The development of economical bipolar plates for fuel cells

Brent Cunningham* and Donald G. Baird

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One of the major challenges in the production of economical polymer electrolyte membrane (PEM) fuel cells for automotive applications is the development of materials for the generation of bipolar plates which meet all the property requirements and can be readily manufactured to impart fine channels for transporting hydrogen and oxygen. Bipolar plates can be made from various materials with the most common being graphite, metal, carbon/carbon, and polymer composites. Each type of material has its strengths and weaknesses. Materials for polymer composites are relatively inexpensive and channels can be formed by means of compression or injection molding. The key is to develop a balance between sufficient electrical conductivity and mechanical properties while allowing for rapid, continuous manufacturing.

Bipolar plates (an example of which is shown in Fig. 1) are by weight, volume, and cost one of the most significant parts of a fuel cell stack. Bipolar plates represent about a third of the overall cost of a fuel cell. Present cost estimates for a working fuel cell are about $200 per kW, which leaves the cost of a bipolar plate at $60–70 per kW. With the DOE cost target for a fuel cell set at $35 per kW for the automotive industry, the cost target for bipolar plates is $10 per kW.

The bipolar plate has three main functions: uniform distribution of gases over the whole area of the membrane electrode assembly (MEA); separation of the fuel (e.g. H₂) and O₂ and the prevention of gas leakage; and collecting the current produced by the electrochemical reactions. Furthermore, the bipolar plate carries the clamping force required to hold the fuel cell stack together. A set of specified targets and requirements for bipolar plates is summarized below:

- Bulk (in-plane) electric conductivity (>100 S cm⁻¹)*
- H₂ permeability (<2 × 10⁻⁶ cm³ cm⁻² s⁻¹)*
- Corrosion rate (<16 μA cm⁻²)*
- Flexural strength >59 MPa#
- Tensile strength >41 MPa#
- Thermal conductivity >10 W mK⁻¹#
- Thermal stability up to 120 °C
- Chemical stability in the presence of fuel, oxidant, water, and acidic conditions
- Rapid and inexpensive manufacturing

* DOE and FreedomCAR targets
# Plug Power targets

Graphite has been the standard material used in the production of bipolar plates due to its high conductivity. Unfortunately, graphite is brittle and has poor mechanical properties. The main difficulty in using graphite to produce bipolar plates is that the production...
of channels in the surfaces requires machining, a very costly and time consuming step. In addition, post processing (such as resin impregnation) is needed to make graphite plates impermeable to gases.\(^8\)

Because of the costly machining step associated with graphite, a variety of metals has been investigated for the production of bipolar plates. Metals such as stainless steel, aluminium, and titanium have been considered with the most promising being stainless steel.\(^6,9\) Metallic plates typically have high bulk electrical conductivity, thermal conductivity, negligible gas permeability, and excellent mechanical properties. Techniques such as etching and batch stamping have been developed for producing channels into metallic plates representing significant improvements over machining. However, due to poor corrosion resistance of metal plates and the possibility for metal ions to leach into the MEA, a coating must be applied to the surfaces of the plates to form a protective layer. The protective coating leads to enhanced electrical resistance at the interface, the magnitude of which has not been reported in the open literature.

Researchers at Oak Ridge National Laboratory developed carbon/carbon bipolar plates. They claimed that the plates exhibited high electrical characteristics along with excellent mechanical properties.\(^10\) The manufacturing process consisted of multiple steps, including the production of carbon fiber/phenolic resin preforms by a slurry-molding technique followed by densification by chemical vapor infiltration (CVI). The CVI process is likely to be too complicated and costly to be used for bipolar plates for automotive applications.

Because material and machining costs for graphite and carbon/carbon plates are prohibitive at least for the automotive industry, and metal plates must be uniformly covered with a protective coating which has shown to be difficult to accomplish,\(^9\) extensive efforts have been made to develop alternative materials for bipolar plate production. Polymer composites have been considered for bipolar plate production because of their potential to be processed rapidly. Molding techniques for polymer composites have shown the greatest potential in reducing bipolar plate manufacturing time and cost over machining or etching. Thermoplastic composite materials can be heated above the melting temperature of the polymer allowing for channels to be molded directly into the surfaces. It has been shown that the cost of molding a polymer composite bipolar plate is 10–20 times less expensive than that of machining.\(^7\) Molding techniques can also reduce production times to several minutes. Researchers at Los Alamos National Laboratories (LANL) have developed compression moldable bipolar plates based on a vinyl ester thermosetting polymer matrix filled with graphite that can be compression molded in about 10 minutes.\(^11\) The advantage in using a thermosetting polymer is that when the polymer is heated and compression molded, the plate cures and does not require subsequent cooling. Therefore, the plate can be immediately released from the mold. However, a post cure may be necessary, and can take as long as one hour to complete.\(^12\) Furthermore, the mechanical properties do not meet the targets (see Table 1). Poly(vinylidene fluoride) (PVDF), a thermoplastic fluoropolymer matrix, has been used with graphite particles and carbon fiber to produce bipolar plates.\(^3\) Bulk conductivity values have reached 109 S cm\(^{-1}\), exceeding the DOE target. However, the

![Fig. 1](image)

**Fig. 1** One side of a bipolar plate showing a 7 channel parallel serpentine style design. Plate dimensions are approximately 12 × 14 cm, 0.3 cm thick. Channel dimensions are 0.08 × 0.08 cm.

