DEVELOPMENT OF A MULTIFUNCTIONAL COMPOSITE FUEL CELL

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ABSTRACT

Weight reduction, efficient use of space, and fuel savings can be achieved in mobile systems by making them multifunctional. In particular, combining the benefits of composite materials technology with other technologies, such as fuel cell technology, can provide many benefits to these systems. In the present work, we explore the fabrication of structural fuel cells using the pultrusion process. We demonstrate that, by introducing multifunctionality into the foam core of a sandwich structure, a fuel cell that has the ability to simultaneously carry load and produce power can be achieved.

1. INTRODUCTION

U.S. Army systems such as ground vehicles and unmanned aerial vehicles are continuously being improved and made more complex as novel technologies are developed. As the capabilities of these systems progresses, a continual goal of the U.S. Army is to efficiently use material mass and volume. The creation of multifunctional materials/devices which can perform multiple tasks can help to accomplish this goal. Particularly, a structural fuel cell, which has the ability to produce power while withstanding structural loads, will allow for more efficient system designs.

The future of sandwich structure technology will undoubtedly include great interest in the development multifunctional designs which are affordable and durable. Previous studies on multifunctional fuel cells have focused on the hand layup process to produce a composite laminate which also has power generation abilities [1]. This process is extremely labor intensive and difficult to scale to large components or high volume. This study focuses on using pultrusion to create a composite, fuel cell sandwich structure. Pultrusion is the most efficient composite manufacturing technique. Its continuous, automated nature can allow for quick, production of structural fuel cells in high volumes [2].

This study explores the development of a multifunctional direct methanol fuel cell. This device is achieved by the incorporation of fuel cell components into the foam core of a sandwich structure. Monopolar, composite plates are used to sandwich a membrane electrode assembly (MEA). These components are then inserted into a structural foam section and encompassed by composite skins during the pultrusion process. Custom fittings are used to allow for the introduction of reactants into the structure, and silicone gasket layers are used to prevent leaks during the operation of the fuel cell. Electrochemical and mechanical properties of the structural fuel cell are investigated.

2. MANUFACTURE OF PULTRUDED FUEL CELL

A custom MEA was ordered from fuelcellstore.com to serve as the heart of the structural fuel cell. The assembly consisted of a 195 cm^2 (30 cm x 6.5 cm) Nafion 117 membrane and 126 cm^2 (28 cm x 6.5 cm) carbon cloth gas diffusion layers. The catalyst loadings used at the electrodes were 2.0 mg/cm^2 platinum-ruthenium on the anode side and 4.0 mg/cm^2 platinum on the cathode side.

Channeled monopolar plates composed of 60% graphite/40% polyphenylene sulphide composite were used for fuel distribution and electrical conduction. The plates had a total area of 174 cm^2 (30.5 cm x 5.7 cm). They were manufactured through compression molding with a custom aluminium mold. A load of approximate 66,725 Newtons was applied to a wetlay precursor at 300°C using a Carver Laboratory Press (Model 2696) for nearly 600 seconds. The plates were allowed to cool and then removed from the mold. Once removed, two holes were drilled into each plate to serve as inlet/outlet pathways for fuel and gas reactants. Custom polyvinyl chloride fittings were manufactured to allow for fuel and air connections to the fuel cell. These fittings were attached to the monopolar plates at the inlet/outlet hole locations using a silicon sealant.

The structural fuel cell assembly was created by the combination of the MEA, two monopolar plates, the polyvinyl chloride fittings, and a silicon gasket material. A gasket was placed on each sides of the MEA. A monopolar plate was then placed on top of each gasket to form the fuel cell assembly. High temperature tape was used around the plate edges to completely seal the system. Trymer 4000®polyisocyanurate foam insulation was obtained from Polycel, Inc. in width, thickness, and length dimensions of 5.7 cm, 3.7 cm, and 2.4 m, respectively. A section which was of the approximate dimensions of the fuel cell assembly was removed from the foam insulation's center and replaced by the assembly. A high temperature tape was then used to contain the ends of the fuel cell assembly section so that no snagging would occur during the pultrusion process.

The pultrusion of the structural fuel cell was accomplished with a standard die for a 6.35 x 4.13 cm tube with a tube wall thickness of 0.318 cm. The process was carried out at Strongwell Corp. The structural foam/fuel cell assembly replaced the area that would be occupied by the inner mandrel during the manufacture of a tube. From the inside to the outside, the components of the pultruded cell were structural foam/fuel cell assembly, an inner mat of M8643 E-Glass, 45 glass rovings (228 m/kg yield), and lastly, a 28 g Nico outside mat. A schematic of the structural fuel cell is displayed in Figure 1.

