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Integrated carbon composite bipolar plate for polymer–electrolyte membrane fuel cells

Ha Na Yu, In Uk Hwang, Seong Su Kim, Dai Gil Lee*

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, ME3221, Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea

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ABSTRACT

The electrical resistance of bipolar plates for polymer–electrolyte membrane fuel cells (PEMFCs) should be very low to conduct the electricity generated with minimum electrical loss. The resistance of a bipolar plate consists of the bulk material resistance and the interfacial contact resistance when two such plates are contacted to provide channels for fuel and air (oxygen) supplies.

Since the interfacial contact resistance is much larger than the bulk resistance in an actual fuel cell stack, an integrated carbon composite bipolar plate is developed in this study to eliminate the contact resistance between contacting bipolar plates. To fabricate this plate with channels for fuel, air and coolant, many stainless-steel pipes of 1 mm diameter are uniformly embedded in the carbon fiber/epoxy composite prepreg and co-cured. The contact resistance, flexural strength and thermal degradation temperatures of the developed composite bipolar plate are then measured.

1. Introduction

A fuel cell efficiently generates electrical power from chemical energy without causing pollution. The exhaust does not contain any toxic pollutants such as NO_x or SO_x; instead, only pure water and heat are produced as by-products of fuel cell operation. The polymer–electrolyte membrane fuel cells (PEMFCs) are expected to be one of the major power sources for future passenger vehicles due to their high specific power and relatively low operating temperature (about 80 °C) [1].

The PEMFC is composed of bipolar plates, end plates, a membrane electrode assembly (MEA) and a gas diffusion layer (GDL). The unit cell in a stack comprises GDL–MEA–GDL layers sandwiched between bipolar plates.

The bipolar plates are a multi-functional component of the PEMFC stack, as they collect and conduct the current from cell to cell and separate the gases and flow channels in the plates to deliver the reacting gases to the electrodes [2]. In a typical stack, the bipolar plates comprise over 80% of the mass and almost all of the volume [3]. The bipolar plates should also possess sufficient mechanical strength and stiffness to support thin membranes and electrodes and to withstand the high clamping forces in the stack assembly [4].

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

Metal is also a good material for bipolar plate construction because it offers good electrical conductivity, excellent mechanical properties and ease of fabrication. It is unable, however, to resist corrosion in fuel cells, and this leads to the release of multivalent cations, a subsequent increase in membrane resistance and poisoning of the electrode catalyst [6–9]. Titanium offers excellent electrical performance and power densities, but it is expensive and requires the application of precious metal coatings for durability. Stain-less steel offers reasonable power and low material and production costs, but provides lower specific power and energy and may require the application of a coating to make it resistant to corrosion.

Carbon-fiber composite bipolar plates are an attractive option for PEMFC fuel cell use. They not only have the advantages 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 may be employed to fabricate composite plates namely, thermoplastic and thermosetting [10].

One of the most important properties of fuel cell bipolar plates is their electrical resistance, which should be very low to conduct

* Corresponding author. Tel.: +82 42 869 3221; fax: +82 42 869 5221.
E-mail address: dglee@kaist.ac.kr (D.G. Lee).

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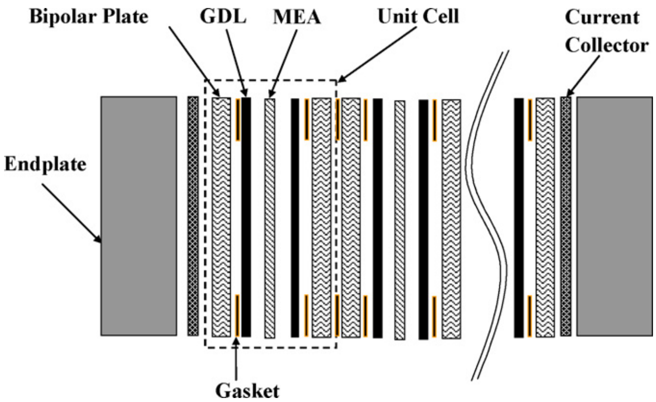

Fig. 1. Schematic drawing of PEMFC.

