Energy Conversion and Management 174 (2018) 814–823

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Flow channel design for metallic bipolar plates in proton exchange membrane fuel cells: Experiments

Diankai Qiu[a,b], Linfa Peng[a,*], Peiyun Yi[a], Xinmin Lai[a], Werner Lehnert[b,c]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research, IEK-3: Electrochemical Process Engineering, 52425 Jülich, Germany
[c] RWTH Aachen University, Modeling Electrochemical Process Engineering, 52062 Aachen, Germany

ARTICLE INFO

Keywords:
Metallic bipolar plates (BPPs)
Flow channel design
Formability
Channel height
Channel thickness
Fuel cell testing

ABSTRACT

This study offers an efficient design method of flow channels of metallic bipolar plates (BPPs) to improve manufacturing technique of BPPs and maximize power density in proton exchange membrane (PEM) fuel cells. Stamped thin metallic BPPs with anticorrosive and conductive coating are promising candidates for replacing conventional carbon-based BPPs. Nevertheless, unlike carbon-based BPPs, the flow channel design of metallic BPPs should take into account not only the reaction efficiency, but also formability due to the possible rupture of the metallic channel during the micro-forming process. In our previous study, a forming limit model was first proposed to predict the maximum allowable channel height by the forming process. This study is conducted to further propose the method of the design and fabrication of metallic BPPs based on the numerical model. In order to determine channel geometry design from formability perspective, response surface method is utilized to build a formability model. Combining the formability model and reaction efficiency, flow field design for metallic BPPs (channel width of 0.9 mm, rib width of 0.9 mm, channel depth of 0.4 mm and radius of 0.15 mm) is proposed. Experiments on BPP fabrication and assembled 20-cell fuel cell testing are conducted to observe forming quality of micro channel and output performance on the real fuel cell. It is shown that the stamping force grows with increasing channel depth in a nonlinear manner and a blank holder is needed to eliminate the sheet wrinkle in the forming process. The uniformity of the voltage distribution in the 1000 W-class stack further proves the reliability of metallic BPPs designed by our method. The methodology developed is beneficial to the fabrication management of metallic BPPs and effective supplement to the channel design principle for PEM fuel cells.

1. Introduction

Despite being considered as a promising alternative to conventional power sources, proton exchange membrane (PEM) fuel cells have not been widely accepted by the commercial market, especially in transportation applications. One of the biggest obstacles to this is cost, which remains 2–4 times higher than internal combustion engines (\$30–50 kW^{-1}) in current status [1]. Long-term competitiveness with other alternative powertrains, extensive research and development efforts are expected to further reduce costs to around \$30 kW^{-1} (DOE Ultimate Goals) [1,2]. Bipolar plates (BPPs), as the main component involved in distributing the reactant, exporting waste products and electrical conduction, account for 30–40% of stack cost and 60–80% of stack weight [3]. Compared with traditional carbon-based BPPs with higher manufacturing cost and greater thickness, thin metallic BPPs with coating have been demonstrated to be a leading solution by virtue of their good mechanical strength, electric conductivity, relative thinness and low cost of mass production [4,5].

Flow channel geometry plays an important role in the nature of the fluid flow, heat and mass transfer and so has an influence on the energy conversion of fuel cells. Many researches based on carbon-based BPPs have been conducted in an effort to optimize the channel geometry and flow field by considering the reactant transport, energy-conversion efficiency of heat and electric conduction, as well as water management [6–12]. Zhu et al. [6] numerically investigated the sensitivity of liquid water to microchannel geometry in low-temperature fuel cells, with the longest detachment time and the largest detachment diameter being found in the rectangular channel with a 0.5 aspect ratio. Wang et al. [7] developed a three-dimensional, two-phase transport model for PEM fuel cells based on the two-fluid method to investigate the effect of the flow

* Corresponding author at: State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail addresses: qdk2009@sjtu.edu.cn (D. Qiu), penglinfa@sjtu.edu.cn (L. Peng).

https://doi.org/10.1016/j.enconman.2018.08.070
Received 15 May 2018; Received in revised form 16 August 2018; Accepted 18 August 2018
0196-8904/

