, β_i, β_{ii} and β_{ij} are the undetermined parameters of the function. For a second-order polynomial model, there are $(n_v + 1)(n_v + 2)/2$ undetermined parameters expressed as vector *C*. Thus, the model can be as follows:

$$f = XC \tag{4}$$

In order to calculate the undetermined parameters, the vector *C* can also be expressed as Eq. (5) as follows [15]:

$$C = (X^{\mathrm{T}} X)^{-1} X^{\mathrm{T}} f \tag{5}$$

According to Eq. (5), by replacing the values of the design variables and the reaction efficiency in Table 1. The undetermined parameters can be obtained (shown in Table 2).

Replacing these parameters to the regression function Eq. (4), the reaction performance model of fuel cell stack as the function of design variables can be obtained as Eq. (6):

$$f_{\mathrm{r}} = 71.444 + 7.228h + 2.398s + 6.759w - 2.489h^2 - 1.569s^2 - 2.331w^2 + 0.209hs + 0.277sw + 0.059wh \tag{6}$$

Table 2
Values of the parameters for the reaction efficiency model

β_0	71.444
β_1	7.228
β_2	2.398
β_3	6.759
β_{11}	−2.469
β_{22}	−1.569
β_{33}	−2.331
β_{12}	0.209
β_{23}	0.277
β_{31}	0.059

Root mean square (RMS), which can be expressed as Eq. (7), is usually used to calculate the error to evaluate the accuracy of the regression function.

$$\mathrm{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2} \tag{7}$$

RMS value of reaction efficiency model is calculated according to Eq. (7). It is 0.062, which means the mode established by RSM is acceptable. By this regression model, the reaction efficiency can be calculated for various flow channel design. Fig. 4 shows the response surface of the reaction performance as the function of design variables (key geometric dimensions of flow channel section shown in Fig. 3). From Fig. 4, it indicates that the flow channel key geometric dimensions definitely are key factors that affect the reaction efficiency. Fig. 4(a) shows the response surface of efficiency (h = 1.0 mm) and Fig. 4(b) is the response surface of efficiency (w = 1.0 mm).

4.3. Responsive surface of the formability for micro-hydroformed metal bipolar plates

4.3.1. Modeling of micro-hydroforming process

By using commercial software code Abaqus-Expilict, the simulation model is developed. Due to the symmetry of the structure and deformation, only half of the flow channel end is modeled by 20-node degenerated solid elements. Material used in this simulation model is stainless steel sheet, which has good

