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Short communication

Bipolar plate made of carbon fiber epoxy composite for polymer electrolyte membrane fuel cells

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ABSTRACT

Polymer electrolyte membrane fuel cells (PEMFCs) are able to efficiently generate high power densities, making the technology potentially attractive for certain mobile and portable applications. Since the bipolar plate is a major part of the PEMFC stack both in weight and volume, the bipolar plate should be developed with its weight and thickness in mind.

For this paper, a bipolar plate for automotive fuel cells was developed with carbon fiber composite by compression molding due to the fact that carbon/epoxy composite has not only high electrical and thermal conductivities, but also high specific stiffness and strength. The mechanical and thermo-electrical properties of the developed composite bipolar plate were measured to investigate its suitability for the automotive fuel cell.

1. Introduction

The polymer electrolyte membrane fuel cell (PEMFC) is expected to be one of the major power sources for future passenger vehicles since it features a high power density at a relatively low operating temperature of about 80 °C. Moreover, it may not only enable vehicle weight reduction, but could also ease cold starts [1]. Fig. 1 shows the stack of a PEMFC that is composed of various components such as bipolar plates, end plates, the membrane electrode assembly (MEA), and the gas diffusion layer (GDL).

The bipolar plate is a multi-functional component in a PEMFC stack. It provides the electrical connection from cell-to-cell and it separates the reactive gases. On the anode side of the plate, hydrogen gas is consumed to produce electrons and protons as follows:

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

The electrons are collected at the anode and the protons enter the electrolyte (oxidation of hydrogen). On the other side of the plate, i.e. at the cathode, oxygen gas combines with electrons from the cathode and protons from the electrolyte to produce water (reduction of oxygen) [2] as follows:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

In addition, the bipolar plate serves the following functions: (i) it facilitates water management within the cell; (ii) it enables heat transfer; (iii) it supports thin membranes and electrodes; (iv) it withstands the clamping forces of the stack assembly [3]. The material requirements shown in Table 1 should be satisfied for the construction of a bipolar plate.

Graphite is the most commonly used material for a bipolar plate. Graphite has a good electrical conductivity and excellent corrosion resistance with a low density of about 2 g cm^{-3}. However, it lacks mechanical strength and has poor ductility. This limits the minimum plate thickness to about 5–6 mm and machining is usually employed to fabricate the flow channels in the bipolar plate. Machining graphite into the often complex designs employed in bipolar plates is prohibitively expensive and time-consuming and is not at all suited to the levels of mass production required for the full scale commercialization of fuel cells [4].

Metal is also a good material for the bipolar plate. It offers good electrical conductivity, excellent mechanical properties and ease of fabrication, but is unable to resist corrosion in fuel cells. Corrosion of a metal bipolar plate leads to the release of multivalent cations, which can lead to an increase in membrane resistance and poisoning of the electrode catalyst [5–8]. Titanium offers excellent electrical performance and power densities, but

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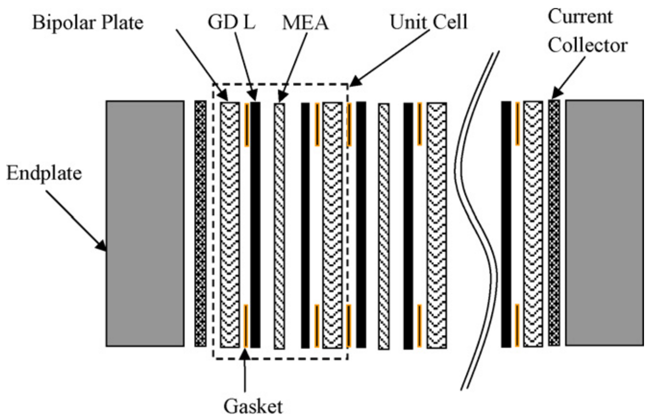

Fig. 1. Schematic drawing of the PEMFC.

Table 1
Required properties for the bipolar plate

In-plane electrical conductivity ($S\,cm^{-1}$)	>100[a]
Thermal conductivity ($W\,(m\,K)^{-1}$)	>20[a]
Gas permeability ($m^3\,m^{-2}\,s^{-1}$)	>2×10^{-8}[a]
Flexural strength (MPa)	>59[b]
Tensile strength (MPa)	>41[b]
Corrosion resistance (pH < 4) ($\mu A\,m^{-2}$)	<16×10^{-4}[a]

[a] DOE targets.
[b] Plug Power targets [14].

it is expensive and requires precious metal coatings for durability. Stainless steel offers reasonable power and low material and production costs, but provides lower gravimetric performance and may require the application of a coating to make it resistant to corrosion.