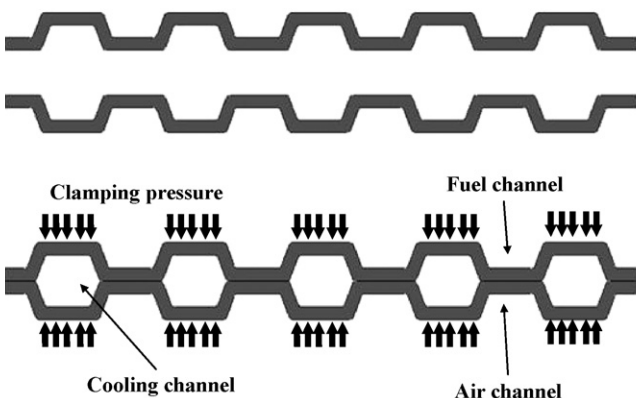

Fig. 2. Schematic drawing of cooling method employed in conventional bipolar plate stacks.

the electricity generated in the fuel cells with minimum electrical loss. The resistance of the bipolar plate of a PEMFC consists of bulk material resistance and interfacial contact resistance, which occurs when two contacting bipolar plates are used for fuel and air (oxygen) supplies. In an actual fuel cell stack, the interfacial contact resistance is much higher than the bulk resistance [11].

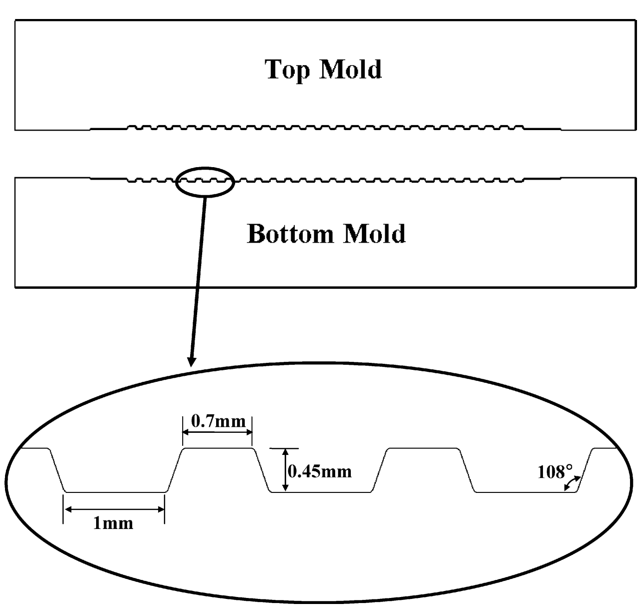

Fig. 3. Schematic drawing of mold for integrated composite bipolar plate.

Table 1
Properties of prepreg USN 150.

Tensile modulus (GPa)	
Longitudinal	131
Transverse	10.8
Shear	5.65
Tensile strength (MPa)	
Longitudinal	2000
Transverse	61
Shear	70
Poisson's ratio (plane)	0.59
Density (kg m^{-3})	1.54×10^3
Fiber properties	
Modulus (GPa)	235
Strength (MPa)	4400
Thickness (m)	0.15×10^{-3}

In this study, an integrated composite bipolar plate that has channels for fuel, air and coolant is developed to eliminate the contact resistance between the bipolar plates. To fabricate this plate with channels for fuel, air and coolant, many stainless-steel pipes of 1 mm diameter are uniformly embedded in the carbon fiber/epoxy composite and co-cured. The contact resistance, flexural strength and thermal degradation temperatures of the developed composite bipolar plate are then measured.

2. Description of integrated composite bipolar plate

Fig. 1 shows the stack of a PEMFC that is composed of the bipolar plates, end plates, MEA and GDL.