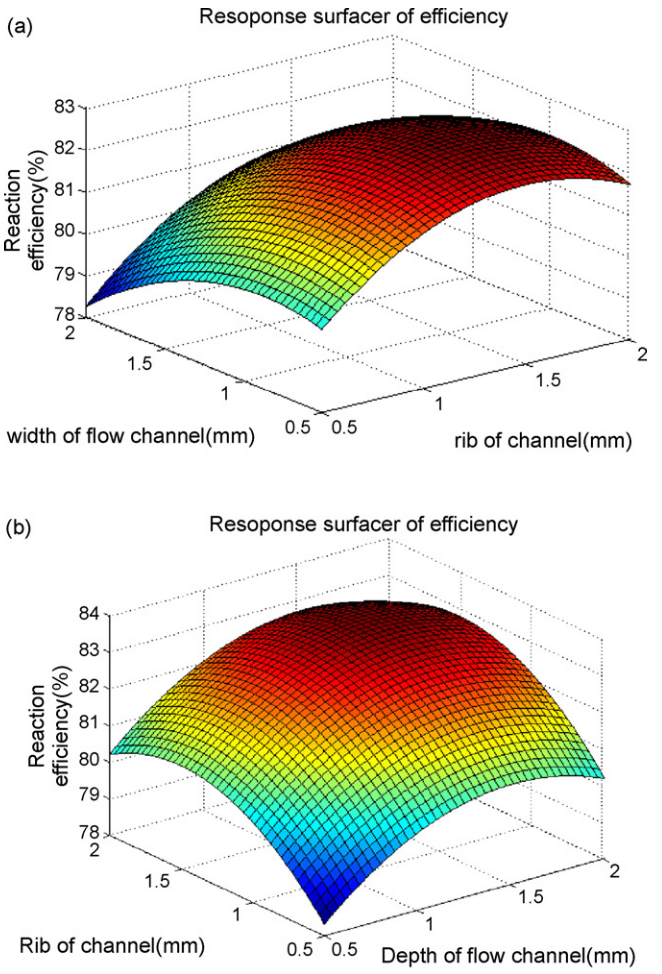

Fig. 4. Response surface of the reaction efficiency for the flow channel section design: (a) Response surface of reaction efficiency ($h = 1.0$ mm). (b) Response surface of reaction efficiency ($w = 1.0$ mm).

performance in corrosion resistance and is widely applied in corrosive environment. It has been proved as a promising material to replace graphite in manufacturing fuel cell bipolar plates. The material's stress–stain curve is approximated by Swift law $\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon}^p)^n$ and the mechanical properties are shown in Table 3, which is obtained by the tensile experiments according to the methods described in the literature [14]. The Coulomb friction law is adopted on the contact surface between the sheet metal and the die and the friction coefficient $\mu = 0.1$. The die is defined as rigid body to simplify the numerical simulation model. The load pressure is uniformly applied to the sheet metal surface and increases step by step until the material fits to the rigid die.

Table 3
Mechanical properties of the SS316L sheet employed in the forming process

E (GPa)	197
v	0.3
σ_y (MPa)	326
K (MPa)	1440
n	0.587
ε_0	0.063

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

Table 4
Design of experiments for hydroforming process simulations

No.	Width w (mm)	Depth h (mm)	Upper radius R (mm)	Formability f_d
1	1.15	0.75	0.5	1.31
2	1.15	0.75	0.7	1.432
3	1.15	1.25	0.5	0
4	1.15	1.25	0.7	0
5	2.05	0.75	0.5	1.451
6	2.05	0.75	0.7	1.571
7	2.05	1.25	0.5	0.946
8	2.05	1.25	0.7	1.278
9	1.6	1.0	0.6	1.359
10	0.7	1.0	0.6	0
11	2.5	1.0	0.6	1.399
12	1.6	0.5	0.6	1.782
13	1.6	1.5	0.6	0
14	1.6	1.0	0.4	1.064
15	1.6	1.0	0.8	1.496

4.3.2. *Simulation experiments by DOE and formability model by RMS*

For the bipolar plate hydroforming process, the most important geometric dimensions are the die radius R, the width of flow channel w and the flow channel depth h which decide whether high quality hydroformed bipolar plates can be obtained or not. The thickness of metal sheet can be obtained by the simulation results and the formability can be calculated according to Eq. (1).

The central composite design (CCD) is a popular method that can be effectively applied to construct the second-order model for RSM. Table 4 shows the table of design variables. The formability f_d can be calculated by the following procedure: put these design variables into simulation models, calculate the thickness of formed parts and replace it into Eq. (1).

The same procedure is applied to calculate the regression model of formability. Second-order polynomial model in the form of Eq. (3) is fitted to the data. The values of regression parameters are calculated according to Eq. (5) and the values of parameters are shown in Table 5.