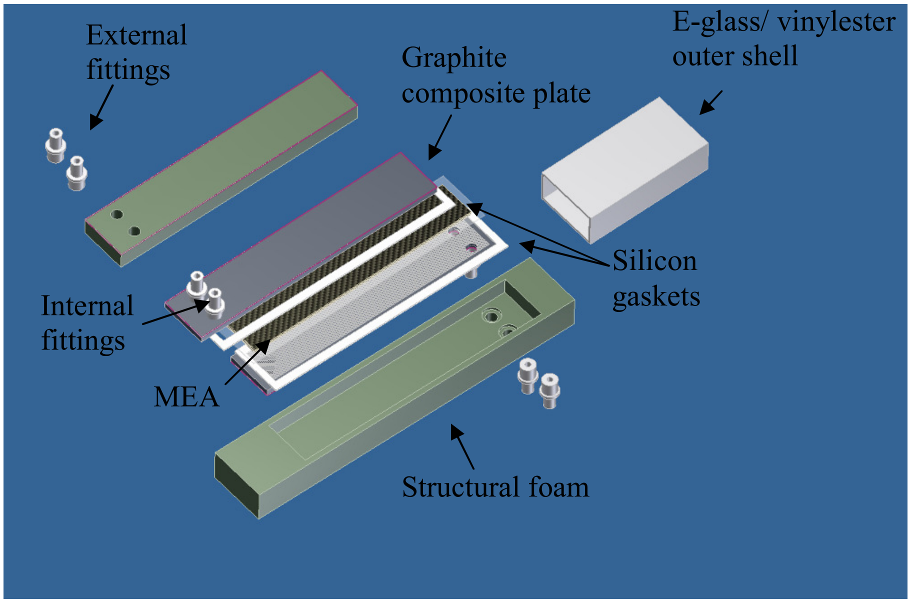

Figure 1: Schematic of pultruded, structural fuel cell

After the pultrusion was complete, an ultrasonic stud finder was used to locate the fuel cell along the length of the beam. Images of the cell were then obtained using an HP Faxitron 43804N cabinet x-ray device. Figures 2 and 3 display radiographic images of the structural fuel cell.

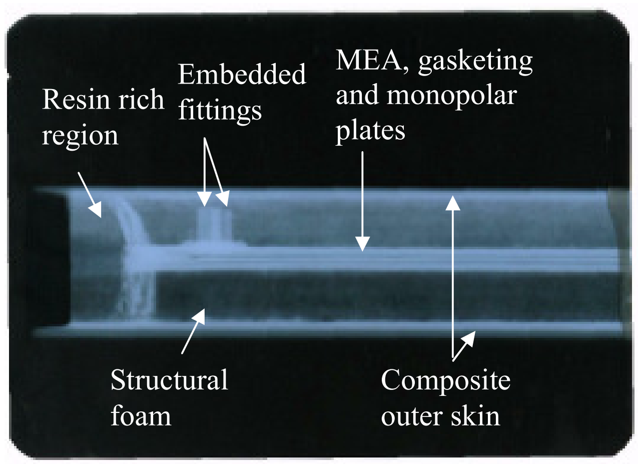

Fig. 2: Radiograph (view from side) of pultruded fuel cell beam.

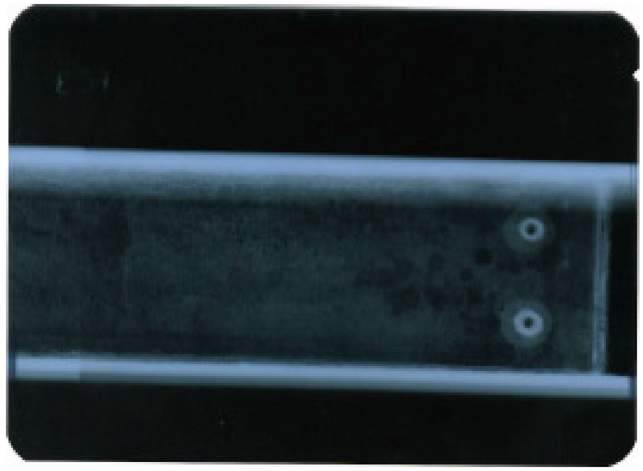

Fig. 3: Radiograph (view from top) of the pultruded fuel cell beam.

