

Stainless steel as a bipolar plate material for solid polymer fuel cells

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Abstract

Stainless steel bipolar plates for the Solid Polymer Fuel Cell (SPFC) offer many advantages over conventional graphitic materials. These include relative low cost, high strength, ease of manufacture and as they can be shaped into thin sheets, significant improvement in the power/volume ratio. However, interfacial ohmic losses across the metallic bipolar plate and the Membrane Electrode Assembly (MEA), reduce the overall power output from a SPFC. Despite a large range of commercially available alloys, 316 stainless steel has traditionally been the alloy of choice for bipolar plates. A number of alternative grades of stainless steel have been evaluated in terms of the electrical resistance of their surface oxide film. This showed that ohmic losses exhibited in fuel cell performance varied depending on the elemental composition of the stainless steel alloy. Three stainless steel alloys, 310, 316 and 904L, were chosen as candidate bipolar plate materials. Increased polarisation was observed in the order $904L < 310 < 316$. This was maintained throughout an ongoing endurance test, where these cells have been run for over 3000 h without significant performance degradation. This difference in polarisation behaviour was attributed to variation in thickness of the oxide film. Analysis has shown no deleterious effect on the surface of the bipolar plate and no evidence of corrosion. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Solid polymer fuel cells; Bipolar plates; Stainless steel; Passivation; Corrosion

1. Introduction

The bipolar plate is a multi-functional component within a Solid Polymer Fuel Cell (SPFC) prismatic stack. Its primary function is to supply reactant gases to the Gas Diffusion Electrodes (GDE) via a flow field in the surface. It must also provide series electrical connection between the individual cells, and effectively remove product water. To satisfy these requirements, the base materials for bipolar plates require certain properties. The majority of SPFC stack producers utilise bipolar plates based on graphite, carbon composites or metals (principally, stainless steel). Each of these materials has characteristics that are beneficial for fuel cell applications, but are limited by others. An ideal bipolar plate would incorporate the merits of these materials, such that it would be high in electrical conductivity and corrosion protection, of low density but with high mechanical strength, impermeable to reactant gases,

chemically inert, and allow for ease of manufacture. To attain suggested performance targets for transport applications of 1 kW l^{-1} and 1 kW kg^{-1} , at a cost of $\$35/\text{kW}$ [1,2], a lightweight, robust, low cost plate material is required.

Current approaches at Loughborough University to achieve these goals have focused on three different types of materials; these being stainless steel and titanium (both with and without surface coatings) and carbon composites. In a recent publication, it has been shown that different plate materials effect the fuel cell performance [3]. The passive film on stainless steel is influenced by the chemical composition of the alloy and affect ohmic losses within a fuel cell. A rapid fabrication procedure for carbon composite-based bipolar plates has also been presented [4]. In this paper, further research findings on the stainless steel approach are discussed. Stainless steel is an attractive bipolar plate material, since despite its high density, it allows for extremely thin plates to be used, and provides a relatively simple mass production technique. By using stainless steel bipolar plates, SPFC cost estimates recently published in the Fuel Cells for Transportation 1998 report,

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carried out on behalf of Ford Motor, showed that a 70-kW SPFC stack cost of $< \$20/\text{kW}$ was achievable [5].

It has been historically perceived that the passivating nature of stainless steel, which has been shown to be corrosion resistant in an SPFC environment, introduces unacceptable ohmic losses that limit the overall power output of a SPFC. To overcome this problem, low surface resistance coatings have been applied to the stainless steel [6], but as these coatings are expensive, this can often outweigh the benefits. However, the operation of fuel cells using uncoated stainless steel bipolar plates is possible without degradation due to corrosion [3]. To date, in excess of 3000-h testing has been conducted without evidence of corrosion products for 316 (18% Cr, 12% Ni), 310 (25% Cr, 20% Ni) and 904L (20% Cr, 25% Ni)

grades. Note, for automotive applications, a fuel cell would have to endure at least 3000–5000 operational hours. Each of these materials gave a different polarisation response on testing in a fuel cell, which we have attributed to the chemical composition of the stainless steel and subsequently the nature of the surface passive film. The power density achieved for the 904L system was close to that observed with graphite.