Bipolar plates for fuel cells should possess high enough mechanical strength and stiffness to support thin membranes and electrodes, and to withstand the high clamping forces in the stack assembly.

Carbon composite bipolar plates are an attractive option for PEM fuel cell use. They not only offer the advantage of low cost, lower weight and greater ease of manufacture than traditional graphite, but their properties can also be tailored by using different reinforcements and resin systems. Two different types of resin are used to fabricate composite plates: thermoplastic and thermosetting [9].

For this paper, high modulus carbon fiber reinforced epoxy composite was employed as the material for bipolar plates in order to meet the requirements shown in Table 1. The flexural strength of the composites was measured for two cases: plate and corrugated specimens. Tensile and compressive tests were performed both at a room temperature of 25 °C and at the fuel cell operating temperature of 80 °C. The thermal and electrical properties of the specimens were also measured.

2. Experimental

2.1. Materials and fabrication for a bipolar plate

For polymers doped with conductive particles or fibers, it is difficult to achieve a high enough conductivity and sufficient mechanical properties simultaneously [10]. Moreover, when channels exist on the surface of a bipolar plate, its mechanical properties will be different from those of a composite plate without channels. In our work, therefore, the high-modulus pitch-based unidirectional carbon fiber epoxy prepreg URN 300 (SK Chemicals, Korea) was chosen for the bipolar plates because it has good electrical and thermal conductivities as well as good mechanical properties. The general properties of URN 300 are listed in Table 2.

Table 2
General properties of prepreg URN 300

Tensile modulus (GPa)	
Longitudinal	380
Transverse	5.1
Shear	5.53
Tensile strength (MPa)	
Longitudinal	1500
Transverse	65
Shear	40
Poisson's ratio	0.3
Density ($kg\,m^{-3}$)	1.75×10^3
Fiber properties	
Modulus (GPa)	640
Strength (MPa)	2600
Density ($kg\,m^{-3}$)	2.12×10^3
Thickness (m)	0.25×10^{-3}

In order to fabricate a composite bipolar plate, the three layers of prepreg were stacked on the bottom mold using the stacking sequence [0/90/0]. Then resin bleeders and porous Teflon films were placed on the prepregs during compression molding with a hot press as shown in Fig. 2 in order to remove excess resin and decrease the contact electrical resistance of the prepregs [11]. The bottom and top molds for the bipolar plates were designed in a corrugated shape that is used for flow channels, as shown in Fig. 2. The corrugated flow channels in the prepregs were formed by applying 20 MPa pressure and 125 °C temperature through the bottom and top molds during the curing process. Composite bipolar plate with flow channels was fabricated as a mirror image of the mold. The density of the composite bipolar plate was $1.82\times10^3\,kg\,m^{-3}$, which was much smaller than that of stainless steel ($7.8\times10^3\,kg\,m^{-3}$).

2.2. Measurement of mechanical properties

In order to verify the feasibility of the composite bipolar plate fabricated for our work, the flexural properties of the composite plate with flow channels and that without flow channels were measured by the three-point bending test according to ASTM D 790-03 at both a room temperature of 25 °C and the fuel cells operating

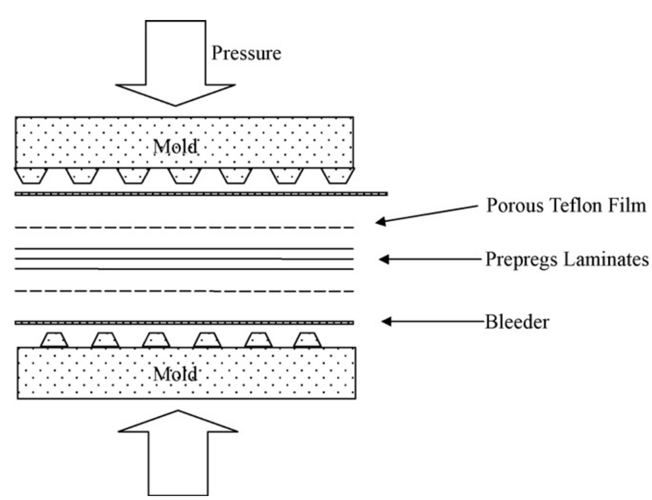

Fig. 2. Schematic drawing of the compression molding of the composite plate.