These images allowed the exact locations of the PVC fittings to be determined. Holes were then drilled through the outer composite layers and into the foam core in order to access the fittings. Inlet/outlet connections, which were compatible with the Swagelok connections from the fuel cell test station, were then made. These connections consisted of custom, hollow PVC bases with standard Swagelok cores inserted. A third hole was drilled through the outer composite and completely through the foam core (down to the monopolar plate) on each side of the cell. This hole allowed for access to the monopolar plate so the electrical connections could be made. A solid copper cylinder was inserted into each hole, and wires were used to make a connection between the cylinder and the fuel cell test station.

3. EXPERIMENTAL CHARACTERIZATION OF FUEL CELL AND COMPONENTS

A series of experiments were conducted on the pultruded fuel cells and individual components of the cells to characterize the multifunctional capability of the system and identify areas for improvement.

3.1 Electrochemical testing of cell

A test station manufactured by Fuel Cell Technologies, Inc. was used to determine the power output capabilities of the structural fuel cell. 2 M methanol solution was delivered to the anode side of the cell via an external peristaltic pump while the cathode side of the cell was supplied with air. The fuel was supplied at a flow rate of 1 cm^3/min while the air was supplied at 500 SCCM.

3.2 Fuel flow path observation

A “half-cell” setup was created to observe the fuel flow path in the structural fuel cell. A section approximating the dimensions of one of the monopolar plates was removed from a rectangular polycarbonate plate. The monopolar plate was placed into this section (channels facing up). Two holes were drilled into another transparent polycarbonate plate and Swagelok fittings were placed into the holes to create for inlet and outlet connections. This plate was then laid on top of the monopolar plate/polycarbonate plate. The flow path taken by a test solution (water/food coloring) was observed under two conditions. In the first condition, a silicon gasket was used along the edges of the monopolar plate for sealing purposes while in the second condition, no such gasketing was employed and a sheet of nafion was pressed against the surface of the monopolar plate (between the monopolar plate and the upper polycarbonate plate). The components of the setup were held together using c-clamps. The test solution was pumped to the setup at a flow rate of 2 cm^3/min.

3.3 Internal Resistance of cell

The internal resistance through the pultruded cell was determined using a Solartron Analytical Frequency Response Analyzer. An AC current with an amplitude of 5 mA was sent through the cell at a frequency of 100 Hz during this test.

3.4 Mechanical testing of structural beams

Three point flexure tests were conducted according to ASTM C393 on structural sandwich beams which did not contain the fuel cell assembly (These beams only contained the outer glass composite layers and the Trymer 4000®foam insulation). The bend tests were conducted at a strain rate of 0.0042 cm/s on an INSTRON 5500R frame with a 2268 kg (5000 lb) load cell. 2.54 cm diameter bars were used for loading nose and support points. Figure 4 displays a flexure test on a beam. Flexure tests were performed on the sandwich beams at spans of 24.8 cm, 38.1 cm, 49.5 cm, 66.0 cm, and 82.6 cm. These spans correspond to L/d ratios of approximately 6, 9, 12, 16, and 20, respectively.

Figure 4: Sandwich beam undergoing flexure test

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Electrical performance of cell

A polarization curve from a pultruded fuel cell is shown in Figure 5. The performance is inferior to what one should expect from a direct methanol fuel cell operating under similar conditions. Under ambient conditions, one should expect an open circuit voltage of approximately 0.7 V and current densities on the order of 100 mA/cm^2(at voltages approaching 0.2 V) [3,4].