Replacing these parameters into Eq. (4), the two second-order polynomial regression models for formability of bipolar plates

Table 5
Values of the parameters for the formability model

β_0	1.725
β_1	0.529
β_2	−1.965
β_3	0.567
β_{11}	−0.782
β_{22}	−1.767
β_{33}	−1.319
β_{12}	2.519
β_{23}	0.467
β_{31}	0.917

can be expressed by Eq. (8) as follows:

$$f_d = 1.725 + 0.529w - 1.965h + 0.567R - 0.782w^2 - 1.767h^2 - 1.319R^2 + 2.159wh + 0.467hR + 0.917Rw \tag{8}$$

The RMS is calculated by the same method described in Section 4.2 and the value is 0.0025. Therefore, the model is acceptable. Fig. 5 shows the response surface of formability. From the figure, it can be seen that the bipolar plate cannot be formed when the depth is more than 1 mm and large fuel channel width is in favor of forming process.

4.4. Optimization method and results

The maximum reaction efficiency is the objective function, while the formability should be more than 1 that guarantees the bipolar plate can be obtained by hydroforming process. Therefore, the optimization model can be expressed as follows:

$$\begin{array}{ll} \max & f_r(w, h, s) \\ st: & f_d(w, h, R \cdots) \geq 1 \end{array} \tag{9}$$

Adaptive simulated annealing (ASA) [16] is one of effective optimization methods. In this study it is used to search the variables domain to find the optimum design for hydroformed bipolar flow channel. Ten initial values of the design variables are randomly chosen in the design domain and input into the optimization model. Table 6 shows 10 optimum results with different initial design variables and the corresponding optimum results. From these results, the optimum result can be chosen. It can be seen that the formability is about 1 and the efficiency is about 79%. Hence, the optimum values of key geometric dimensions for channel width, rib width, channel depth and transition radius are obtained ($w = 1.0$ mm, $h = 0.5$ mm, $s = 1.6$ mm and $R = 0.5$ mm). And the corresponding formability is 1.001 and the performance is 79%.

5. Discussion

According to Kumar and Reddy research [8], the optimum dimension values for channel width, rib width and channel depth are close to 1.5, 0.5 and 1.5 mm, respectively in order to obtain high hydrogen consumptions (~80%). Unfortunately, these parameters cannot be directly applied in the hydroforming process design. Fig. 6a shows these hydroformed parts with only consideration of reaction efficiency ($w = 1.5$ mm, $h = 1.5$ mm, $s = 1.0$ mm). It can be seen that the part cannot be formed correctly because of rupture. Similarly, Fig. 6b shows the formed part only consideration formability ($w = 1.5$ mm, $h = 0.5$ mm,