2. Experimental

2.1. Surface resistance of bipolar plate materials

Significant ohmic losses are encountered across the bipolar plate/GDE interface. The relative nature of the

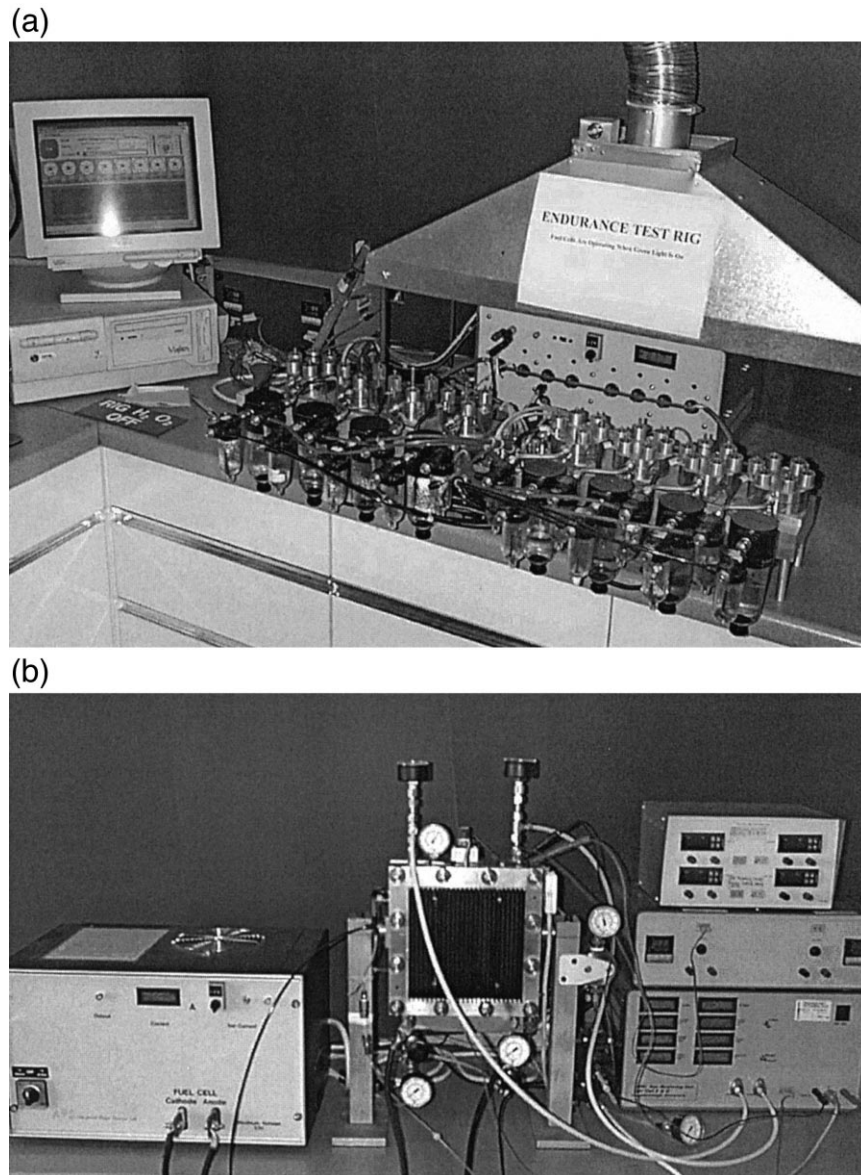


Fig. 1. SPFC test rigs. (a) Long-term SPFC endurance rig. (b) 200 cm² bipolar plate single cell test station.

resistive surface film on candidate materials, was determined using a method described in detail elsewhere [3]. This basically involved measuring the potential difference across two pieces of the plate material, which sandwiched two pieces of a gas diffusion layer (CARBEL® CL), whilst a fixed electrical current was passed through the arrangement. The potential difference was monitored as the compaction on the assembly was periodically increased, thus the relative surface resistivity for each material could be determined. The bipolar plate samples were tested as received, apart from thorough degreasing and cleaning in distilled water.

2.2. Fuel cell testing

Small scale evaluation and long-term endurance testing were conducted in pressurised cells with an active surface area of 11.8 cm². The endurance test rig is shown in Fig. 1a. This purpose built rig allows for simultaneous testing of up to eight independent single fuel cell units under a variety of operating conditions. Because in this case these cells can only accommodate one Membrane Electrode Assembly (MEA), the flow field track designs, to distribute the reactant gases to the electrodes, were machined on one side of the plate only, and as such these plates should be strictly referred to as mono-polar. For the constant current endurance test, this rig was operated, under the conditions detailed in Table 1. The test cycle entailed 100-h intervals where the rig was under electronic load, followed by a period of approximately 68 h, where the rig was allowed to cool to 20°C under no load condition. To ensure there was no source of contamination from auxiliary supply systems, all materials and fittings were either PTFE or 316 stainless steel.