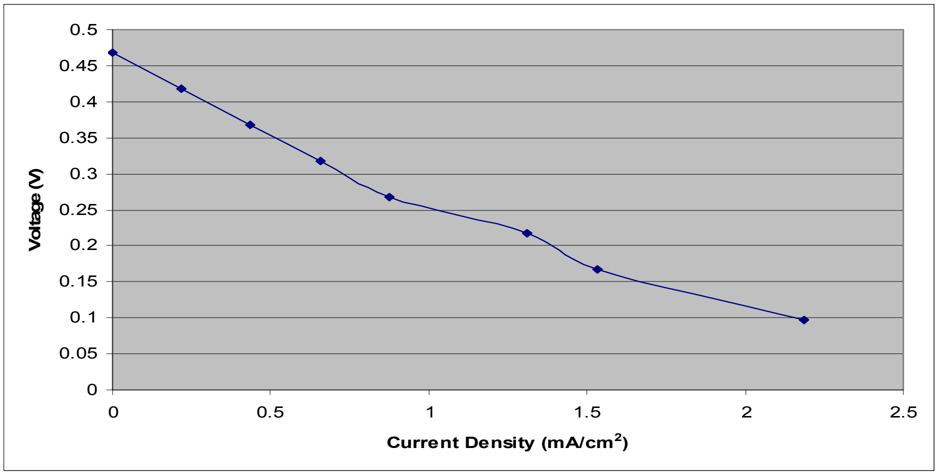

Figure 5: Polarization curve for pultruded fuel cell

4.2 Fuel flow behaviour

Figures 6 and 7 display the flow path followed by the test solution as it is pumped to the "half-cell" setup. Figure 6 displays the flow path followed by the test solution in the "half-cell" setup containing the silicon gasket. The flow initially traveled along the length of the monopolar plate (following the direction determined by the channels). Soon after, however, it also began to travel across the width of the channel (perpendicular to the channel direction). This is most likely allowed by space between the monopolar plate and the upper polycarbonate plate. This space was created by the silicon gasket material. It is important that flow follows the path created by the channels in order for efficient use of the MEA's active area and optimum power output from the device. Figure 7 displays the flow path taken by the solution when the gasket material was removed from the setup and a sheet of nafion was laid between the plates. The flow under these conditions generally followed the path created by the channels in the monopolar plate. Leaking at the edges of the plate, as seen in Figure 7, occurred when a backpressure was applied at the setup's exit.

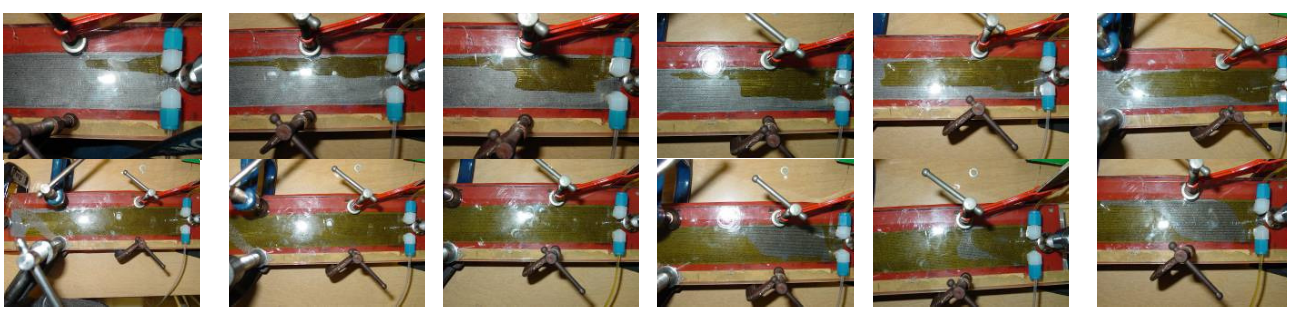

Figure 6: Flow behaviour of solution with silicon gasket sealing material. (Photos taken sequentially from left to right).

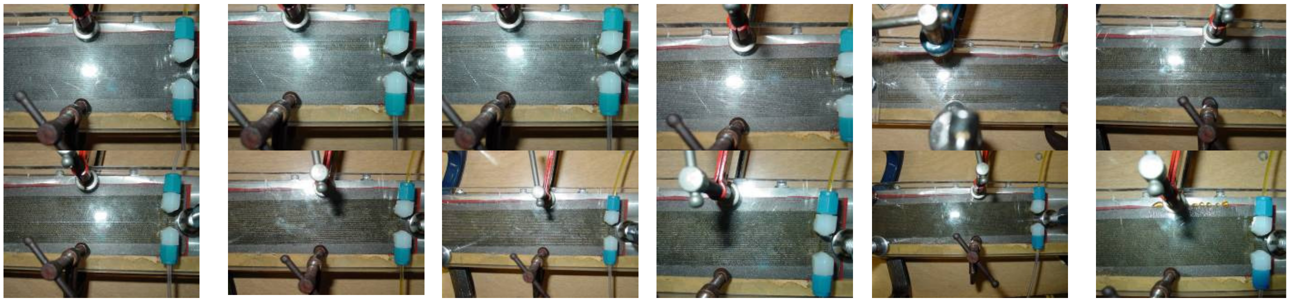

Figure 7: Flow behaviour of solution with no silicon gasket sealing material. (Photos taken sequentially from left to right).

4.3 Internal resistance of cell

The internal resistance of the pultruded cell was determined to be 139 Ω cm^2. This is much higher than literature value of 0.56 Ω cm^2 obtained for a direct methanol fuel cell operating under similar conditions [5]. This high resistance could likely at least in part be due the thickness of the silicon gasket and the space that it creates in the cells as previously discussed. The gasket likely reduces the contact between the monopolar plates and the MEA and therefore increases the associated contact resistances. The high contact resistance exhibited by the structural cell is detrimental to the power output by the device.

