Journal of Power Sources 185 (2008) 1252–1256

Contents lists available at ScienceDirect

Journal of Power Sources

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

Short communication

Contact mechanics approach to determine contact surface area between bipolar plates and current collector in proton exchange membrane fuel cells

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ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 26 August 2008
Accepted 28 August 2008
Available online 7 September 2008

Keywords:
Fuel cells
Contact surface areas
Contact mechanics

ABSTRACT

A significant portion of the power loss in a fuel cell stack can be attributed to the contact resistance between the gas diffusion layer/bipolar plate and the current collector/bipolar plate interfaces, especially when an oxide layer is formed on a stainless steel bipolar plate. Researchers have already studied methods to decrease the contact resistance between fuel cell components, but never has a theoretical contact mechanics model been applied to contact resistance problems in fuel cells. Therefore, the purpose of this research is to utilize a theoretical contact mechanics model in order to study real contact area in fuel cell components as a function of surface roughness, material properties, and clamping force. Specifically, the effects of bipolar plate surface roughness, coating thickness of the gold plating on the current collector, and the clamping force on real contact area have been studied. It was found that smoother materials, thicker gold coating, and higher clamping force resulted in a higher real percentage contact area.

1. Introduction

A fuel cell is an energy conversion device that generates electricity through the electrochemical reaction of hydrogen and oxygen, producing only water as a byproduct. The decrease of fossil fuel resources coupled with the increased risk of global warming is causing fuel cell technology to be an area of rising interest. Of all of the different types of fuel cells, proton exchange membrane (PEM) fuel cells are the ones that have attracted the most interest, due to a low operating temperature, short start-up time, high power density, and nearly zero emissions. Thus, the PEM fuel cell would be desirable in transportation devices where pollution and temperature are major issues.

PEM fuel cells, see Fig. 1, have great potential to be environmentally friendly, but there are still several problems that need to be solved before they can be mass-produced. The contact resistances between the gas diffusion layer/bipolar plate interface and the current collector/bipolar plate interface contribute to a significant power loss in a fuel cell [1]. The contact resistance is affected by the clamping pressure, the surface geometry and material properties of contact components.

Several researchers have studied the contact resistance of fuel cell components. The effect of gas diffusion layer clamping pressure on fuel cell performance was studied by Lee et al. [2]. They suggested that fuel cell performance can be affected by changes in electrical contact resistance due to varying pressures. Too much pressure can result in damage to the gas diffusion layer, and too little pressure can cause high contact resistance. Determining the optimal assembly pressure is crucial in order to reduce power loss in a fuel cell. Jung et al. [3] studied contact resistance for different flow field combinations in fuel cells. Wang et al. [4] considered stainless steel as a possible material for a bipolar plate by testing the contact resistance between stainless steel and carbon paper. Mishra et al. [5] compared results from predicted contact resistance and the experimental contact resistance of different gas diffusion layer materials with variable contact pressure. They utilized a fractal asperity model to determine contact resistance based on clamping pressure, material properties, and surface geometry. Ihonen et al. [6] measured the contact resistance of un-plated and plated stainless steel. Zhang et al. [1] developed two semi-empirical methods for estimating the contact resistance between a bipolar plate and gas diffusion layer. They reported good agreement between their predictions and their experimental contact resistance results.

It is well known that contact resistance depends strongly upon real contact area and there have been many successful theoretical models developed to determine real contact area as a function of surface roughness and material properties [7]. To date, these models have not been applied to contact resistance problems in fuel cells. Therefore, the objective of this research is to utilize a previously developed contact mechanics model to study real contact area at the current collector/bipolar plate interface in a fuel cell as a function of surface roughness and material properties and clamping pressure. Upon successful application of the contact mechanics model to the current collector/bipolar plate interface, the model

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0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2008.08.091

Nomenclature

E	equivalent modulus of elasticity
$g(x, y)$	gap between contact bodies
g_0	initial gap between the reference planes of two surfaces
G	equivalent shear modulus
$p(\xi, \eta)$	contact pressure distribution
$p_j(x, y)$	contact pressure for a given point
$q(\xi, \eta)$	tangential force
R_a	average roughness
R_t	roughness total
R_q	root mean square roughness
R_z	Ten point height
$u(x, y)$	vertical surface displacement

Greek symbols

δ	surface approach
ν	Poisson's ratio

will be applied to the gas diffusion layer/bipolar plate interface in future research after the surface roughness distribution for the gas diffusion layer becomes available.