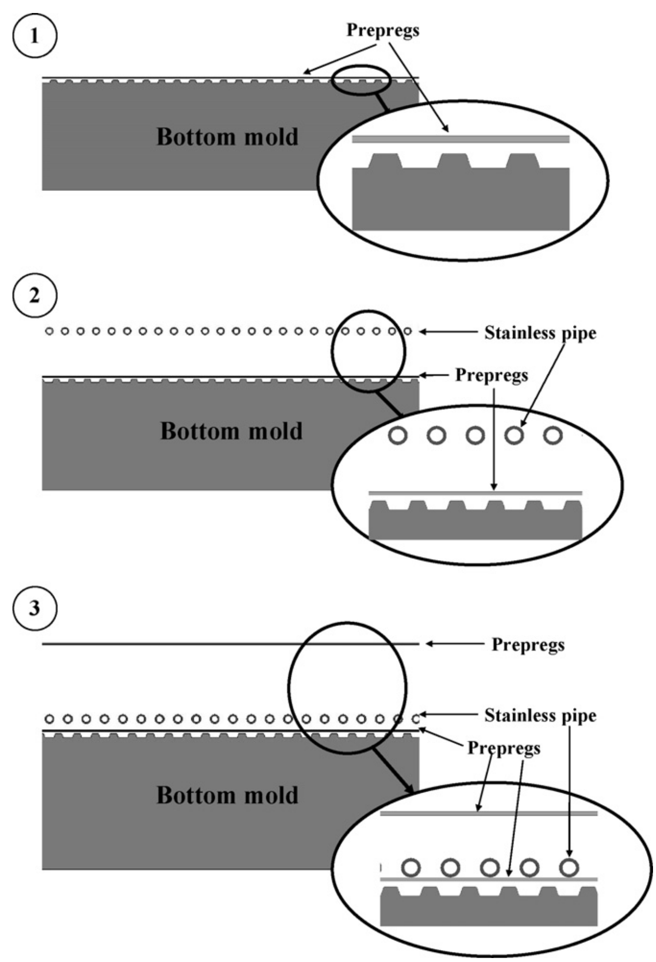

Fig. 4. Schematic representation of stacking steps.