4.4 Bending properties of sandwich beam

Results from the flexure tests on the sandwich beams are shown in Figures 8 and 9. The plots seem to agree with expected trends as the maximum failure load decreases as span length increases while the maximum deflection increases as the span increases. Shear properties tend to dominate at the shorter spans while bending deflection dominates at the larger spans. Following the graphical method described in [6], a shear stiffness (kGA) of 11340 $\frac{kg}{cm^2} \cdot cm^2$ and a bending stiffness (EI) of 6.2E6 kg·cm^2 were calculated for the beam.

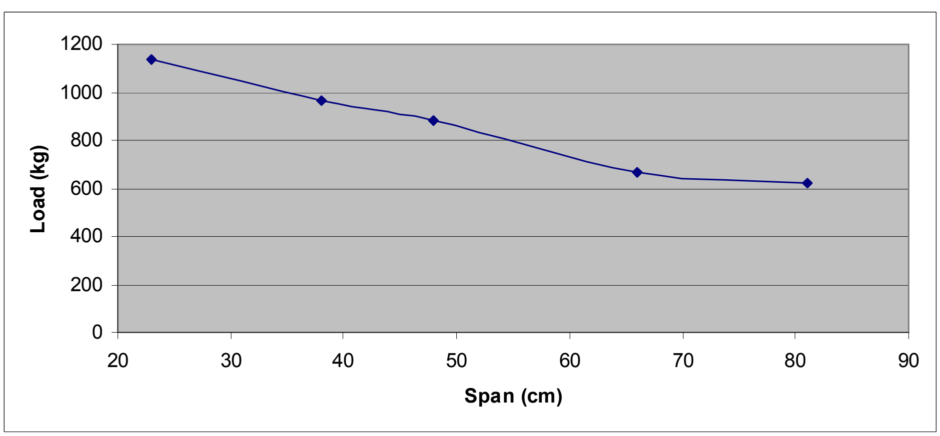

Figure 8: Load vs. Span for composite sandwich beam.

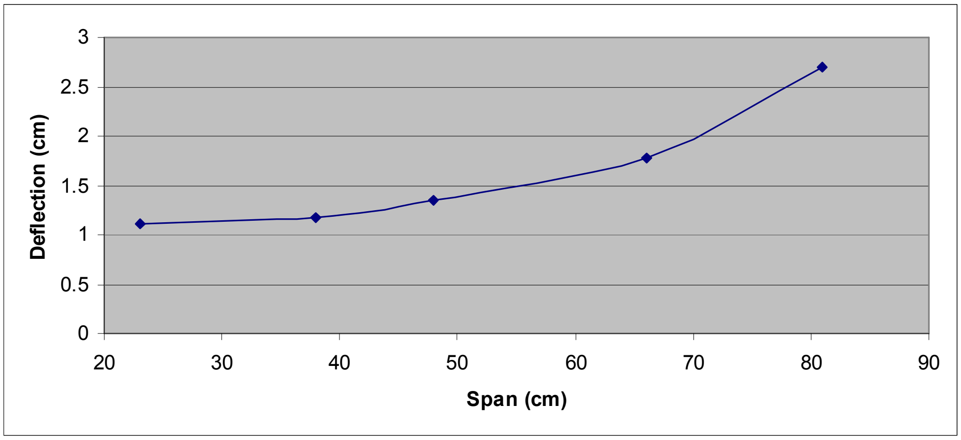

Figure 9: Deflection vs. Span for composite sandwich beam.

5. CONCLUSIONS

A multifunctional fuel cell based on sandwich structure technology has been achieved through the pultrusion process. The overall power output by the device is much lower than should be expected from a direct methanol fuel cell operating under comparable conditions. The contact resistances between the monopolar plates and the MEA likely play a large role in this reduced performance. "Half-cell" flow tests using the silicon gasket sealing material which was used in the structural cells show that this gasket material may separate the monopolar plate and the GDL. This may both prevent fuel from following the flow channels in the plate, allowing a "short circuit" of the fuel flow path, and increase the overall contact resistance in the cell. These resistances occur at all interfaces inside the fuel cell, but the interface between the conductive plates and the GDL is definitely the most important. Understanding these resistances and optimizing the pressure holding these components together is very important to achieving optimum fuel cell performance [7]. Tests have shown that better compression may double the power output by these types of cells [8]. Mechanical characterization of the structural sandwich beams via three-point bend tests has also been accomplished in the present study.

ACKNOWLEDGEMENTS

Research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-06-2-0014. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

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