2. Contact mechanics model

The contact mechanics model used in this research was developed by Hu, Barber, and Zhu [8]. When two rough surfaces are in contact, the gap between the deformed surfaces in contact $g(x, y)$ can be expressed as

$$g(x, y) = g_0 - \delta + z(x, y) + u(x, y) \quad (1)$$

where g_0 is the initial separation between two surfaces in contact when there is no external load. When a certain load is applied, the two surfaces are deformed, and they have an approach distance of δ. The surface roughness $z(x, y)$ is calculated as

$$z(x, y) = z_1(x, y) + z_2(x, y) \quad (2)$$

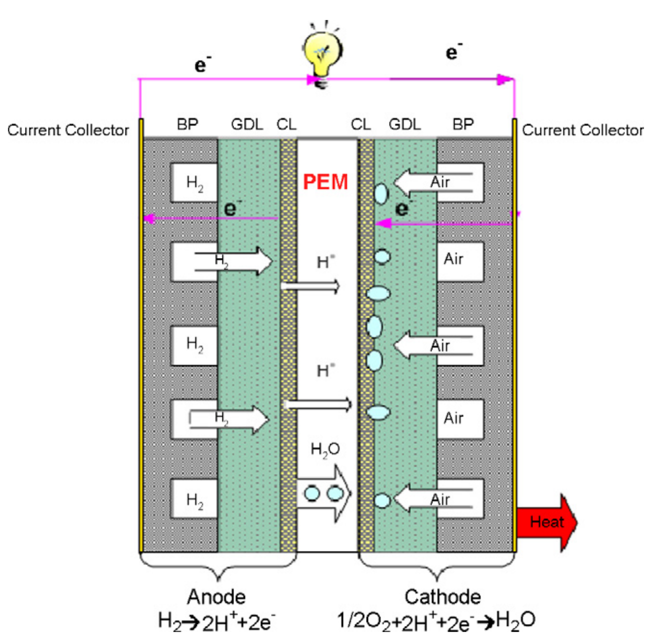

Fig. 1. Schematic of PEM fuel cell.

where the subscripts 1 and 2 represent the surfaces 1 and 2, respectively. $u(x, y)$ is the vertical surface displacement due to a distributed normal pressure $p(\xi, \eta)$ and tangential force $q(\xi, \eta)$, and it can be obtained by the following equation:

$$u(x, y) = \frac{2}{\pi E} \iint \frac{p(\xi, \eta)}{\sqrt{(x-\xi)^2 + (y-\eta)^2}} \mathrm{d}\xi \, \mathrm{d}\eta - \frac{1}{\pi G} \iint q(\xi, \eta) \frac{\xi - x}{\sqrt{(x-\xi)^2 + (y-\eta)^2}} \mathrm{d}\xi \, \mathrm{d}\eta \quad (3)$$

where E is the equivalent Young's modulus and G is the equivalent shear modulus given by

$$\frac{1}{E} = \frac{1}{2}\left(\frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2}\right) \quad (4)$$