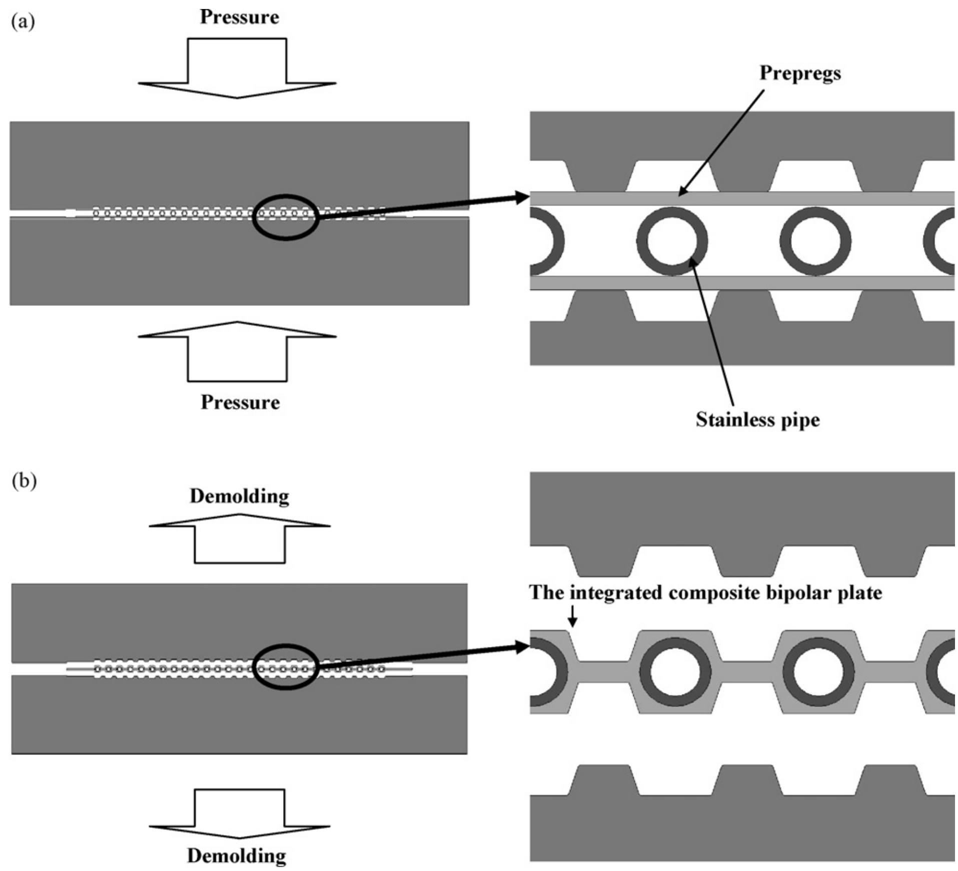

Fig. 5. Schematic drawing of compression molding of composite plate.

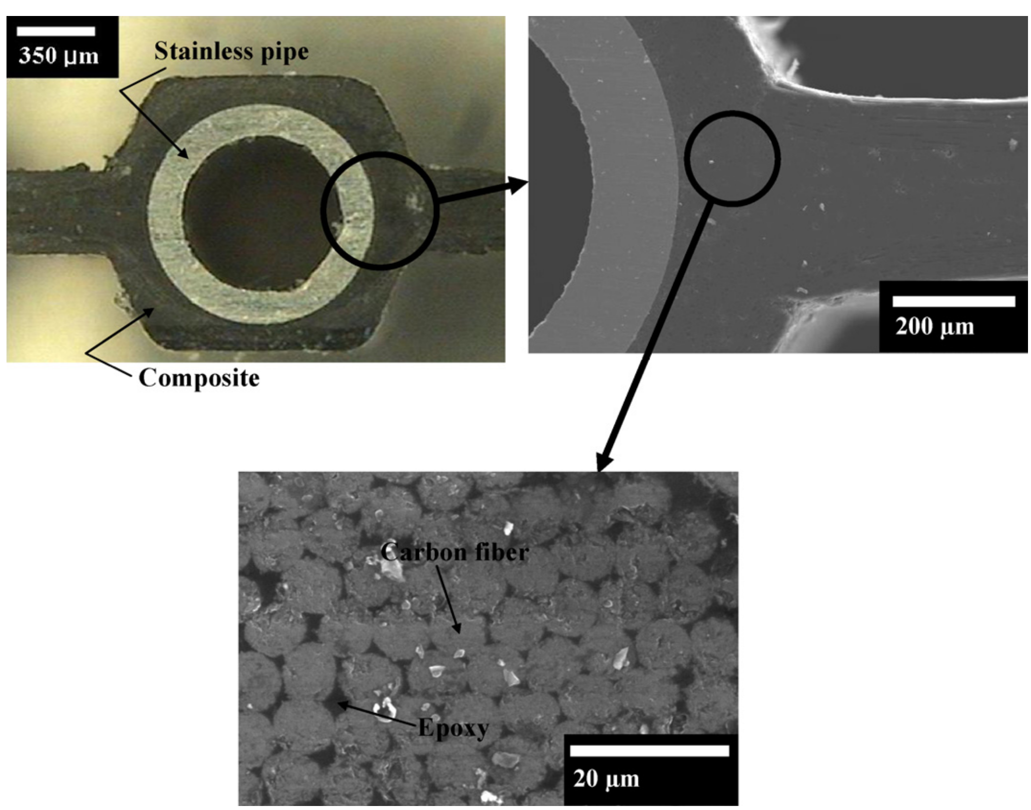

Fig. 6. Cross-section of integrated composite bipolar plate.

