Axiomatic Design of Carbon Composite Bipolar Plates for PEMFC Vehicles

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Abstract

A PEMFC (Polymer Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell) stack is composed of Gas Diffusion Layers (GDLs), Membrane Electrode Assemblies (MEAs), endplates and bipolar plates. The bipolar plates are multifunctional components as they collect and conduct the current from cell to cell, separate the fuel and oxidant gases and provide flow channels in the plates to deliver the reacting gases to the fuel cell electrodes. The electrical resistance of bipolar plates should be very low in order to conduct the electricity generated in the fuel cell with minimum electrical loss. In this study, the concept of the continuous carbon fiber composite bipolar plate coated with graphite foil is suggested by Axiomatic Design Theory and verified experimentally. Consequently, the total resistance in the through thickness direction of composite bipolar plate was reduced by 86% compared to that of conventional composite bipolar plates through the employment of a graphite coating layer.

Keywords:
PEMFC, Bipolar plate, Axiomatic Design, Graphite coating method

1 INTRODUCTION

A polymer electrolyte membrane fuel cell or proton exchange membrane fuel cell (PEMFC) is an electrochemical energy converter that converts the chemical energy of fuel directly into DC electricity when hydrogen and oxygen are supplied to the anode and cathode, respectively, producing water and electricity through the electrochemical reaction without making any pollutants. Therefore, the PEMFC is a promising power source candidate for automobiles, small-scale stationary power generations, and portable power applications [1-3]. A PEMFC stack is composed of Membrane Electrode Assembly (MEAs), Gas Diffusion Layers (GDLs), endplates and bipolar plates as shown in Figure 1.

The bipolar plates have several functions in the fuel cell stack. They provide flow channels for reactant gases to maintain a proper pressure distribution over the whole active area of membrane electrode assembly, transmit electrons from an anode to its adjacent cathode in a unit cell, transfer the reaction heat from active area to coolant and provides coolant flow paths as shown in Figure 2 [1]. Therefore, there have been many research projects about the development of bipolar plates using various materials such as graphite, metal, and composites. However, graphite is not at all suited to the levels of mass production required for the full-scale commercialization of fuel cells because of its sophisticated machinery manufacturing process. Metallic bipolar plates have corrosion problems because the inside of a fuel cell is a very corrosive environment due to the presence of strong acids ranging from pH 2 to 3. From an Axiomatic Design perspective, both the graphite and metallic bipolar plate designs are typical coupled-designs where the number of design parameters (DPs) is less than the number of functional requirements (FRs) [4]. Continuous carbon fiber reinforced composite bipolar plates are plausible options for PEMFCs because they not only offer the advantages of low cost, high corrosion resistivity, lower weight and greater ease of manufacture than traditional graphite, but also their mechanical properties are strong enough to meet the DOE target [5,6].

However, the high interfacial contact electrical resistance of the composite material in the through-thickness direction is an obstacle to overcome. The high electrical conductivity of bipolar plate materials in the through-thickness direction is very important for the efficiency of the PEMFCs. The lower the electrical resistance of bipolar plates for the PEMFC, the less electrical loss or higher energy conversion efficiency will be. The resistance of the bipolar plate of the PEMFC consists of bulk material resistance and interfacial contact resistance (ICR). The bulk resistance is not a significant source of voltage loss in fuel cells, even for relatively high-resistivity plates. Although the electrical conductivity of the composite is several orders of magnitude lower than the conductivity of the metallic plates, the bulk resistive losses are on the order of several millivolts. Much higher resistance results from the interfacial contacts, such as between the bipolar plate and GDL [1, 7].