Full size bipolar plate testing (200 cm²), with enhanced gas flow fields, was conducted on the test rig shown in Fig. 1b. The gas flow field design of these bipolar plates was provided by Advanced Power Sources, and produced by a Photo-Chemical Machining technique. Polarisation data was obtained by galvanostatically controlling the cell and recording the cell potential.

In both cell designs, care was taken to ensure the PEM did not directly contact the metal bipolar plates, which can provide a possible source of corrosion due to shunt currents[7].

2.3. MEA pre-treatment

Each MEA (Gore PRIMEA® Series 5510)¹ was pre-conditioned to ensure the optimum hydration state. The

Table 1
Fuel cell operating conditions for endurance testing

MEA	Gore PRIMEA® Series 5510 (based on GORE-SELECT® membranes, 30 μm), 0.3 mg cm ⁻² Pt. CARBEL® CL as gas diffusion media
Hydrogen pressure	3 bar (g)
Air pressure	3 bar (g)
Hydrogen utilisation	70%
Air utilisation	35%
Cell temperature	50°C
Humidification:	50°C
Compaction force	220 N cm ⁻²
Current density	0.7 A cm ⁻²

cell potential was cycled between 0.6 and 0.3 V whilst monitoring performance with respect to time; changing potential when a steady state power output was achieved. A steady cell performance was achieved after several 0.3/0.6 V conditioning steps. After leaving overnight, the pressure and temperature of each cell were maintained at the test operating conditions, and subjected to a fixed current density, unless otherwise stated.

3. Results and discussion

3.1. Interfacial resistance losses

Fig. 2 summarises the change in comparative surface resistance results of the stainless steel alloys, before and after the tested samples were run in the endurance test rig. For all samples, an increase in the compaction force resulted in a decrease in the interfacial resistance. In the fuel cell experiments, the compaction force imparted on a cell was typically about 220 N cm⁻², thus the variation in interfacial resistance at this value was of most importance. Over the experimental period, there was a difference in the surface resistance between the ‘used’ and the original samples. Visual inspection of the bipolar plate indicated a slight surface deposit, of white plastic appearance similar to the sealant material, near to the gasket region. This was attributed to gasket degradation causing a slight ‘spreading’ of the gasket material into the active cell region. Apart from this deposit, the properties of the alloy and passive film had changed little, and the surface resistance for each remained the same. This was contrary to that observed with other passivating metals such as titanium, whose electrical resistivity increases with respect to time, causing the cell to fail [3].

¹ GORE-SELECT, PRIMEA and CARBEL are trademarks of W.L. Gore and Associates.

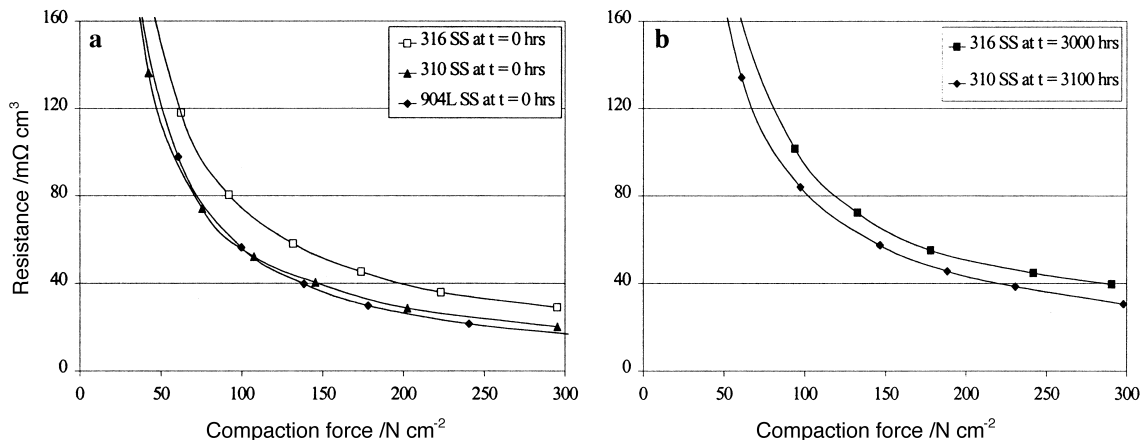


Fig. 2. Variation in interfacial resistance dependency on compaction force. (a) Before endurance testing. (b) Sometime into endurance testing. 904L cell has not yet been dismantled after 1300-h testing, thus the interfacial resistance difference could not be measured.