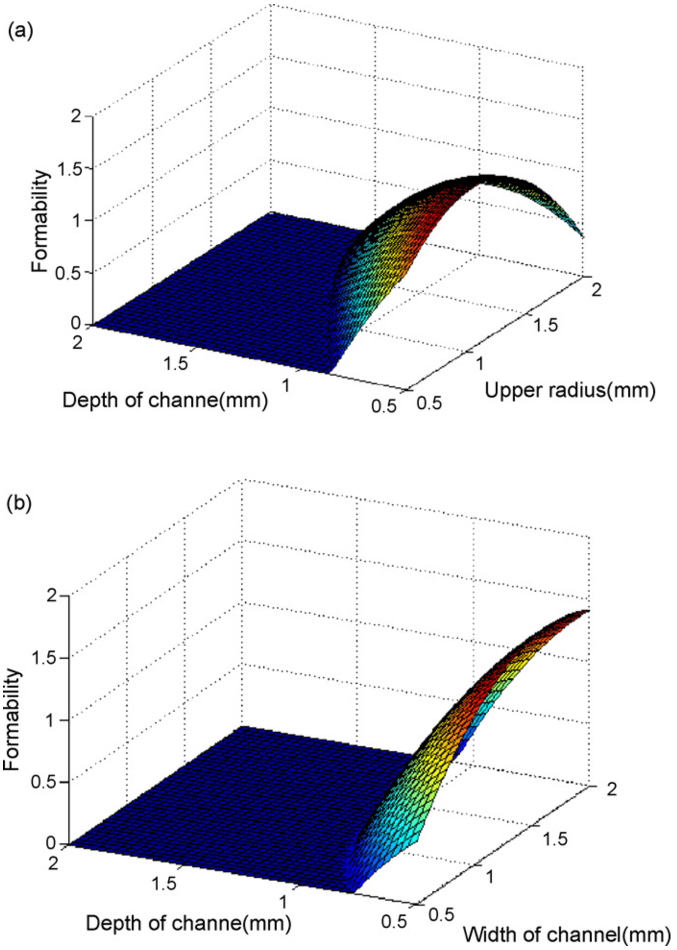

Fig. 5. Response surface of the formability for the flow channel section design: (a) Response surface of formability ($w = 1.0$ mm). (b) Response surface of formability ($R = 0.5$ mm).

Table 6
Values of the design variables and objectives

Initial values of the design variables				Optimum values of the design variables				Formability f_d	Reaction efficiency f_r (%)
w	h	s	R	w	h	s	R		
1.0	1.0	1.0	1.0	0.966	0.5	1.528	0.414	1.001	79.389
1.54	1.98	1.31	0.85	0.966	0.5	1.528	0.414	1.001	79.389
0.54	1.02	0.84	1.3	1.245	0.5	1.788	0.544	1.001	79.353
1.03	2.24	1.5	0.89	1.088	0.506	1.646	0.473	1.002	79.465
0.5	1.51	0.69	0.5	1.236	0.561	1.959	0.629	1.001	79.126
1.17	1.05	2.12	1.32	1.136	0.502	1.678	0.489	1.001	79.462
1.71	0.89	2.08	1.26	1.12	0.587	1.93	0.615	1.003	79.135
1.78	1.08	0.77	0.48	1.104	0.509	1.67	0.485	1.002	79.448
0.69	1.71	0.76	1.36	0.862	0.5	1.46	0.381	1.001	79.214
0.53	0.51	1.75	0.75	1.116	0.578	1.892	0.596	1.000	79.20

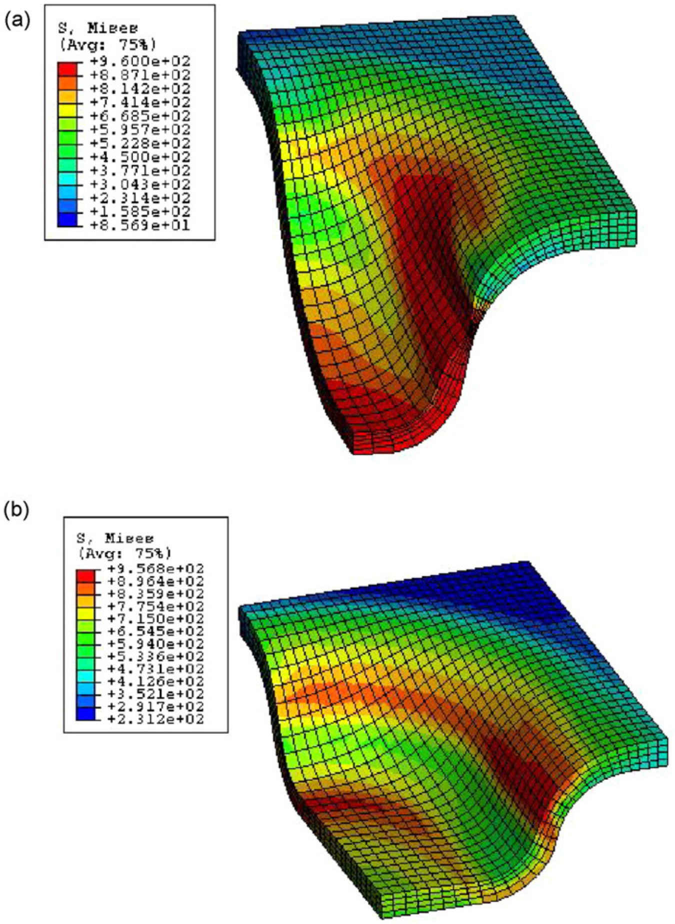

Fig. 6. Hydroformed parts of the different designs with consideration of the reaction efficiency or formability: (a) Only the reaction efficiency considered. (b) Only the formability considered.