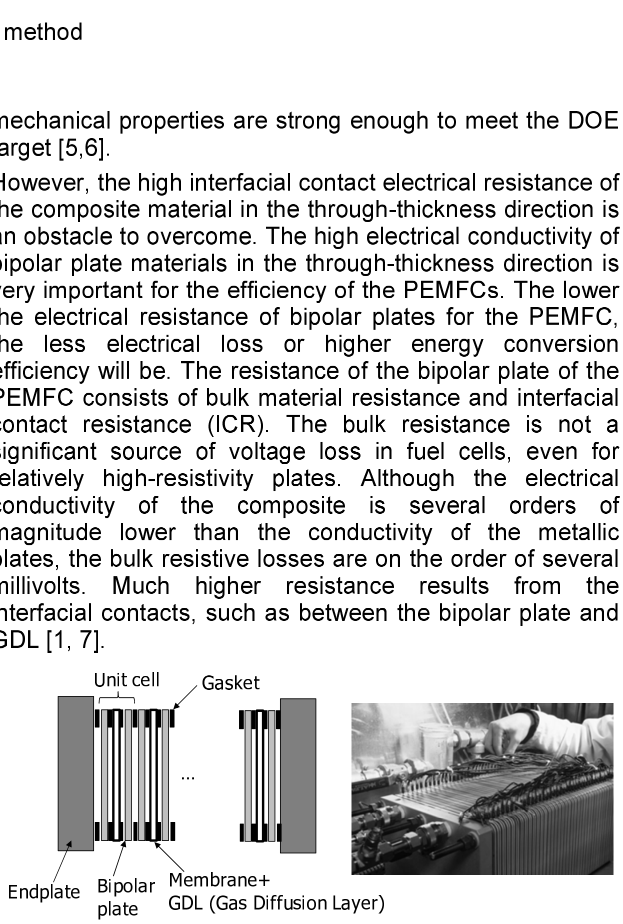

Figure 1: Proton exchange membrane fuel cell stack components.

In this study, this coupled-design problem of the PEMFC was solved based on Axiomatic Design Theory. Since the ICR between the GDL and composite bipolar plate is a function of the surface hardness of the composite, graphite was coated on the composite bipolar plate in order to lower the surface hardness while keeping high mechanical strength and stiffness of the composite bipolar plate. Then, the effectiveness of this design method was experimentally verified.

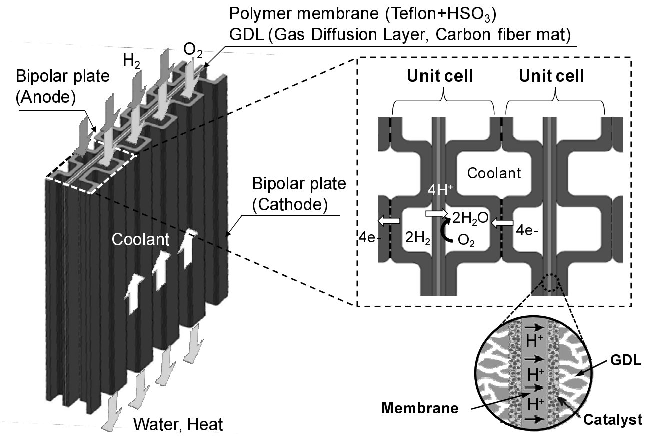

Figure 2: Unit cell of the PEMFC stack.

2 AXIOMATIC DESIGN OF THE COMPOSITE BIPOLAR PLATE

The functional requirements of bipolar plates can be summarized using Axiomatic Design Theory as follows:

FR_1 = Reduce the electrical resistance of cells in series connection.

FR_2 = Provide the structural support for the stack.

FR_3 = Separate the fuel and oxygen gases in adjacent cells.

FR_4 = Have corrosion resistance.

FR_5 = Provide flow channels.

In order to satisfy the functional requirements (FRs), in this work, the following design parameters (DPs) were developed and a design matrix was established as follows:

DP_1 = Carbon composite materials with high electrical conductivity

DP_2 = High strength and stiffness carbon composites

DP_3 = Consolidation of composites

DP_4 = Resin with high corrosion resistivity

DP_5 = Formability of carbon fibers

As shown in Figure 3, the design matrix reveals that the bipolar plate design is an acceptable decoupled-design by using the continuous carbon fiber reinforced composite with high electrical conductivity and high structural strength [8].

	DP_1	DP_2	DP_3	DP_4	DP_5
FR_1	X	0	0	0	0
FR_2	0	X	x	0	0
FR_3	0	0	X	0	0
FR_4	0	0	0	X	0
FR_5	0	0	0	0	X

Figure 3: Design matrix of the carbon composite bipolar plate.