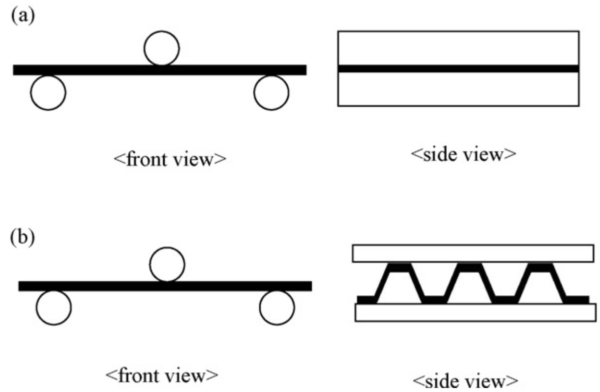

Fig. 3. Schematic drawing of the three-point bending tests: (a) plate; (b) corrugated specimen.

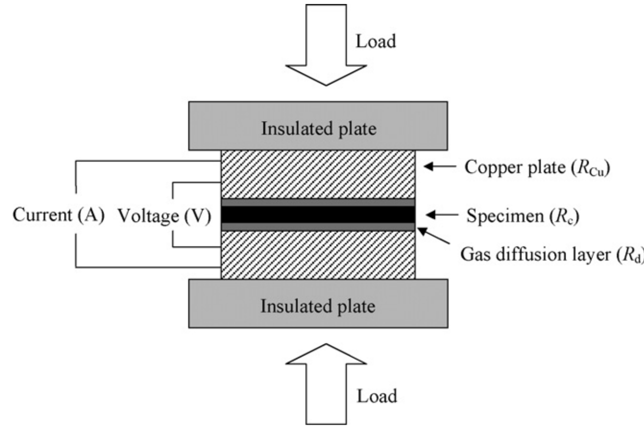

Fig. 5. Schematic drawing of the area specific resistance measurement.

temperature of 80 °C. Fig. 3 shows a schematic of the three point bending test.

In addition, to verify whether the bipolar plate supports the clamping forces of a PEMFC stack, the compressive tests of the composite bipolar plates with flow channels were conducted at 25 °C and 80 °C following the specification of ASTM D 695-02a. Also, tensile strength was measured according to the specification of ASTM D 638.

2.3. Measurement of the electrical conductivity and contact resistance

The prepregs of URN 300 were stacked in order to prepare laminate specimens using the stacking sequence $[0/90]_{3s}$ to measure the in-plane electrical conductivity. The specimens were cut with a diamond wheel cutter to the dimensions shown in Fig. 4. Electrodes for the specimen were produced at the specimen sides by application of silver paste to supply uniform electrical current. With the measured resistance, the electrical conductivity (σ) was calculated as follows:

$$\sigma = \frac{L}{RA} \quad (3)$$

where R is the electrical resistance, A is the area of the plane, and L is the length of the specimen.

The area specific resistance (ASR) of the composite was measured with the experimental setup shown in Fig. 5. A direct current of 2.0 A and alternating current with an amplitude of 0.2 A were supplied via the two copper plates in the electrochemical workstation IM6 (ZAHNER-elektrik GmbH & Co. KG, Germany). Two compaction pressures of 1.0 MPa and 0.5 MPa were applied to the specimen using the INSTRON 5566.

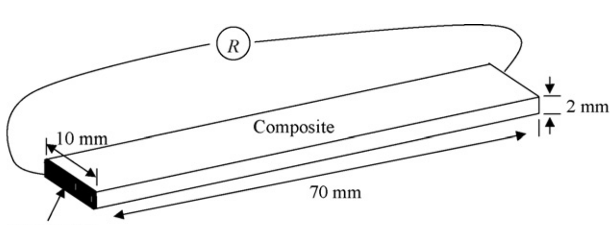

Fig. 4. Schematic drawing of the in-plane electrical conductivity measurement.

2.4. Measurement of thermal properties

Thermal properties were measured by using the specimen with a stacking sequence of [0/90/0]. In-plane and through-thickness thermal conductivities were measured with a Xenon flash apparatus (Nanoflash LFA 447, Netzsch, Germany).

In addition, the thermal stability of the bipolar plate was measured using thermal degradation temperatures, such as T_1 and T_2, by thermogravimetric analysis (TGA) with a Thermal Analyzer (Setsys 16/18, Setaram, France). The values of T_1 and T_2 were determined from the TGA curves at 5% weight loss and at maximum rate of weight loss, respectively [3]. Furthermore, the mass loss at constant temperature (120 °C) for 2 h, which is the highest operating temperature, was also measured.

The coefficient of thermal expansion of the carbon composite was measured with a TMA 2940 (TA Instruments, USA).

2.5. Measurement of gas permeability

To determine the gas permeability of the bipolar plate, air was supplied to the specimen and amount of the air transmitted was measured, as shown in Fig. 6.