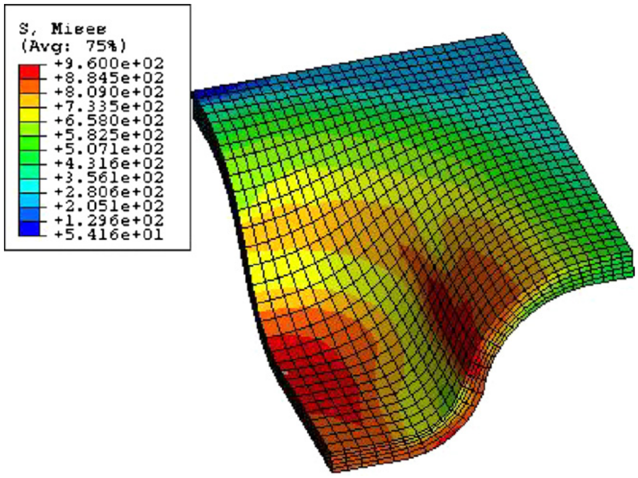

Fig. 8. Formed parts of the optimum design.

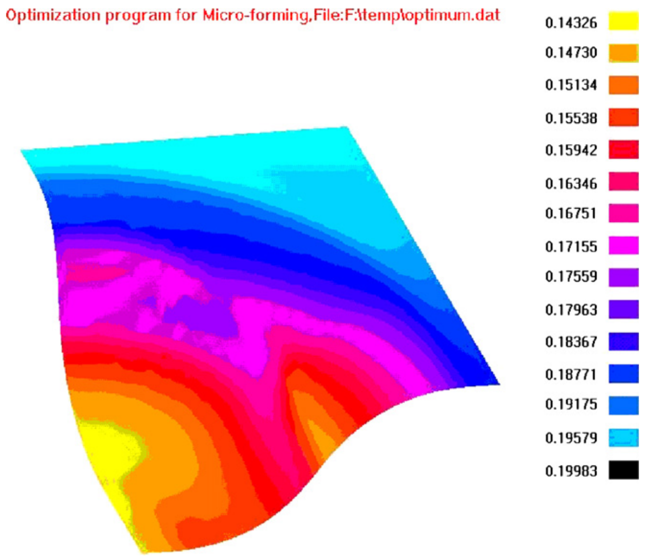

Fig. 9. Thickness distribution of the optimum design flow channel.

$s = 1.5$ mm, $R = 0.5$ mm). Though it can be properly formed, the reaction efficiency is not acceptable. Fig. 7 shows the thickness distribution of these two designs. It shows that the final thickness of Kumar and Reddy design with consideration of reaction efficiency is 0.027 mm that means the metal sheet will rupture.

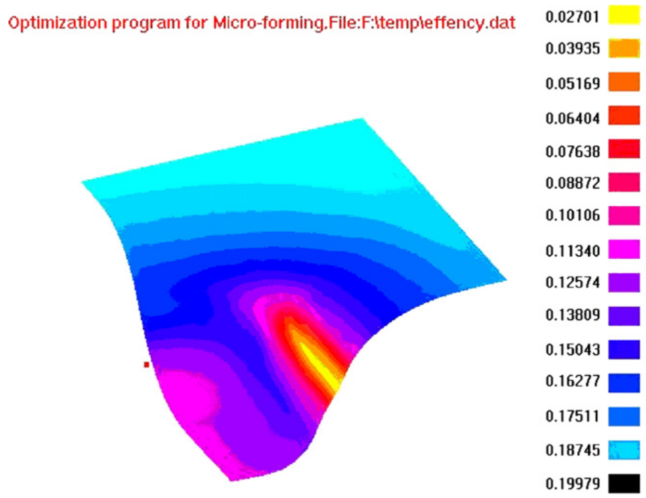

Fig. 7. Thickness distribution of the formed parts with only reaction efficiency considered.