3 AXIOMATIC DESIGN FOR THE ELECTRICAL CHARACTERISTICS OF THE COMPOSITE BIPOLAR PLATE

3.1 Decomposition of FR of the composite bipolar plate

At the highest level of design, it was found that the continuous carbon fiber composite could satisfy the functional requirements of the bipolar plate. However, a voltage loss occurs due to the bulk resistance of the bipolar plate material and the interfacial contact resistance between the bipolar plate and the GDL. Therefore, the FR_1 was decomposed as follows:

FR_1 = Reduce the electrical resistance of cells in series connection.

FR_{11} = Have low bulk resistance.

FR_{12} = Have low interfacial contact resistance.

The bulk resistance of the composite bipolar plate depends on the volume fraction of the carbon fiber while the interfacial contact resistance is related to the contact surface conditions. The ICR is affected by not only the surface electrical conductivity of the materials but also the contact surface area and contact pressure. The lower surface hardness is suitable for reducing the interfacial contact resistance, however, it does not meet the requirement of the mechanical strength for the bipolar plate. Decomposing the FR_1 as FR_{11} and FR_{12}, composite bipolar plate design is coupled as shown in Figure 4 [4,8].

3.2 Decoupled-design of the composite bipolar plate

In this study, the surface treatment method of the composite plate was proposed as the new design parameter to decouple the composite bipolar plate design as shown in Figure 5. As a result, DPs and FRs equalized in number, and the DP_{11} and DP_{12} could be written as follows:

DP_1 = Carbon composite materials with high electrical conductivity

DP_{11} = Carbon fiber volume fraction of composites

DP_{12} = Surface characteristics of composites

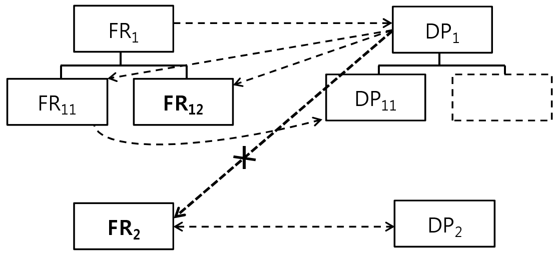

Figure 4: Coupled-design by decomposing the FR_1.

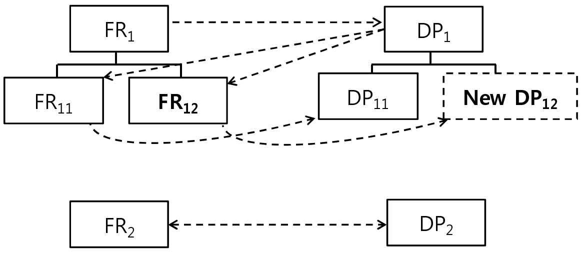

Figure 5: Decoupled-design by creating the DP_{12}.

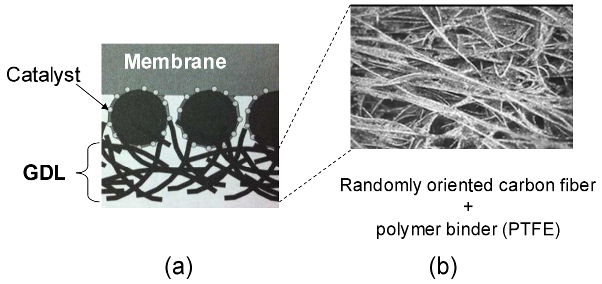

Figure 6: GDL: (a) Schematic diagram, (b) Microscope image.

It was known that the graphite foil has very low contact resistance due to its conformability. The interfacial contact resistance is affected by the surface condition of the GDL, which provides pathways for reactant gases from the flow field channels to the catalyst layer, allowing them access to the entire active area as well as the electrical connections from the catalyst layer to the bipolar plate [9]. As shown in Figure 6, the GDL consists of a randomly oriented carbon fiber mat. The randomly oriented carbon fiber side is the contact surface with the bipolar plate. Considering the surface condition of the GDL, a graphite layer with low hardness on the composite surface could increase the contact area effectively as shown in Figure 7. Therefore, the composite bipolar plate is a decoupled-design without compromising its mechanical strength and stiffness by creating a design parameter which is a graphite foil coating method.

