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Cathode/anode integrated composite bipolar plate for high-temperature PEMFC

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ABSTRACT

Carbon fiber reinforced polymer composites are ideal substitutes for the brittle graphite bipolar plate in lightweight proton exchange membrane fuel cells (PEMFCs) because of their high specific strength and stiffness. Among the various types of carbon composite bipolar plates, non-woven carbon felt based composites have recently attracted attention because they require much lower curing pressures than unidirectional carbon fiber or carbon fabric composites.

In this work, a carbon felt composite bipolar plate is developed for a high-temperature PEMFC (HT-PEMFC) using randomly oriented non-woven carbon felt and a cyanate ester-modified epoxy. The cathode and anode are integrated into a single bipolar plate to reduce the thickness and weight of the HT-PEMFC stack. The developed composite bipolar plate exhibits superior electrical properties because of the bare carbon fibers exposed on the surface by the soft layer method. In addition, the bipolar plates are dimensionally stable under high-temperature and high-pressure conditions. Finally, a cell test is performed on a 3-cell HT-PEMFC stack to investigate the cell performance.

1. Introduction

The proton exchange membrane fuel cell (PEMFC) is an electrochemical energy converter that uses hydrogen and oxygen as fuels to generate electricity. Among the various types of PEMFCs, the polybenzimidazole (PBI) membrane-based high-temperature PEMFC (HT-PEMFC) has recently attracted attention. Compared with the low-temperature PEMFCs (LT-PEMFCs), the operating temperature of the HT-PEMFCs is in the range of 120–180 °C, which offers many advantages: a higher tolerance to carbon monoxide (CO) of up to 1% [1–3], which enables a wider choice of fuels; less sensitivity of the proton conductivity to humidity, leading to the simplification of water management; and the possibility of using the exhaust gases for on-board fuel reforming or other thermal systems [4–6]. Similar to LT-PEMFCs, the main components of the HT-PEMFC are bipolar plates, proton exchange membranes, gas diffusion layers (GDLs), end plates, and gaskets, as shown in Fig. 1(a). Among these components, the bipolar plate is a multifunctional key component for HT-PEMFCs that often contributes more than 80% of the stack weight and volume [7]. The two key requirements among the various functional requirements of the bipolar plates are a high electrical conductivity in the through-thickness direction and high mechanical properties [8]. A high electrical conductivity is required to minimize the ohmic loss, while high mechanical properties are required to withstand the high compaction pressure in the stack assembly and maintain the dimensional stability at high temperature.

Many materials, such as graphite, metals, and composites, have been proposed for the bipolar plate to satisfy these requirements. Compared with conventional graphite or metals, carbon fiber reinforced polymer composites have a high specific strength and stiffness, which supports the development of a compact and lightweight PEMFC stack [9]. However, composite bipolar plates have several drawbacks that prevent their substitution for conventional materials. A large areal specific resistance (ASR) resulting from the high electrical contact resistance with the GDL due to the resin-rich area that forms on the surface of the composite has been an obstacle for carbon fiber reinforced polymer composite bipolar plates to be employed as bipolar plates [10,11]. Additionally, bipolar plates for a PEMFC require complex flow channels for fuels, which complicates the compression mold design and composite manufacturing process. Finally, conventional epoxy systems are not suitable due to the high operating temperatures of HT-PEMFCs.

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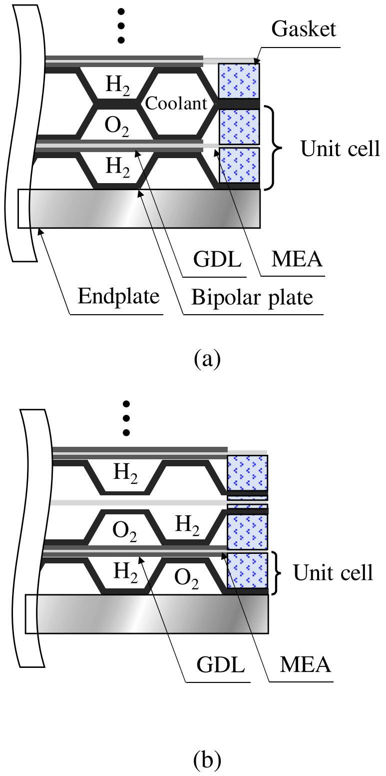

Fig. 1. Bipolar plate design: (a) conventional bipolar plate; (b) cathode/anode integrated bipolar plate.

In this study, the soft layer method, randomly oriented non-woven carbon felt, and a cyanate ester-modified epoxy were chosen to mitigate the drawbacks and develop a carbon composite bipolar plate for HT-PEMFCs. The soft layer method was used during the compression molding to expose bare carbon fibers on the composite surface, which decreased the ASR of the bipolar plate without necessitating additional surface treatments or coatings [12,13]. Randomly oriented non-woven carbon felt with low fiber volume fraction (V_f) has been adopted as a reinforcement, as it is less sensitive to the curing pressure and able to follow the complex shape of the compression mold. A cyanate ester-modified epoxy, whose glass transition temperature (T_g) is over 200 °C, was adopted as a matrix.