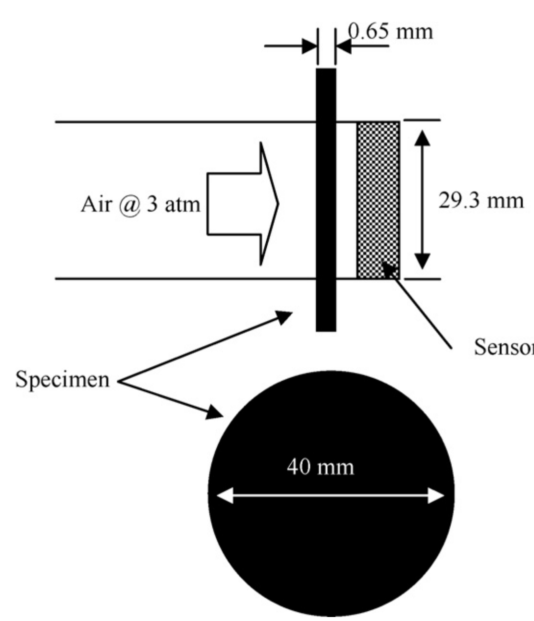

Fig. 6. Schematic drawing of the gas permeability measurement.

Table 3
Mechanical properties of several polymer composite bipolar plates.

Manufacturer	Polymer	Graphite/fiber (wt%/wt%)	Flexural strength (MPa)	Tensile strength (MPa)
Target	–	–	>59	>41
GE [12]	PVDF	64/16 CF	42.7	–
LANL [13]	Vinyl ester	68/0	29.6	23.4
Plug Power [14]	Vinyl ester	68/0	40.0	26.2
DuPont [15]	–	–	53.1	25.1
Virginia Tech [16]	PET	65/7 GF	53	36.5
Virginia Tech [10]	15% PVDF laminate	70/6 CF	54.4	32.7
Virginia Tech [17]	PPS	70/6 CF	95.8	57.5

CF: carbon fiber, GF: glass fiber.

2.6. Morphology

The morphology of the carbon composite bipolar plate was characterized using a scanning electron microscope (SEM) (HITACHI S4300, Japan).

3. Results and discussion

3.1. Mechanical properties

The flexural strengths of the previous composite bipolar plates were primarily significantly lower than the target value of 59 MPa, as listed in Table 3. However, the composite bipolar plate without corrugated flow channels had a flexural strength of 316 MPa at both room temperature and operating temperature, and the composite bipolar plate with corrugated flow channels had a flexural strength of 195 MPa at room temperature and 180 MPa at operating temperature. The strength of the bipolar plate with corrugated flow channels was reduced because of a stress concentration at the corner of the channel due to its prismatic shape and the load concentration at several points.

The clamping force affects permeability and diffusion of the reactant gas and the transport of liquid water due to the deformation of the GDL and porosity variation. A low clamping force increases the interfacial electrical resistance, but a high clamping force decreases the GDL porosity and thus increases the transport resistance of the gas as well as liquid water [18]. Therefore, the composite bipolar plate should be able to support a minimum constant clamping force. The compressive test showed that the composite bipolar plate could endure up to 3.3 MPa at room temperature and 2.9 MPa at operating temperature, which was far more than the required clamping force of 1.2 MPa.

The composite bipolar plate had a tensile strength of 520 MPa at room temperature and 460 MPa at operating temperature, which is much greater than the other previous composite bipolar plates shown in Table 3.

3.2. Electrical conductivities

The in-plane electrical conductivity of the cross-ply composite used for this work was 300 S cm^{-1} which was much higher than the DOE target of 100 S cm^{-1}. This is because the pitch based continuous carbon fiber has high electrical conductivity. The fiber volume fraction was high due to the high-applied pressure during the compression molding shown in Fig. 7.

The area specific resistance is an important property in the fuel cell stack because the energy loss in the fuel cell is proportional to the value of ASR. The values of ASR for the composite bipolar plate were 42 mΩ cm^2 and 58 mΩ cm^2 when the compaction pressures were 1.0 MPa and 0.5 MPa, respectively.

3.3. Thermal conductivities

The thermal conductivity of the bipolar plate should be higher than 20 W $(m\,K)^{-1}$ for the efficient cooling of fuel cells. The thermal conductivities of the composite bipolar plate in the in-plane and through-thickness directions were 85 W $(m\,K)^{-1}$ and 5 W $(m\,K)^{-1}$, respectively. The high in-plane thermal conductivity of the plate was due to the high thermal conductivity of high-modulus continuous carbon fiber. The through-thickness thermal conductivity of 5 W $(m\,K)^{-1}$ was lower than the target value of 20 W $(m\,K)^{-1}$. However, since the thickness of the composite bipolar plate was very small and the in-plane thermal conductivity was high, the heat generated in the bipolar plate during operation may be efficiently transferred from the inside to outside of a stack through in-plane thermal conductive layers.