4 COMPOSITE BIPOLAR PLATE WITH THIN GRAPHITE LAYER

The composite bipolar plate design was verified experimentally. A thin layer of graphite could be coated on the carbon/epoxy composite plate surfaces by using the prepregs coated with the graphite foil. Therefore, the graphite coating method did not require any post process after demolding the composite plate from the mold. Figure 8 shows the process of the graphite coating method, where the graphite foils with a backup film were placed on the both surfaces of the stacked prepregs.

It was laminated using the hot roller of 80°C to make the sticky resin of prepregs hold the graphite foil, and then the backup films were removed. Finally, it was found that a thin graphite layer was transferred on the surfaces of the stacked prepregs.

4.1 Experiment

The materials used in this study were carbon/epoxy prepreg USN 020 (SK Chemicals, Korea) and the thin graphite foil was BD-100 (Samjung CNG, Korea). The properties of USN 020 and BD-100 are listed in Table 1. The graphite layers were coated on the stacked composite prepregs surfaces. Then with the stacked prepregs, the composite bipolar plate was manufactured by a compression molding method under a pressure of 11 MPa at 160°C for 40 minutes. The stacking sequence of the specimen was $[0]_8$ and the thickness of the carbon/epoxy composite plate was 0.15 mm.

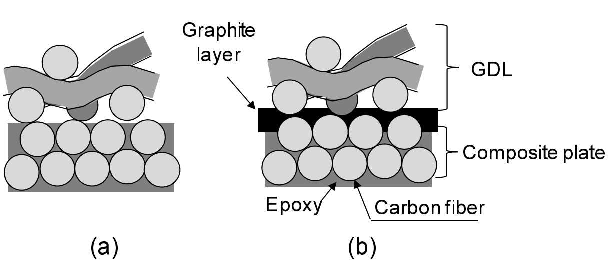

Figure 7: Schematic drawings of interfacial contact condition between the GDL and the composite plate (a) without treatment, (b) with the graphite coating method.

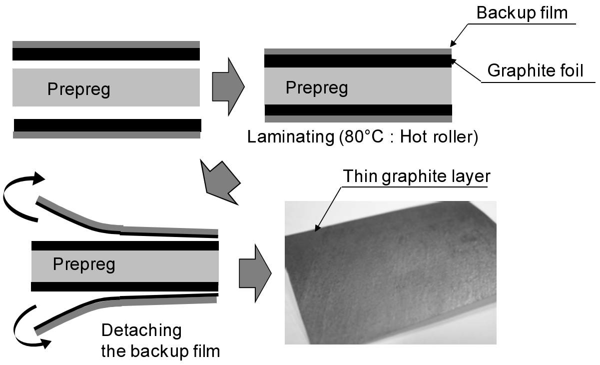

Figure 8: Graphite coating process of the composite prepreg.

The morphology of the thin composite bipolar plates with the graphite coating layer of 2 µm was observed with a scanning electron microscope (SEM) (Sirion, FEI, Netherlands).

Also, the electrical resistance in the through-thickness direction of the thin composite plate was measured using a specimen size of 100 mm × 100 mm with the experiment setup as shown in Figure 9. The electrical resistance depends on several resistances in series, such as the resistance of the two copper electrodes (R_{Cu}), two GDLs (R_{GDL}), the bulk resistance of the specimen (R_b), and more significantly the contact resistances between the GDL and the specimen ($R_{GDL/b}$). They were measured under the four bipolar compaction pressures of 0.5 MPa, 0.8 MPa, 1.0 MPa and 1.5 MPa [10]. Also the electrical resistances of the graphite plate (0.4 mm) and the composite plate without treatment were measured to compare with that of the composite plate with graphite layer.