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**Table 1** Comparison of electrical and mechanical properties for polymer composite material used for the production of bipolar plates

<table>
<thead>
<tr>
<th>Source</th>
<th>Polymer</th>
<th>Graphite/glass or carbon reinforcing fiber (wt/wt%)</th>
<th>Conductivity/S cm(^{-1})</th>
<th>Mechanical strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LANL(^12)</td>
<td>Vinyl Ester</td>
<td>68/0</td>
<td>&gt;100(^a)</td>
<td>41.0(^b) 59.0(^b)</td>
</tr>
<tr>
<td>GE(^3)</td>
<td>PVDF</td>
<td>64/16 CF</td>
<td>60</td>
<td>23.4 29.6</td>
</tr>
<tr>
<td>Virginia Tech(^8)</td>
<td>PET</td>
<td>65/7 GF</td>
<td>109</td>
<td>36.5 53.0</td>
</tr>
<tr>
<td>Virginia Tech(^14)</td>
<td>PPS core</td>
<td>70/6 CF</td>
<td>230</td>
<td>36.5 53.0</td>
</tr>
<tr>
<td>Virginia Tech(^14)</td>
<td>PPS skin</td>
<td>80/0 laminate</td>
<td>147–350</td>
<td>34.4 48.9</td>
</tr>
</tbody>
</table>

\(^a\) DOE target for conductivity.\(^15\) \(^b\) Plug Power targets for mechanical strength.\(^7\)
flexural strength was only 42.7 MPa, lower than the goal of 59 MPa. Liquid crystalline polymer–graphite mixtures have been considered for bipolar plate production because of their ability to be used with injection molding due to the low viscosity of the polymer. The injection molding process allows for a relatively short cycle time of 30 seconds. Bulk conductivities have reached as high as 100 S cm\(^{-1}\), just reaching the minimum target, but no mechanical properties or through-plane conductivities were reported and it is anticipated that the properties may not reach the targets.

Huang and coworkers\(^8\) have reported the development of conductive polymer composite materials generated by means of a wet-lay process. The wet-lay process was chosen because of its potential to create conductive, strong composite plaques when compression molded. Poly(phenylene sulfide) (PPS) based wet-lay generated composites exhibited bulk conductivities and mechanical properties that meet the targets and are higher than those of any other polymer composite material used to produce bipolar plates as shown in Table 1. An area that needs improvement for the wet-lay based material is through-plane conductivity and formability of channels into the surfaces.

In an effort to address the through-plane conductivity and formability of the wet-lay based material, Huang and coworkers\(^8\) have developed a laminate approach to produce compression moldable polymer composite materials using a combination of wet-lay based material and a fluoropolymer–graphite mixture. PVDF was used as the polymer in the laminate layer to create a surface much more amenable for molding, while wet-lay material was used to produce a solid, strong core material. The laminate approach offered several significant advantages. First, the laminate structure was shown to increase through-plane conductivity by 25–35%. Second, PVDF had a much lower melting temperature than PPS (about 100 °C lower) offering a shorter heating and subsequent cooling cycle. Third, when channels were compression molded into the PVDF–graphite powder, significant improvements in channel formation were observed. The smoother surfaces were due to the absence of fibers in the laminate layer. It was believed that smoother surfaces would reduce the contact resistance between the bipolar plate and MEA. The half-cell resistance of the laminate bipolar plates showed a significant reduction over that of wet-lay based bipolar plates. Thus, the performance of laminate bipolar plates in a functioning fuel cell was enhanced over that of wet-lay based bipolar plates.

The main drawback in using polymer composite materials is their relatively low conductivity when compared to graphite and metal plates. While mechanical strength exceeds that of graphite plates, polymer composite plates exhibit a much lower strength than that of metal plates. There are also concerns about whether thermoplastic polymer composite bipolar plates will perform well in a fuel cell because at operating temperatures there may be some loss of mechanical strength and stiffness depending on the choice of thermoplastic.

It is believed that the defining factor in developing economical bipolar plates relies on the design of a rapid, continuous molding scheme. Bipolar plates based on the laminate approach can potentially be continuously manufactured. It is possible to pre-consolidate sheets of wet-lay material by continuously rolling the material through calendar or embossing rolls. The laminate powder can be metered onto the consolidated plaque, where the laminate surfaces are heated to prepare for the final molding step. Because the powder layer is thin and has a high thermal conductivity due to the high concentration of graphite particles, the time associated with molding has been estimated to be less than 10 seconds.

Furthermore, it has been estimated that the part can be heated to its processing temperature by means of radiation in well under 60 seconds. Therefore, there is potential for the development of laminate polymer composite bipolar plates to be commercially manufactured.

In summary, the major challenge is the generation of composite materials which can be processed rapidly to produce bipolar plates with adequate electrical conductivity and mechanical properties. Significant progress has been made, but there is still room for improvement.

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