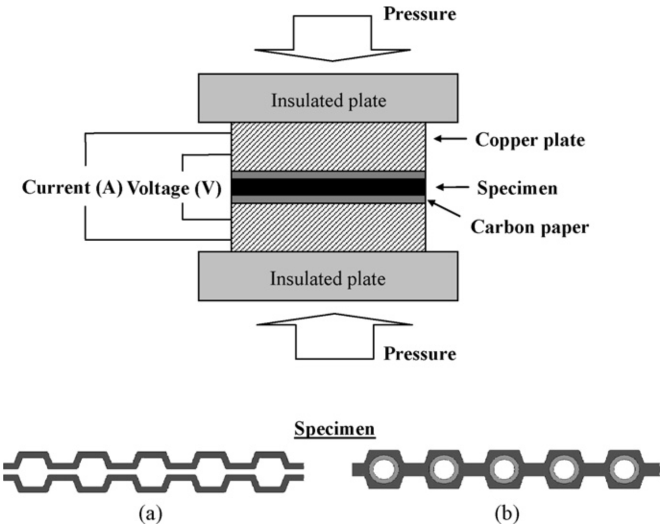

Fig. 7. Schematic drawing of experiment set-up to measure total resistance of (a) conventional-type composite bipolar plate and (b) integrated composite bipolar plate.

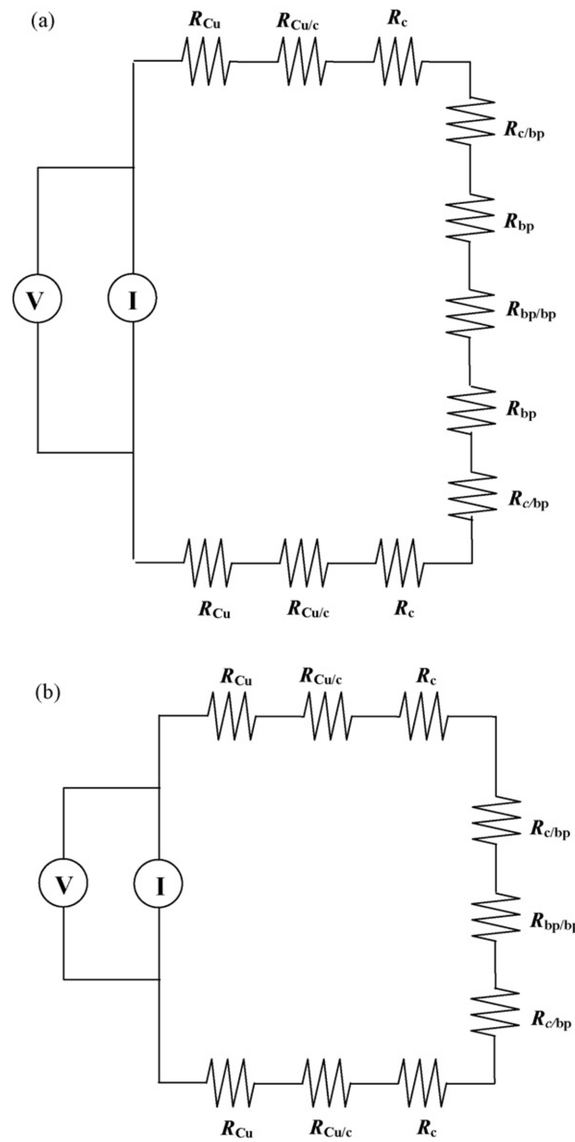

Fig. 8. Schematic drawing of electrical circuit of experimental set-up: (a) conventional composite bipolar plate and (b) integrated composite bipolar plate.

Cooling channels in the conventional type of PEMFC are usually produced as two corrugated bipolar plates, which are closely contacted by a high pressure, as illustrated in Fig. 2. Such a construction induces energy loss due to the electrical contact resistance between the bipolar plates. In addition, tight sealing with high pressure is required between the bipolar plates.

When the channels for fuel, air and coolant are embedded, as in the integrated composite bipolar plate, this reduces the assembly and sealing processes and eliminates the energy loss that would otherwise from the electrical contact resistance between the bipolar plates.