Fig. 8 shows the final formed part of metal bipolar plates with optimum flow channel section shape design obtained above. It indicates that the formed part has good quality and the thickness distribution shows the minimum thickness of the formed part is 0.143 mm (seen in Fig. 9). According to Eq. (1), the value of the formability is 1.001 and the performance is 79% by Eq. (5). As a result, the optimum design of flow channel for bipolar plate can be well formed by micro-hydroforming process while keeps high reaction performance.

6. Conclusion

Hydroforming process is a promising technique to manufacture metal bipolar plates which are cheaper and lighter than traditional graphite bipolar plates. The flow channel section design, especially some key dimensions, is an important factor on the reaction efficiency of fuel cell while it also plays a decisive role in whether it can be properly obtained by the hydroforming process. Therefore, both the reaction efficiency and formability should be considered simultaneously in flow channel section design. DOE theory is applied to acquire the design variable table and simulations are performed to calculate the reaction efficiency and formability. Subsequently, the second-order polynomial approximate models for the formability and reaction efficiency are established by RSM. Taking the reaction efficiency as the objective, the formability of hydroforming process as constraints, key geometric dimensions of flow channel section as design variables and ASA as the optimization method, an optimization model is proposed in this study. Optimization results show that the optimum dimension values for channel depth, channel width, rib width and transition radius are 0.5, 1.0, 1.6 and 0.5 mm, respectively with the highest reaction efficiency (79%) and the acceptable formability (1.0). Consequently, their use would lead to improved fuel cell efficiency for low cost hydroformed metal bipolar plates for PEM fuel cell.

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References

[1] I. Bar-On, R. Kirchain, R. Roth, J. Power Sources 109 (2002) 71–75.

[2] P. Costamagna, S. Srinivasan, J. Power Sources 102 (2001) 253–269.

[3] H. Tawfika, Y. Hung, D. Mahajan, J. Power Sources 163 (2007) 755–767.

[4] X. Li, I. Sabir, Int. J. Hydrogen Energy 30 (2005) 359–371.

[5] D.P. Davies, P.L. Adcock, M. Turpin, et al., J. Power Sources 86 (2000) 237–242.

[6] Muammer Koc, Sasawat Mahabunphachai, Journal of Power Sources 172 (2007) 725–733.

[7] Sasawat Mahabunphachai, Muammer Koc, Journal of Power Sources 175 (2008) 363–371.

[8] A. Kumar, R.G. Reddy, J. Power Sources 113 (2003) 11–18.

[9] D.S. Watkins, K.W. Dircks, D.G. Epp, US Patent 4,988,583 (1991).

[10] L. Peng, X. Lai, J. Ni, et al., ASME-The 4th International Conference on Fuel Cell Science Engineering and Technology, Irvine, CA, USA, June 2006.

[11] S.H. Zhang, Z.R. Wang, Y. Xu, et al., J. Mater. Process. Technol. 151 (2004) 237–241.

[12] T. Hama, M. Asakawa, A. Makinouchi, J. Mater. Process. Technol. 150 (2004) 10–17.

[13] L.H. Lang, Z.R. Wang, D.C. Kang, et al., J. Mater. Process. Technol. 151 (2004) 165–177.

[14] L. Peng, X. Lai, J. Ni, Proceedings of the 7th ICFDM2006 International Conference on Frontiers of Design and Manufacturing, Guangzhou, China, 19–22 June, 2006.

[15] D. Liu, X. La, J. Ni, et al., J. Power Sources 172 (2007) 760–767.

[16] J.-Y. Yeh, J.C. Fu, Expert Syst. Appl. 33 (2007) 706–715.