4.2 Result

Figure 10 shows the cross section of the composite plate surface with the graphite layer of 2 µm. In Figure 11, The electrical resistance in the through-thickness direction of the composite bipolar plate with the graphite coating layer of 2 µm decreased 86% compared to that of the composite bipolar plate without surface treatment under the compaction pressure of 1 MPa. Therefore, it was found that the thin graphite layer could reduce the interfacial contact resistance between the composite and the GDL effectively.

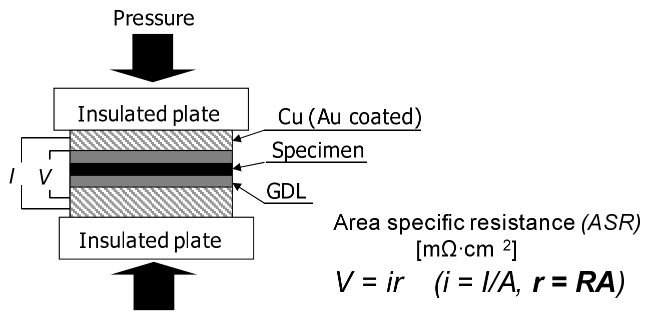

Figure 9: Experimental setup to measure the electrical resistance in the through-thickness direction.

Carbon prepreg (USN 020, SK chemical, Korea)	Fiber properties	Modulus (GPa)	230
		Strength (GPa)	3.5
	Ply thickness (mm)		0.02
Graphite foil (BD-100, Samjung CNG, Korea)	Density (kg/m^3)		1.0
	Thickness (μm)		100

Table 1: Properties of prepreg (USN 020) and graphite foil (BD-100).

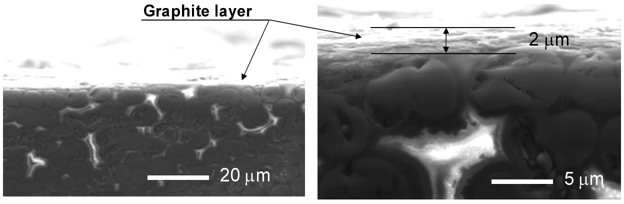

Figure 10: SEM images of the composite plate coated with the graphite layer of 2 μm.

5 CONCLUSION

In this study, the concept of a continuous carbon fiber composite bipolar plate coated with graphite foil was suggested by Axiomatic Design Theory. Carbon composites satisfied the functional requirements of the bipolar plate at the highest design level. However, in the process of decomposing the functional requirement on the electrical resistance, the design became a coupled-design because the soft materials to reduce the interfacial contact resistance, and the requirement of enough mechanical strength and stiffness to support the stack components were incompatible. Therefore, a new design parameter was developed to make the composite bipolar plate design decoupled. To this end, a thin graphite layer coating method was devised to lower the surface hardness of the composite plate.

The decoupled design was verified by measuring the electrical resistance in the through-thickness direction of the composite plate. As a result, the total resistance in through thickness direction of the composite bipolar plate with the graphite coating layer was reduced 86% compared to that of the conventional composite bipolar plate without compromising its mechanical properties. It was found that the continuous carbon composite coated with the graphite layer was a promising material for the bipolar plate of PEMFC by Axiomatic Design.

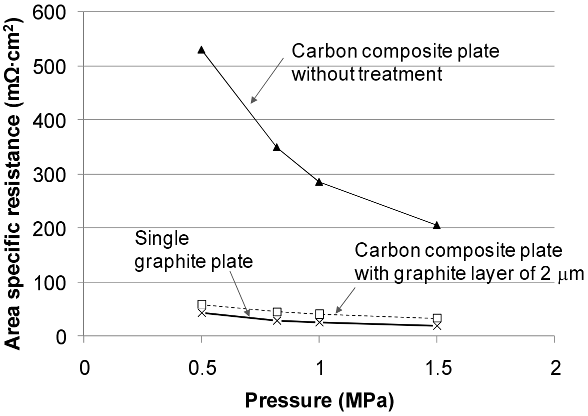

Figure 11: Area specific resistances of the specimens in the through-thickness direction with respect to the kinds of materials and surface conditions.

6 ACKNOWLEDGMENTS

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