3. Experimental

3.1. Material and fabrication of integrated composite bipolar plate

The materials used in this study were carbon epoxy prepreg USN 150 (SK Chemicals, Korea) and many stainless-steel pipes with outer and inner diameters of 1.0 and 0.7 mm, respectively. The properties of USN 150 are listed in Table 1 [12].

In order to fabricate the integrated composite bipolar plate, the molds were prepared as shown in Fig. 3. The molds consist of symmetrical top and bottom parts.

The process of stacking the composite prepregs and stainless-steel pipes is depicted in Fig. 4. The laminates made of prepreg of USN 150 (SK Chemicals, Korea) were stacked on the bottom mold and the stainless pipes were placed at equal distances. The same amount of prepreg laminates was then stacked over the stainless-steel pipes. The integrated composite bipolar plate was formed by curing the composite prepreg laminates. A pressure of 40 MPa and a temperature of 125 °C were applied throughout the bottom and top molds during compression molding, as illustrated in Fig. 5.

The cross-section of the cured integrated composite bipolar plate, which is the mirror image of the mold, is shown in Fig. 6.

3.2. Effect of contact resistance

The total resistance of the integrated composite bipolar plate, essentially just the bulk material resistance as there is no contact resistance in the integrated composite bipolar plate, was measured

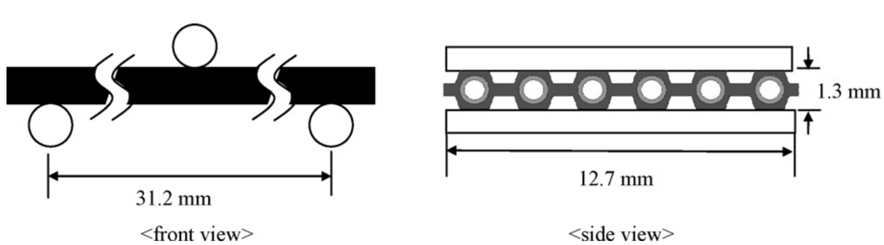

Fig. 9. Schematic representation of three-point bending tests of integrated composite bipolar plate.

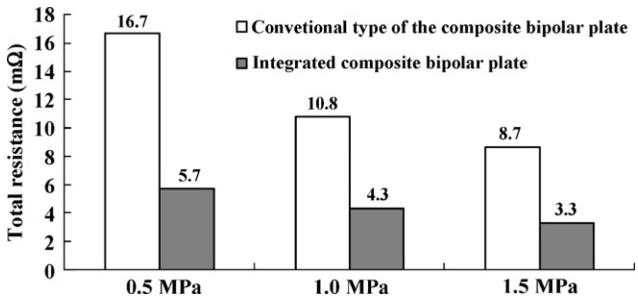

Fig. 10. Total resistance with respect to compaction pressure.

using a specimen 40 mm × 45 mm in size with the experiment set-up shown in Fig. 7. The total resistance depends on several resistances in series, such as the resistance of the two copper electrodes (R_{Cu}) and the two carbon paper layers (R_c), the bulk resistance of the specimen (R_{bp}), and (more significantly) the contact resistances between the carbon paper and the specimen ($R_{c/bp}$) and between the conventional type bipolar plates ($R_{bp/bp}$), as shown schematically in Fig. 8. The electrical resistances were measured under compaction pressures of 0.5, 1.0 and 1.5 MPa.

3.3. Measurement of mechanical properties of bipolar plates

The flexural strength of the integrated composite bipolar plate with corrugated flow channels was measured by a three-point bending test according to ASTM D 790-03. A schematic drawing of the three-point bending test is given in Fig. 9.

