Composite Structures 160 (2017) 976–982

Contents lists available at ScienceDirect

Composite Structures

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

Development of non-woven carbon felt composite bipolar plates using the soft layer method

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ARTICLE INFO

Article history:
Received 24 October 2016
Accepted 25 October 2016
Available online 26 October 2016

Keywords:
Carbon fiber composite
Electrically conductive
Bipolar plate
Non-woven carbon felt
Soft layer method

ABSTRACT

Carbon fiber reinforced polymer composites are ideal substitutes for brittle graphite for electrically conductive bipolar plates because of their high mechanical property and productivity. Early composite bipolar plates suffered from high electrical contact resistance due to the resin-rich area formed on the surface. To decrease the electrical contact resistance, the "soft layer method" was developed, which exposed bare carbon fibers on the composite surface. This method significantly improved the electrical as well as mechanical properties of composite bipolar plates. The remaining problem for wider commercialization of composite bipolar plates is their high fabrication pressure.

In this work, a non-woven carbon felt composite bipolar plate was developed to obtain improved electrical properties with low fabrication pressure. The soft layer method was also used to expose bare carbon fibers. Compared to conventional high fiber volume fraction composite bipolar plates, the developed bipolar plate exhibited superior electrical properties.

1. Introduction

The bipolar plate is a multifunctional key component for energy conversion systems such as proton exchange membrane fuel cells (PEMFCs) and energy storage systems such as vanadium redox flow batteries (VRFBs). The three crucial functional requirements of the bipolar plate are *high electrical conductivity* in the through-thickness direction, *high mechanical properties*, and *low gas permeability* in the through-thickness direction [1]. First, bipolar plates should have high electrical conductivity to effectively conduct electricity with minimum ohmic loss. Second, high mechanical properties are required to withstand high compaction pressure in the stack assembly for PEMFC applications. In VRFB applications, the megawatt scale VRFB stack requires a large area bipolar plate often greater than 1 m^2 with a plate thickness of less than 1 mm, which requires high mechanical properties. Therefore, brittle materials such as graphite seldom meet the requirement. Third, the gas permeability should be very low to prevent mixing of fuels or electrolytes. In this regard, a carbon fiber reinforced polymer composite is an ideal material for bipolar plates [2,3].

Many studies have focused on developing bipolar plates based on continuous carbon fiber/epoxy composites due to their high specific strength and stiffness [4,5]. However, high electrical resistance in the through-thickness direction has been the largest drawback of the carbon/epoxy composite bipolar plates, which is caused by the resin-rich area formed on the surface of the bipolar plate during the manufacturing process. The resin-rich area prevents direct contact between carbon fibers of the bipolar plate and adjacent components, resulting in high areal specific resistance (ASR). Many methods have been developed for reduction of ASR. Surface treatment methods such as mechanical abrasion and plasma treatment have been used [6,7]. Additionally, methods to attach a conductive graphite layer or randomly oriented carbon fibers were employed [8–10]. Among various methods to reduce ASR, the "soft layer method", which can remove the resin-rich area and expose bare carbon fibers on the composite surface, has been the most effective method with high productivity and ASR lower than 20 $m\Omega \cdot cm^2$ at a compaction pressure of 1.38 MPa, which is the standard compaction pressure to measure the ASR established by the United States Department of Energy (DOE) [11–14].

There is still one remaining problem for the widespread use and commercialization of the carbon/epoxy composite bipolar plate. The fabrication molding pressure required for the continuous uni-directional carbon fiber composite and woven carbon fabric

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http://dx.doi.org/10.1016/j.compstruct.2016.10.107
0263-8223/

composite bipolar plates is 20 MPa. Considering the size of the bipolar plates, this requires a large capacity hot press for manufacturing. Therefore, it is essential to reduce the fabrication pressure.

In this study, composite bipolar plates were developed based on a non-woven carbon felt whose fiber volume fraction was much smaller compared to that of conventional woven carbon fabrics. The soft layer method was adopted to expose the carbon fibers on the surface, and the specimens were fabricated with respect to the applied pressure. The electrical and mechanical properties and gas permeability of the fabricated bipolar plates were evaluated.

2. Advantages of the low fiber volume fraction composite

Generally, many studies have concentrated on increasing the fiber volume fraction (V_f) of the composite to increase the electrical conductivity because high V_f is necessary to allow the carbon fibers to contact one another as shown in Fig. 1(a). However, very high fabrication pressure is required to increase V_f over 70%. In contrast, the electrical conductivity of non-woven carbon felt does not depend as much on fiber to fiber contact because the carbon fibers are pre-aligned in the through-thickness direction and function as direct electrical paths as shown in Fig. 1(b). This direct path provides higher electrical conductivity even with low V_f. To investigate this effect, the ASRs of bare fibers without matrix were measured. The ASRs of 3 plies of 1 k plain weave carbon fabric (C-112, SK Chemicals, Korea) and non-woven carbon felt (Graphite felt, Newell, China) were measured using the experimental setup shown in Fig. 2. Material properties of the fibers are shown in Table 1 and Fig. 3 shows the ASR curves of each fiber. The ASR of the woven carbon fabric at a compaction pressure of 1.5 MPa was 166 mΩ·cm^2, as shown in Fig. 3(a). Therefore, if the woven carbon fabric composite bipolar plate is manufactured at 1.5 MPa fabrication pressure, it may exhibit an ASR of 166 mΩ·cm^2 at a compaction pressure of 1.5 MPa, where it is assumed that there is no resin-rich area at the surface nor between fiber bundles. On the other hand, the ASR of the non-woven carbon felt was much lower, as shown in Fig. 3(b). The ASR of the non-woven carbon felt at a compaction pressure of 1.5 MPa was 22 mΩ·cm^2, which indicates