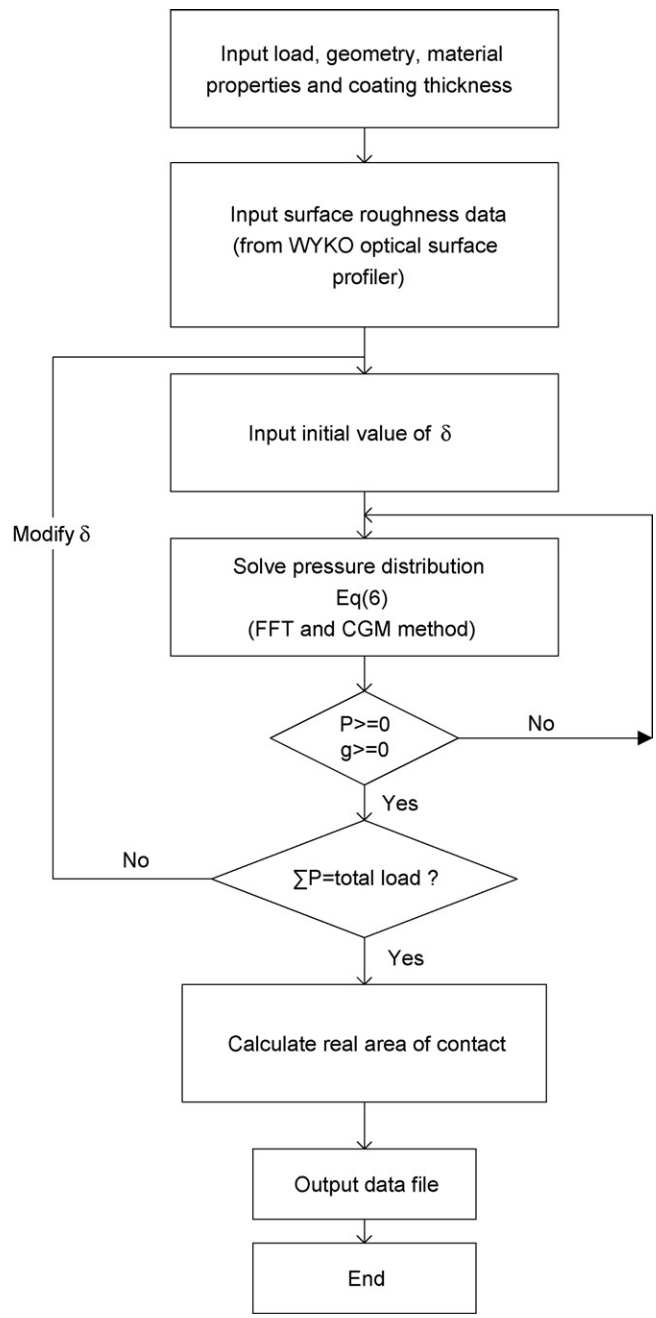

Fig. 2. Flowchart for numerical procedure.

$$\frac{1}{G} = \frac{1}{2}\left(\frac{(1+\upsilon_1)(1-2\upsilon_1)}{E_1} - \frac{(1+\upsilon_2)(1-2\upsilon_2)}{E_2}\right) \tag{5}$$

where ν is Poisson's ratio.

It is assumed that the friction force is proportional to the normal force, and the coefficient of friction, μ, is a constant. Then, the force–displacement relation can be given by

$$u(x, y) = \frac{2}{\pi E}\iint p(\xi, \eta) \times \left(\frac{1}{\sqrt{(\xi-x)^2+(\eta-y)^2}} - \frac{E}{2G}\frac{\mu(\xi-x)}{\sqrt{(\xi-x)^2+(\eta-y)^2}}\right) d\xi\, d\eta \tag{6}$$

Eq. (6) is not a complete solution since it requires the knowledge of either pressure distribution or displacement distribution, neither of which is known in advance except the load and surface geometry. Therefore, the additional constraints needed to solve Eq. (6) are

$$g(x, y) \geq 0 \qquad p(x, y) \geq 0 \tag{7}$$

where the assumption of no tension stress and no surface penetration leads to a non-negative constraints for both surface gas and contact pressure.

Eq. (6) with constraints (7) is solved through a fast Fourier transformation (FFT) based approach [8,9] and a conjugate gradient method (CGM) [9,10]. The flowchart of the numerical procedure is shown in Fig. 2. The real contact pressure distribution between the current collector and the bipolar plate can be obtained through the model. Based on the pressure distribution, the real area of contact is calculated, which is the sum of the areas with positive pressure acting on them. The real contact ratio is the ratio between the real area of contact and the nominal area of contact.

The inputs required for the model are: Young's modulus and Poisson's ratio for the current collector and bipolar plate, clamping load, nominal contact area, surface roughness data and coating film thickness. The inputted surface roughness data consists of digital surface height data measured with a WYKO optical surface profiler.

3. Results

The contact mechanics model is utilized to study the effects of roughness of the graphite plate, thickness of the gold coating of the current collector, and normal load between the current collector and the bipolar plate on real contact area. A PEM fuel cell typically makes use of a copper current collector coated with gold and a graphite bipolar plate. Properties for these materials, which were inputted to the contact mechanics model, are given in Table 1. A clamping load of 44.3 N was applied on a nominal contact area of 4.94 mm^2. This produces a clamping pressure higher than that typically used in fuel cell stacks. However, the trends seen in this study should be applicable in any pressure range.