3.4. Measurement of thermal stability

The thermal stability of the bipolar plate was investigated using thermal degradation temperatures, such as T_1 and T_2, from thermogravimetric analysis (TGA) results measured with a thermal-gravimetry analyzer (TG 209 F3, NETZSCH, Germany). The values of T_1 and T_2 were determined from the TGA curves at 5 wt.% loss and at the maximum rate of weight loss, respectively. The mass loss occurring at the constant temperature of 120 °C over a 4-h duration was also measured (this is the highest operating temperature [4]).

3.5. Morphology

The morphology of the integrated composite bipolar plate was observed with a scanning electron microscope (SEM) (HITACHI S4300, Japan).

4. Results and discussion

4.1. Contact resistance effect

The total resistance of the integrated composite bipolar plate was about 60% smaller than that of conventional types of composite bipolar plates under the compaction pressure of 0.5 MPa, as shown in Fig. 10. This is, of course, because there was no contact resistance between the bipolar plates ($R_{bp/bp}$), as exists in the conventional-type composite bipolar plates (as shown in Fig. 8). Fig. 10 shows that the rate of decrease of total resistance in conventional type composite bipolar plates was considerable, as the compaction pressure was increased while that of the integrated composite bipolar plate was small because the compaction pressure increased the contact area between the bipolar plate and the carbon paper only. Therefore, integrated bipolar plates are not required to be compacted with a high pressure to reduce the electrical contact resistance existing between the conventional bipolar plates.

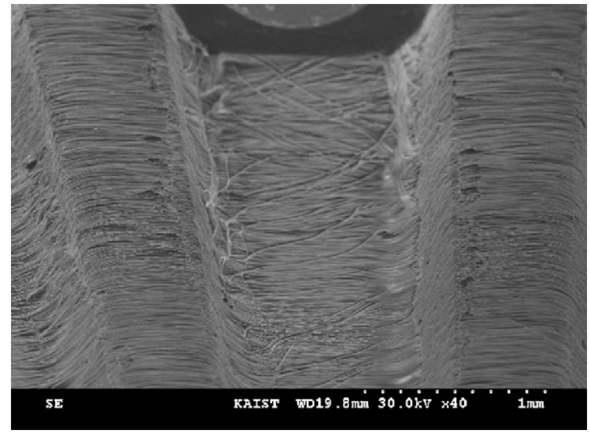

Fig. 11. Scanning electron micrographs of top section of integrated composite bipolar plate.

4.2. Flexural strength

The flexural strength of the integrated composite bipolar plate is 450 MPa, which is significantly higher than the target value of 59 MPa and values for previous composite candidates, as listed in Table 2. This is because high-strength, continuous carbon fiber/epoxy is used and because the carbon fibers suffer little damage during the manufacturing process, as shown in Fig. 11.

4.3. Thermal degradation temperatures

The thermal degradation temperatures T_1 and T_2 of the integrated composite bipolar plate are 460 and 480 °C from the measured thermogravimetric properties shown in Fig. 12. These are much higher than the PEMFC operating temperature of 80 °C. Furthermore, there is no loss of mass of the bipolar material when subjected to 120 °C for over 4 h, as seen in Fig. 13. As previously noted, this is the maximum operating temperature of the PEMFC. These experimental data indicate that the integrated composite bipolar plate developed in this work is thermally stable for PEMFC operation.

Table 2
Mechanical properties of several polymer composite bipolar plates.

Manufacturer	Polymer	Graphite/fiber (wt.%/wt.%)	Flexural strength (MPa)	Tensile strength (MPa)
Target	–	–	>59	>41
GE [13]	PVDF	64/16 CF	42.7	–
LANL [14]	Vinyl ester	68/0	29.6	23.4
Plug Power [15]	Vinyl ester	68/0	40.0	26.2
DuPont [16]	–	–	53.1	25.1
Virginia Tech [17]	PET	65/7 GF	53	36.5
Virginia Tech [18]	15% PVDF laminate	70/6 CF	54.4	32.7
Virginia Tech [19]	PPS	70/6 CF	95.8	57.5

CF: carbon fiber; GF: glass fiber.