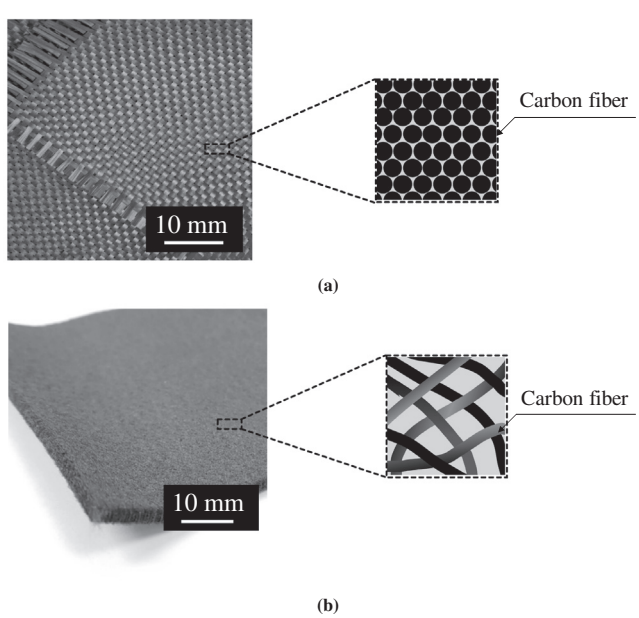

Fig. 1. Photographs of bare carbon fibers and schematic diagrams of their cross-sections: (a) 1 k plain weave woven fabric; (b) non-woven carbon felt.

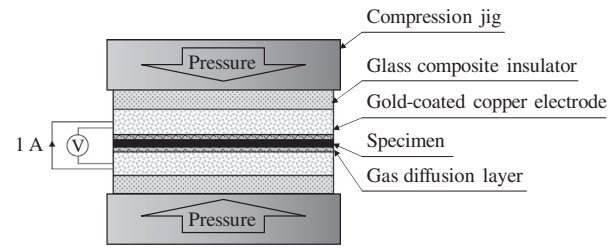

Fig. 2. Experimental setup for the areal specific resistance (ASR) measurement.

Table 1
Properties of carbon fibers.

Material	Properties	
1 k plain weave carbon fabric	Precursor type	PAN
	Fiber diameter (μm)	7
	Fiber areal density (g/m^2)	120
	Thickness (mm)	0.12
Non-woven carbon felt	Precursor type	PAN
	Fiber diameter (μm)	7
	Fiber volume fraction (%)	3.3
	Thickness (mm)	3

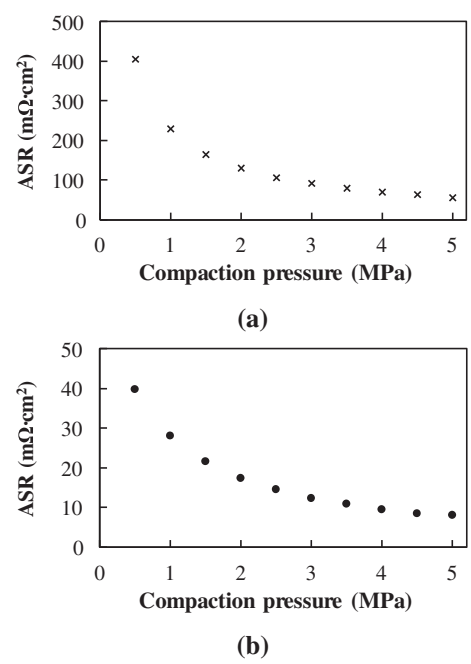

Fig. 3. ASR curves of: (a) woven carbon fabric; (b) non-woven carbon felt.

the carbon felt composite bipolar plate will exhibit ASR of 22 mΩ·cm^2 at a compaction pressure of 1.5 MPa if manufactured at 1.5 MPa fabrication pressure. Therefore, a low V_f carbon felt composite bipolar plate might be more suitable for manufacturing the bipolar plate at low fabrication pressure due to a lower bulk electrical resistance.

In addition to the bulk electrical resistance, the soft layer method can be more effective in reducing the interfacial contact resistance for low V_f composites. Fig. 4(a) shows the deformation of the soft layer simulated by a finite element analysis model developed in the previous study for uni-directional (UD) continuous fiber composites with V_f = 78% [11]. A pressure of 20 MPa was required for the soft layer to be compressed into two adjacent