3.4. Gas permeability

Both the high carbon fiber volume fraction and strong bond between carbon fiber and epoxy resin induce low gas permeability in the composite. The measured permeability was about 1.4×10^{-8} $m^3\,m^{-2}\,s^{-1}$, which was smaller than 2×10^{-8} $m^3\,m^{-2}\,s^{-1}$ for the bipolar plate application.

3.5. Thermal stability

The measured thermal degradation temperatures T_1 and T_2 of the composite were 412 °C and 355 °C. There was no loss of mass at the maximum temperature of 120 °C for the PEMFC, as shown in Fig. 8.

The coefficient of thermal expansion (CTE) of the bipolar plate is important because a large CTE might allow gas to leak due to the dif-

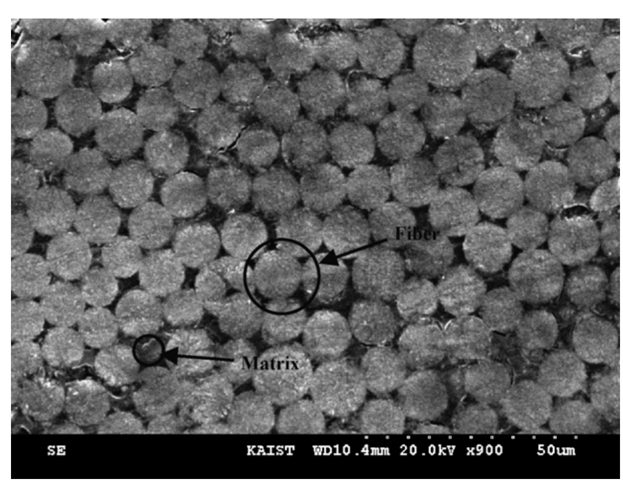

Fig. 7. SEM image of the composite bipolar plate.

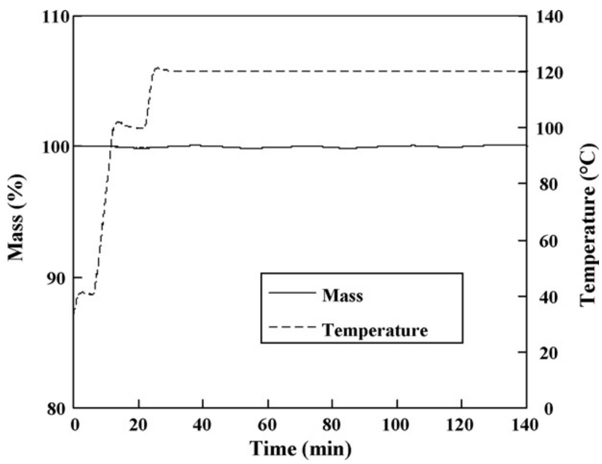

Fig. 8. Mass loss of the composite bipolar plate at 120 °C.

ference in CTE between the gasket and the bipolar plates. The value of CTE for the composite bipolar plate was -0.1×10^{-6} m (m °C)$^{-1}$, which was much smaller than 11–15 $\times 10^{-6}$ m (m °C)$^{-1}$ usual for stainless steel.

These data indicate that the composite bipolar plate developed during this work was thermally and dimensionally stable at the operating temperatures of a PEMFC.

4. Conclusion

The bipolar plate for a PEMFC for automobiles was developed with a high-modulus pitch based continuous carbon fiber epoxy composite. The mechanical and thermo-electrical properties of the composite bipolar plate were measured. From the experiments, it was found that the flexural strength of the corrugated composite bipolar plate was about 195 MPa at both room temperature and the operating temperature of 80 °C, which was much higher than for other candidate materials and well beyond the target value of 59 MPa. The in-plane electrical conductivity was 300 S cm^{-1}, which was three times higher than the target value of 100 S cm^{-1}. The thermal conductivity was 85 W (m K)$^{-1}$, which was much higher than the target value of 20 W (m K)$^{-1}$. The thermal stability of the composite bipolar plate was verified by TGA and the gas permeability of 1.4×10^{-6} cm^3 (cm^2 s)$^{-1}$ for air at 0.3 MPa was also satisfactory for the bipolar plate application.

From our work, it can be concluded that high-modulus pitch based carbon fiber reinforced polymer composite is a very promising material compared with conventional materials, which have low mechanical strength and are difficult to fabricate into bipolar plates.

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