3.2. Electrochemical performance of materials

The difference in interfacial resistance for each alloy (Fig. 2) was reflected in the fuel cell performance, where the polarisation response was shown to vary depending on the bipolar plate alloy composition (Fig. 3a). This difference was due largely to the ohmic loss imparted by the interfacial resistance losses between the different alloys and the gas diffusion media of the MEA. Note that the total resistance within the fuel cell system also includes the ionic resistance in the membrane, and to a lesser extent, other electrical interfaces, such as that between the current collectors and the bipolar plates. Thus, ex situ interfacial resistance losses measured earlier, do not exactly translate

to that observed in the polarisation data. This may be due to the difference in test assembly for the ex situ measurements compared to the fuel cell testing. Here, the interface between each electrode and the membrane also contributes to the ohmic drop. Comparative fuel cell performance at 0.7 A cm⁻² realised cell potentials of 0.66, 0.61 and 0.49 V for 904L, 310 and 316 stainless steel, respectively.

Throughout the long-term endurance test, this variation in the polarisation response was maintained. Fig. 3b. shows typical polarisation plots for each of the alloys at some time into the test. Increased polarisation was observed such that the fuel cell performance of 904L > 310 > 316.

Fig. 4 gives the average cell potential for each arrangement over each 100-h test period. Over the specified

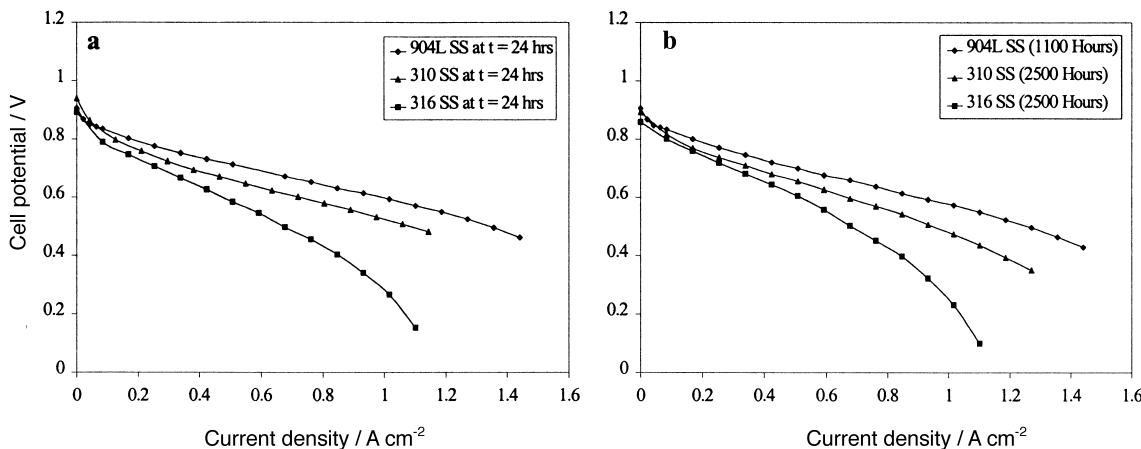


Fig. 3. Polarisation plot for each fuel cell (11.8 cm²) arrangement. Data taken at (a) after 24 h. (b) At sometime into the long-term test.

duration, no catastrophic degradation due to the bipolar plate material was observed for any of the arrangements.

This difference in performance, as already stated, was due to the variation in the property of the passive film on the stainless steel alloys. We have previously shown this to be brought about by the thickness, and hence the resistivity through the surface film [4]. The principle constituent of this film is oxygen. By means of Auger Electron Spectroscopy (AES), it has been shown that the oxide film is thicker in stainless steel alloys containing less nickel and chromium. Thus, a general trend in the thickness of this film is such that as the concentration of nickel and chromium is increased, so the oxygen-rich film thickness is decreased.

Following the outcome of these preliminary small scale tests, full size bipolar plates (200 cm^2) were prepared, with optimised gas flow fields for both the anode and cathode. To date, 316 and 310 stainless steel alloys have been tested on this scale. (A production problem with 904L is that it is not currently possible to etch to the precision demanded by this application). Fig. 5 shows the polarisation response for these materials on the 200 cm^2 system. Also included are comparative data for a proprietary low surface resistant coating on 316 stainless steel plate. All data from this single cell were recorded at 2 bar (g) humidified hydrogen and air, and at a cell temperature of 50°C .