Table 1
Material properties for current collector and bipolar plate

Material	Copper	Gold	Graphite
Young's modulus (GPa)	128	77	11
Poisson's ratio	0.33	0.42	0.31

3.1. Effect of surface roughness

Three different bipolar plate surface roughness values were used. Surface 1 was an actual three-dimensional surface roughness measurement of a ground graphite bipolar plate from an actual PEM fuel cell shown in Fig. 3. To obtain a range of roughness values, surface 2 and surface 3 height values were obtained by multiplying surface 1 values by a factor of 5 and 10, respectively. Surface 1 was found to have an arithmetic average roughness, R_a, value of 1.1 μm. Thus, surface 2 had a R_a value of 5.5 μm, and surface 3 had a R_a value of 11.0 μm. The roughness for the current collector was measured from an actual current collector and was found to have a R_a value of 0.073 μm as shown in Fig. 4. The height data from these roughness measurements were inputted into the computer simulation and the output was the real contact area between the bipolar plate and the current collector. The calculated real percentage contact areas calculated from the contact mechanics model versus surface roughness are shown in Fig. 5. The calculated areas are the sum of all contact points between the bipolar plate and the current collector. As expected, the real percentage contact area was the highest, 78.3%, for the smoothest plate followed by the intermediate roughness specimen with 43% contact area, and finally the roughest specimen with a contact area of 27.4%.

3.2. Effect of coating thickness

Three different coating thicknesses on the current collector were studied. Surface 1 had a coating thickness of 7.5 μm, surface 2 had a

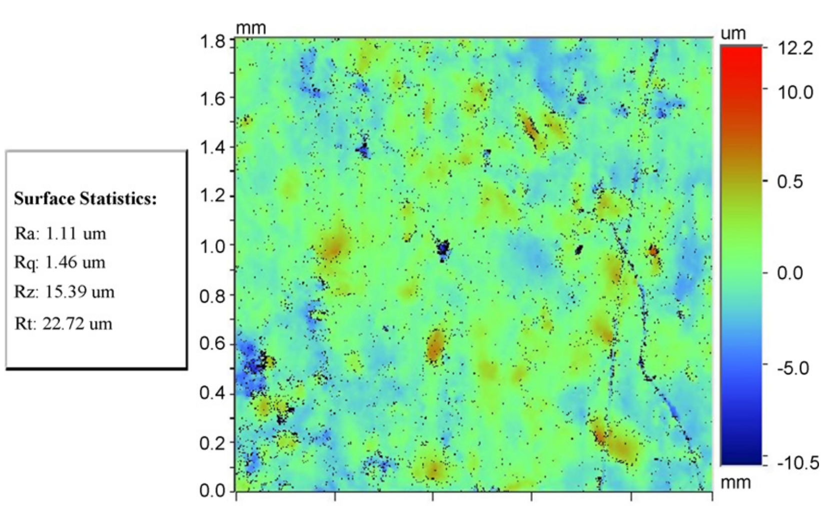

Fig. 3. Three-dimensional surface trace of graphite plate. (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

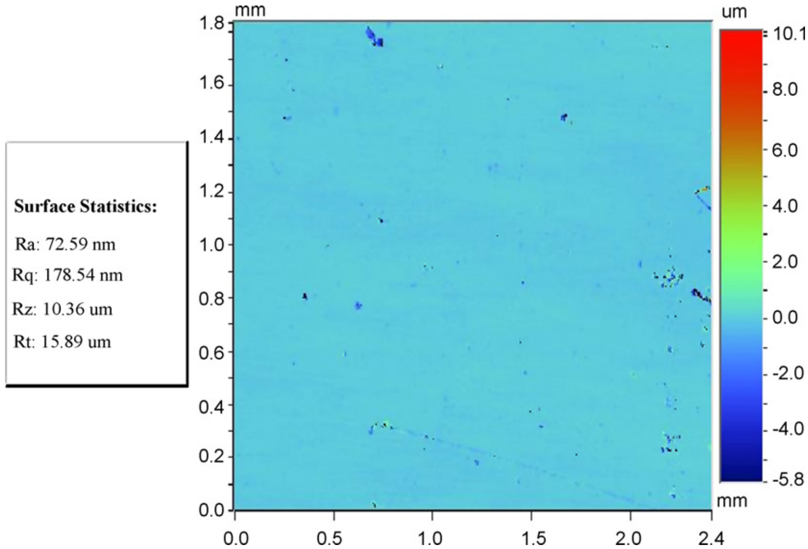

Fig. 4. Three-dimensional surface trace of current collector. (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

coating thickness of 12.5 μm, and surface 3 had a coating thickness of 25 μm. The coating thickness was inputted into the computer model and the output was the real percentage contact area between the current collector and the bipolar plate as shown in Fig. 6. The highest real contact area, 80.2%, was obtained with a coating thickness of 25 μm, followed by the intermediate coating thickness of 12.5 μm with a 78.8% contact area, and the lowest contact area, 72.5%, was obtained with the 7.5 μm coating thickness.