Because the heat removal from the HT-PEMFC is easy due to its high operating temperature and its performance is less sensitive to the temperature, the coolant channel was removed, and the cathode and anode were integrated into a single bipolar plate, as shown in Fig. 1(b). By integrating the cathode and anode bipolar plates, the thickness of a unit cell was reduced to half, which contributed to the reduction in material cost, and also decreased stack volume and weight. The electrical and mechanical properties of the developed bipolar plate were investigated by measuring the ASR and creep deformation, respectively. Finally, a cell test was performed on a 3-cell HT-PEMFC stack to investigate the cell performance.

2. Finite element analysis of compression molding

Bipolar plates for a PEMFC require complex-shaped flow channels for hydrogen and oxygen. Fig. 2(a) shows a cross-section of a typical compression mold used for the fabrication of a composite bipolar plate. When a pressure is applied on the composite laminate of uniform thickness between the upper and lower molds, the pressure applied on the cross-section of thickness t_3 will be lower than that applied on the thickness t_1 because of the height difference in the thickness direction. The applied pressure should be sufficient for the soft layer method to function properly and provide high electrical conductivity by exposing carbon fibers on the surface. However, if the mold is designed to match $t_1 = t_3$, t_2 would be very thin, which will pose a problem of enduring the high compaction pressure during the PEMFC operation. Therefore, the mold was designed to match $t_1 = t_2$, even though the applied pressure may differ from place to place.

Therefore, a finite element analysis (FEA) was performed using commercial FEA software (Abaqus 6.12, Dassault Systemes, France) to investigate the pressure distribution during compression molding. The upper and lower molds were assumed as a rigid body. Based on the compression test results of the felt, an isotropic Young's modulus of 130 MPa and a Poisson's ratio of 0.01 were assigned to the carbon felt. A frictionless contact condition was assigned between the molds and the felt. The effect of the resin was neglected because the viscosity of the resin at high temperature before cure was very low. Periodic and fixed boundary conditions were assigned at the two sides and bottom, respectively. Fig. 2(b) shows the stress distribution in the through-thickness direction when a pressure of 10 MPa was applied on the top of the upper mold. As expected from Fig. 2(a), the applied pressure is maximal at the cross-section of t_1, while it is approximately 70% lower at the cross-section of t_3. However, the pressure difference is not significant in the contact areas where the bipolar plate and GDL contact. In addition, although the pressure applied to the felt differs from place to place, the ASR of the carbon felt composite bipolar plates may change little because the ASR of the carbon felt composite is not significantly sensitive to the curing pressure unless the applied pressure is too low. Fig. 3 shows the ASRs of two types of composite bipolar plates with respect to the curing pressure. Compared to the unidirectional (UD) carbon fiber composite bipolar plate developed in the previous study [14], the carbon felt bipolar plate required much lower curing pressure to achieve the target ASR of 20 mΩ cm^2 (until 2017) established by the United States Department of Energy (DOE target), under the compaction pressure of 1.38 MPa [15]. Therefore, the carbon felt composite is a suitable material to fabricate the complex-shaped PEMFC bipolar plate.

3. Fabrication of the composite bipolar plate

Fig. 4 shows the basic concept of the cathode/anode integrated composite bipolar plate. Unlike conventional unidirectional carbon fiber and carbon fabric composites whose thicknesses are designed to be uniform throughout, as shown in Fig. 4(a), carbon felt composites can be designed to have varying thicknesses, as shown in Fig. 4(b). Using this unique characteristic, manifolds can be formed at the thicker "flat area", as shown in Fig. 4(c). Hydrogen supplied from the H_2 manifold will flow in the upper channels, while oxygen supplied from the O_2 manifold will flow in the opposite side channels. Fig. 5 shows the compression mold for the cathode/anode integrated composite bipolar plate. Short cylindrical protrusions were provided on the upper mold to fabricate holes for the tie bars during compression molding.

The composite bipolar plate was fabricated by impregnating a film-type resin sheet to the randomly oriented non-woven carbon felt (Graphite felt, Newell, China) whose properties are shown in Table 1. Two plies of carbon felt laminates were stacked to fabricate a bipolar plate. A cyanate ester-modified epoxy resin (H23, SK Chemicals, Korea) consisting of a mixture of the diglycidyl ether of bisphenol A epoxy and cyanate ester resin was adopted to combine the advantages of both cyanate ester and epoxy: the outstanding thermal property of cyanate ester and the excellent toughness