Again, the variation trend shown on the small-scale experiments is repeated here. In terms of peak DC electrical power output, a 310 stainless steel arrangement will comfortably deliver over 100 W per plate. Thus, with these thin bipolar plates (0.6 mm), it is estimated that with current MEA technology, and allowing for an active cell to cooler cell ratio of 4:1, a prismatic SPFC stack using 310 stainless steel would be capable of delivering a mid-stack volumetric and gravimetric power density of 1.8 kW l^{-1} and 0.6 kW kg^{-1} , respectively. These values assume stack operation at a cell potential of 0.7 V per plate, and are

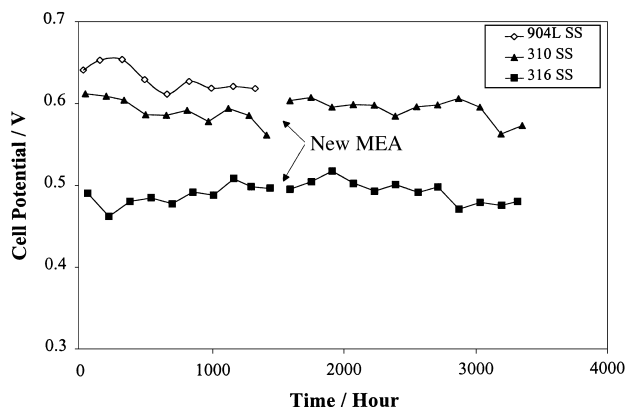


Fig. 4. Average weekly cell potential. Average cell potential data for each 100-h period the cells were under load.

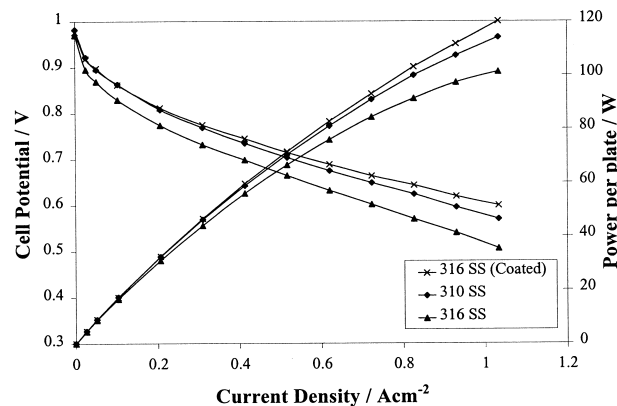


Fig. 5. 200 cm^2 bipolar plate comparison of 316, 310 wrt propriety coated 316.

based on current stack technology developed by Advanced Power Sources.

4. Conclusions

The bulk resistivity of stainless steel is insignificant with respect to the surface resistance imparted by the passive film that protects the metal from corrosion. The chemical composition of this film affects its physical characteristics, which leads to variations in its electrical conduction. There is a general trend whereby the interfacial resistivity of stainless steel alloys decreases with increasing nickel and chromium content. Because it is known that metal ions, such as nickel, will poison the PEM by restricting proton transfer, there is concern that highly alloyed stainless steel would be unsuitable for SPFC bipolar plates. However, in over 3000-h endurance testing, we have seen no evidence of corrosion of these bipolar plates that would cause poisoning of the PEM. The observed slight decay in cell performance with the stainless steel samples over this time period, was similar to that of the equivalent graphite plate arrangement. By optimising the chemical composition of the alloy, it would be feasible to use uncoated stainless steel bipolar plates, to provide a low cost fuel cell system with power densities approaching that observed with graphite.

Acknowledgements

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References

- [1] C.E. Borroni-Bird, J. Power Sources 61 (1996) 33.
- [2] K. Prater, J. Power Sources 51 (1994) 129.

- [3] D.P. Davies, P.L. Adcock, M.T. Turpin, S.J. Rowen, *J. Applied Electrochem.* (1999) Accepted for publication.
- [4] P.L. Adcock, D.P. Davies, S.J. Rowen, M. Turpin, British Patent Application No. 9915925.3, Flow Field Plates, 1999.
- [5] J. Adams, FY 1998, US DoE's Fuel Cells for Transportation programme, Contractors Annual Progress Report 1 (1998) 3.
- [6] P.L. Hentall, J.B. Lakeman, G.O. Mepsted, P.L. Adcock, J.M. Moore, *J. Power Sources* 80 (1999) 235–241.
- [7] C. Zawodzinski, M.S. Wilson, S. Gottesfeld, in: Fuel Cell Seminar, Orlando, Florida, November 17–20, 1996, pp. 659–662, Extended Abstracts.