Nomenclature

C	clearance between punch and die
f	regression function of response surface model
h	height of the channel of BPPs
h_{max}	maximum forming channel height
m	number of variables in the response surface model
r	radius of the channel of BPPs
r_d	radius of the die
r_p	radius of the punch
s	width of the rib of BPPs
w	width of the channel of BPPs
w_d	groove width of the die
w_s	rib width of the die
$\hat{y}_i$	the *i*th model response value
y_i	the *i*th experimental response
$\bar{y}$	average response value
B	coefficients in the function of response model
φ	ratio of the channel's area to the total area of BPPs
B	coefficient matrix of response surface model
R^2	multiple correlation coefficient
X	variable matrix of response surface model
SST	sum of squares for total
SSR	sum of squares for regression

channel size on cell performance. Rezaie et al. [8] proposed a novel flow field design by applying an angle of 0.3° to the channels so as to increase pressure loss of reactant flow. Rostami et al. [10] found an optimum of between 0.8 and 1.2 mm for serpentine flow channels. Experimental work has also been performed to investigate the channel dimension influences [11,12], with various flow field designs being proposed to improve PEM fuel cell performance [13–16]. In general, these design guidelines are carried out with respect to the reaction efficiency of the fuel cell with graphite BPPs, in which manufacturing problems need not to be taken into account due to their high thickness in the machining process.

Nevertheless, thin metallic BPPs, with a thickness of around 0.1 mm, are usually fabricated by the stamping process [17,18], hydroforming process [3,19] and rubber pad forming [20,21]. During these forming processes, ruptures are commonly observed because of excessive localization of the stress and strain at the channel without consideration of material manufacturability in the flow channel geometry design [17,20]. In order to improve formability of the metallic sheet, multi-step forming is tried to use recently. However, the multi-step technology is not mature yet. Reactant leakage or short circuits would inevitably occur if the BPP with the micro rupture is assembled in the fuel cell. Therefore, the channel geometry design of a metallic BPP could not entirely copy that of the graphite one. In order to fabricate a metallic BPP with high quality, reliability and production, it is necessary to take material manufacturability into consideration in the design and manufacture of the metallic BPP, especially for the high-aspect-ratio channel.

In our previous study [22], a numerical methodology was introduced to improve the design of the flow channel in terms of manufacturability, where an instability criterion with size effect in micro stamping was proposed and the forming limit was predicted as a function of material properties, forming technology parameters and channel dimensions. As an extension of the previous work, this study proposed a method for designing and fabricating of the metallic BPPs to improve the manufacturing technique of BPPs based on the numerical model. The metallic BPPs will also be evaluated by real fuel cell testing. The remainder of the paper is organized as follows. The second section elaborates on the flow channel design with consideration to manufacturability and reaction efficiency based on the forming limit prediction and response surface method (RSM). The third section describes the fabrication and testing process of metallic BPPs. In the fourth section, the forming results of the metallic BPPs and performance of the fuel cell are measured to observe the reliability of the design guideline proposed in this study. It should be mentioned that this study is conducted based on one-step stamping process.

2. Flow field design

In practice, the formability of metallic sheets is influenced by multiple factors, such as the material properties, sheet thickness, mould design and forming height, as presented in our previous work [22]. In order to focus on the design of channel dimensions, a formability model is built to foster the relationship between the fabricated result and process parameters using the response surface method (RSM) based on the forming limit prediction in previous work [22]. The effect of channel geometry on the energy-conversion efficiency of fuel cells is then taken into account to finish the metallic BPP design.

2.1. Formability model

2.1.1. Response surface method

RSM [13] is a useful tool in process design and product improvement. As a collection of experimental design and optimization techniques, it enables the experimenter to establish 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 RSM, supposing that there are m variables and the regression function is f, f can be expressed by a second-order polynomial model, as in Eq. (1):

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

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

$$f = XB \tag{2}$$

In order to calculate the undetermined parameters, the vector B can also be expressed as follows:

$$B = (X^T X)^{-1} X^T f \tag{3}$$

After the mathematical model is established, multiple correlation coefficient R^2 is used to evaluate its significance, as presented in Eq. (4):

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{m} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{m} (y_i - \bar{y})^2} \tag{4}$$

where SSR and SST represent the sum of squares for regression and total, respectively. $\hat{y}_i$, y_i, and $\bar{y}$ are the *i*th model response value, the *i*th experimental response, and the average response value, respectively. R^2 is always between 0 and 1. The closer the R^2 value approaches 1, the higher the accuracy for the response data evaluated by the fitted mathematical model.

2.1.2. Formability model

Fig. 1 shows the section of the formed flow channel in the stamping process and the typical graphite BPP in the fuel cell. As is shown in Fig. 1 (a), the formability of the metallic sheet is related to some key