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Contact behavior modelling and its size effect on proton exchange membrane fuel cell

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HIGHLIGHTS

- Numerical model is developed to predict contact behavior in the fuel cell.
- Numerical results show good agreements with experimental results.
- Size effect resulting channel variation on contact behavior is proposed.
- For $\eta \rightarrow 1$, significant increase occurs in contact resistance and porosity.
- Different assembly processes are needed when channel size is altered.

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ABSTRACT

Contact behavior between the gas diffusion layer (GDL) and bipolar plate (BPP) is of significant importance for proton exchange membrane fuel cells. Most current studies on contact behavior utilize experiments and finite element modelling and focus on fuel cells with graphite BPPs, which lead to high costs and huge computational requirements. The objective of this work is to build a more effective analytical method for contact behavior in fuel cells and investigate the size effect resulting from configuration alteration of channel and rib (channel/rib). Firstly, a mathematical description of channel/rib geometry is outlined in accordance with the fabrication of metallic BPP. Based on the interface deformation characteristic and Winkler surface model, contact pressure between BPP and GDL is then calculated to predict contact resistance and GDL porosity as evaluative parameters of contact behavior. Then, experiments on BPP fabrication and contact resistance measurement are conducted to validate the model. The measured results demonstrate an obvious dependence on channel/rib size. Feasibility of the model used in graphite fuel cells is also discussed. Finally, size factor is proposed for evaluating the rule of size effect. Significant increase occurs in contact resistance and porosity for higher size factor, in which channel/rib width decrease.

1. Introduction

Proton exchange membrane (PEM) fuel cells are considered promising clean power source systems for vehicles, portable and stationary application by virtue of the fact that they emit zero emissions, have a low operating temperature, fast start-up and high efficiency [1,2]. A fuel cell stack is comprised of a multitude of individual cells in series and is a complex system assembled from a number of components with various mechanical behaviors. The proton exchange membrane is inserted between two gas diffusion layers (GDL) coated with a catalyst layer (CL) to form the membrane electrode assembly (MEA), which is in turn sandwiched and clamped between two bipolar plates (BPPs). The contact behavior is one of the key factors determining the output performance of a fuel cell. In the assembled stack, proper contact between the GDL and BPP is essential to reducing the electrical contact resistance (ECR) and preventing leaking. However, excessive contact may lead to

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Nomenclature

a	Rib width
b	Channel width
c	Clearance between the punch mould and die mould
E_w	Combined modulus
AB	Bottom flat surface of the stamped rib
BC	Bottom transition fillet of the stamped rib
CD	Free sloping part of the stamped channel/rib
DE	Top transition fillet of the stamped channel
EF	Top flat surface of the stamped channel
l	Length of each part in the channel/rib
w_p	Width of the punch mould
w_d	Width of the die mould
r	Fillet
r_p	Fillet of the punch mould
r_d	Fillet of the die mould
R_{tot}	Entire contact resistance between BPP and GDL
s_0	Contacting width between rib and GDL
t	Thickness of metallic sheet
u_0	Assembly displacement in the fuel cell
p	Contact pressure
P	Function of contact pressure distribution
v	Poisson's ratio
h_G	GDL thickness
λ_0, λ_1	Fitting parameters of the "mechanical-electrical" relationship
ρ	Contact resistivity
φ	GDL porosity
φ_0	Initial GDL porosity
θ	Forming angle of the channel/rib
Φ	Channel/rib profile

variation in porosity and damage to the GDL. Moreover, the mass, water and heat transport through the GDL are also influenced by the contact behavior. Hence, understanding the contact behavior mechanism in the assembly process is essential for high performance of the fuel cell stack [3–5].

Previous studies of the assembly process have usually been carried out on the basis of the contact analysis between the GDL and traditional graphite BPP, which is fabricated by the milling process [6–8]. However, the poor formability of graphite gives fuel cell utilizing it a high manufacturing cost, large thickness requirement and low power density. In recent years, thin metallic BPP has been increasingly applied to candidates for BPP owing to its good mechanical strength, thermal conductivity and relatively low cost in mass production. For BPP fabrication, the stamping process is the preferred choice because of its high efficiency and low cost [9–11]. In this stamping process, micro and dense features are formed on thin stainless steel sheets to provide the channels for the gas and water products. The fillet and forming angle are generated on the high-aspect ratio microstructures so as to avoid the rupture of thin sheets resulting from the localization of the stress and stain at the corner of the channel and rib (channel/rib) [12,13]. As a result, there is a significant difference in the channel/rib shape formed between metallic BPP and traditional graphite BPP, as shown in Fig. 1 (a). During the assembly process, a large deformation is produced on the GDL, carbon fiber-based material with high porosity when subjected to the clamping of the fuel cell. The irregular trapezoid channel/rib profile is likely to lead to more sophisticated contact behavior between the GDL and BPP, which affects the fuel cell's performance. In order to improve the fuel cell's performance, it is important to achieve a clear understanding of the contact mechanism between the easily-deformed GDL and BPP with irregular channel/rib.

In recent years, some attention has been paid to the contact behavior between GDL and metallic BPP in the fuel cell assembly. In Andre et al.'s [14] study, the contact resistances between GDL and commercial alloy materials in different surface states were compared to understand the respective influence on the contact behavior of roughness, bulk composition and surface treatment. Peker et al. [11] investigated surface topography changes during the long-run micro-stamping of BPPs, and established a relationship between surface topography and contact resistance change by fabricating 2000 pieces of BPPs. Netwall et al. [15] found that the interface dependencies should be the focus of reducing contact resistance after the contact pressure surpassed 1.0 MPa. In our previous study [3,16,17], manufacturing errors resulting from the stamping process were studied in an effort to reveal their effect on contact pressure in the fuel cell. It can be seen that studies on contact behavior focusing on metallic BPP were still limited to the material surface influence. As far as the literature reviewed by the authors is concerned, research on contact behavior prediction and assembly mechanisms based on metallic BPP have not been reported. Furthermore, all of the above-mentioned studies were carried out by experimental measurement and the finite element analysis (FEA) method, which is costly in both monetary and temporal terms. Moreover, it is difficult to construct an ideal simulation of the fuel cell due to the huge contact analysis and computing requirements resulting from the multiple scales across the dimensions of the components. Two-dimensional simplified models were thus adopted in these simulations. Therefore, to achieve more effective and realistic results, the analytical approach is more extensively considered.

The present study is intended to illustrate the contact behavior mechanism in the assembly process of fuel cells with stamped BPP by means of a numerical method. The remainder of the study is organized as follows. The second section elaborates the modelling process of contact behavior with consideration of the BPP fabrication and assembly processes, including the mathematical description of channel/rib geometry, contact pressure distribution and contact resistance and GDL porosity as evaluations of contact behavior. The third section outlines the experiments with various stamped BPPs in order to validate the derived contact behavior model, which will be also discussed through the application in the graphite fuel cell. The size effect on contact resistance resulting from the variation of channel/rib configuration is found by the comparison of experimental cases. In the fourth section, the mechanism of the size effect is investigated with the numerical model. Its influence on contact resistance and porosity is systematically discussed.

2. Modelling of contact behavior prediction

As is mentioned above, the contact behavior of fuel cell with metallic BPP is different from that of a fuel cell with a graphite BPP. Its complex rib geometry has a strong connection with the characteristics of fabrication technology. Hence, the stamping process is given substantial attention in this study. In the modelling of contact behavior, a mathematical description of the channel/rib profile of a metallic BPP is established according to the actual measurement,