3.3. *Effect of clamping force*

Two different clamping forces were used. One clamping force was 44.3 N and the other was 92.0 N. These were inputted into the computer simulation and the output was the real contact area between the bipolar plate and the current collector. As expected, the highest real contact area (83.0%) was obtained with the higher clamping load. The clamping load of 44.38 N had a real contact area of 78.3%.

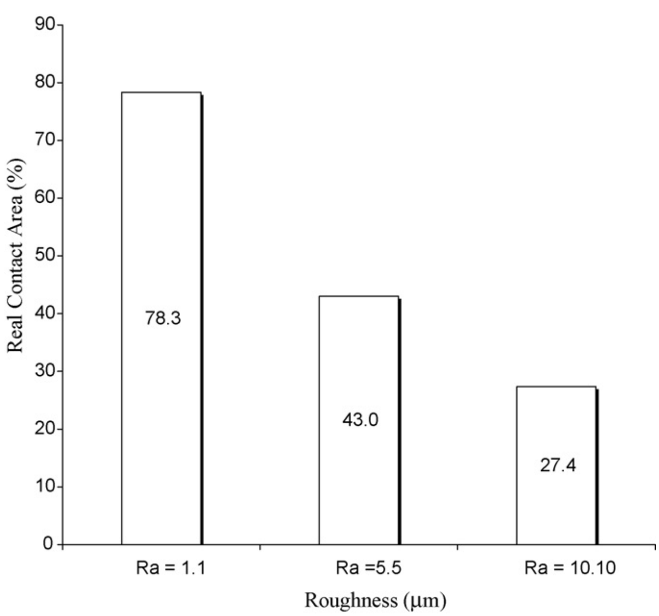

Fig. 5. Real contact area percentage vs. roughness of graphite plate.

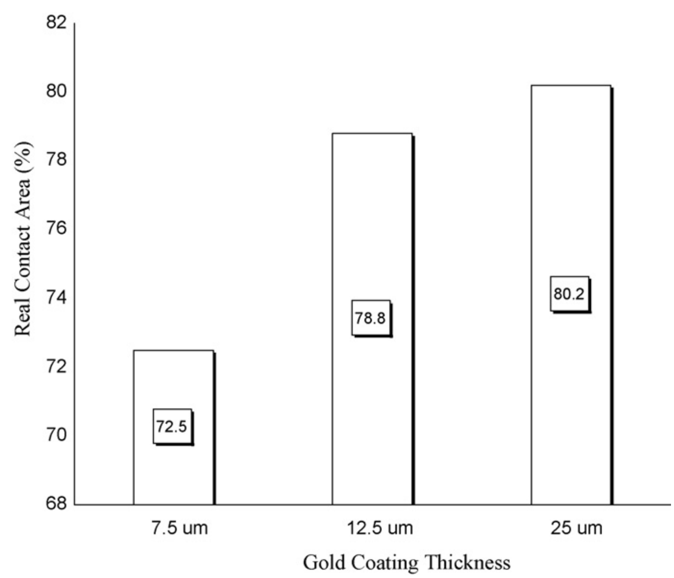

Fig. 6. Real contact area percentage vs. gold coating thickness.

4. Conclusions

In this paper, a contact mechanics model was used to determine the effects of surface roughness, coating thickness, and clamping force on the real contact area between the current collector and bipolar plate. From the data, the following conclusions are drawn:

1. When the surface is rougher, there is a lower real percentage contact area. It is important that the bipolar plate and current collector are finished to be as smooth as economically possible. Also, graphite is known to be highly porous, so graphite bipolar plate materials should be processed and selected with the minimum porosity.

2. The real contact area increases with thicker gold coatings on the current collector. This is likely due to the lower elastic modulus of the gold coating as compared to the copper base material. The gold elastically deforms more than copper with a resulting increase in real contact area.
3. A larger contact load leads to higher real contact area. The largest clamping load possible should be used in PEM fuel cells without damaging the gas diffusion layer.
4. The contact mechanics model was successfully used to determine the real contact area between the current collector and the bipolar plate. This model has the potential to be utilized at other contact interfaces in PEM fuel cells and to study the effects of new materials and various contact geometries in PEM fuel cells.

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