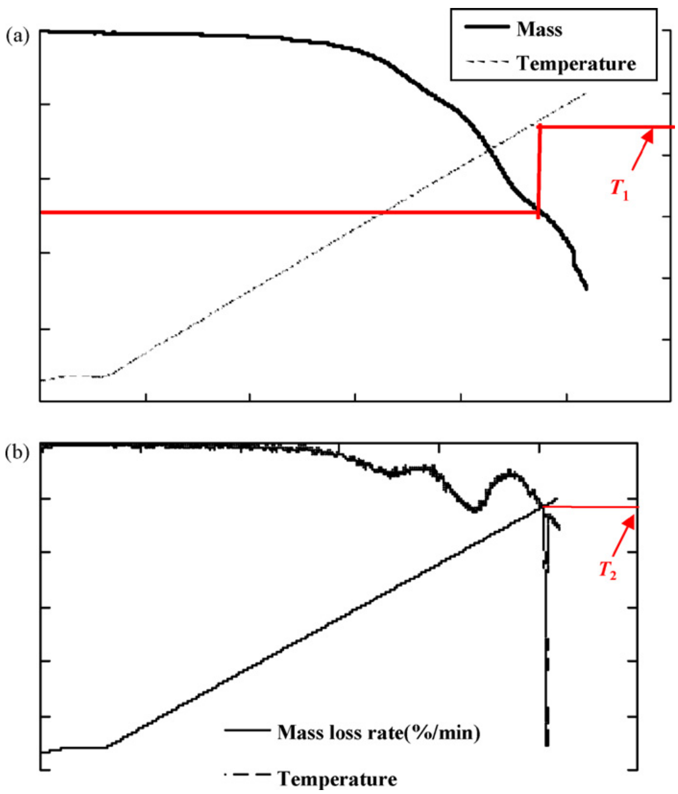

Fig. 12. Thermogravimetric properties of composite bipolar plate: (a) mass of composite with respect to temperature and (b) mass loss rate with respect to temperature.

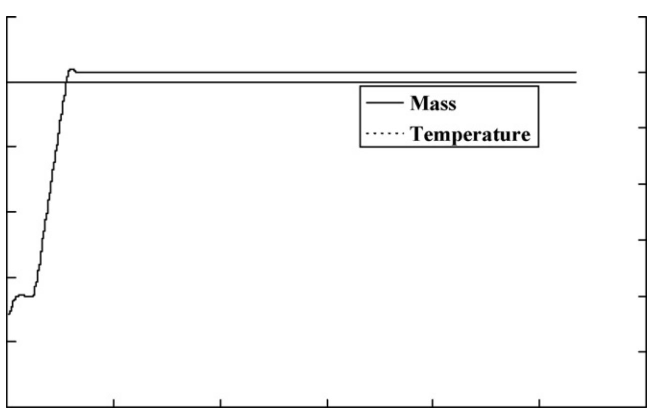

Fig. 13. Mass loss of composite bipolar plate at 120 °C.

5. Conclusions

Stainless-steel pipes of 1 mm diameter have been uniformly embedded in carbon fiber/epoxy composite prepregs to function as cooling channels in the design of an integrated composite bipolar plate for PEMFC applications. The embedded design eliminates the contact electrical resistance that exists between bipolar plates that are pressed tightly together in conventional bipolar plate designs of fuel cell.

The flexural strength and thermal degradation temperatures of the composite bipolar plate have been measured and the absence of an effect of electrical contact resistance is verified. It is found that the flexural strength of the integrated composite bipolar plate is about 450 MPa, which is much higher than the target value of 59 MPa. The thermal degradation temperatures T_1 and T_2 of the integrated composite bipolar plate are 460 and 480 °C, which are much higher than the operating temperatures. The electrical resistance of the integrated composite bipolar plate is 60% lower than that of conventional bipolar plates due to the elimination of contact resistance. Also, the integrated bipolar plates are not required to be compacted with a high pressure to reduce the electrical contact resistance between conventional bipolar plates.

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