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Effect of Corrossion on the Electrical Conductivity of Metals and Polymer Composite

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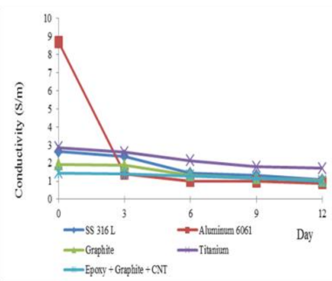
Graphical abstract



Abstract

Applications of a metallic bipolar plate in a proton exchange membrane fuel cell (PEMFC) are currently being developed in the market. The main challenge for metal usage is the effect of corrosion on the overall performance of a PEMFC. The materials used in this study are stainless steel 316L (SS316L), aluminum 6061, titanium, compressed graphite, and graphite/CNTs/epoxy nanocomposite. The materials and its measurements were studied using digital multimeter to obtain the conductivity of the material, potentiostatic test to determine the corrosion rate, pH meter to determine the pH level of the sulfuric acid, and microscope to study the topography surface of the corrosion material before and after the corrosion test. Results show that aluminum corrosion is the fastest and the most severe, followed by SS316L, titanium, compressed graphite, and graphite/CNTs/epoxy nanocomposite. Corrosion decreases the electrical conductivity of the material and the pH level of sulfuric acid, consequently making the material dull and coarse. Metal plates face more severe corrosion problems compared with compressed graphite and graphite/CNTs/epoxy nanocomposite. Despite the corrosion problems it creates, metal use is low cost, easy to fabricate, light, and has good heat and electric conductivity. Hence, the development of the metallic bipolar plate shows high potential, and its modification is encouraged.

Keywords: PEMFC; bipolar plate; corrosion; potentiostatic test; metal plate; composite plate

Abstrak

Aplikasi plat logam dwikutub dalam sel fuel membran penukaran proton (PEMFC) banyak dibangunkan di pasaran sekarang. Cabaran utama penggunaan logam adalah kesan kakisan pada prestasi keseluruhan PEMFC. Bahan-bahan yang digunakan dalam kajian ini adalah keluli tahan karat 316L (SS316L), aluminium 6061, titanium, grafit termampat dan Komposit-nano grafit/CNT/epoksi. Bahan-bahan dan ukuran telah dikaji dengan menggunakan multimeter digital untuk mendapatkan kekonduksian bahan, ujian potentiostatik untuk menentukan kadar kakisan, pH meter untuk menentukan tahap pH asid sulfurik, dan mikroskop untuk mengkaji permukaan topografi bahan kakisan sebelum dan selepas ujian kakisan. Keputusan kajian ini menunjukkan bahawa aluminium kakisan adalah yang paling pantas dan yang paling teruk, diikuti oleh SS316L, titanium, grafit termampat, dan Komposit-nano grafit/CNT/epoksi. Kakisan mengurangkan kekonduksian elektrik bahan dan tahap pH asid sulfurik tersebut, akibatnya menjadikan bahan kusam dan kasar. Plat logam menghadapi masalah hakisan yang lebih teruk berbanding dengan mampat grafit dan Komposit-nano grafit/CNT/epoksi. Walaupun masalah kakisan yang terhasil, penggunaan kos bagi logam adalah rendah, mudah untuk difabrikasi, ringan dan mempunyai kekonduksian haba dan elektrik yang baik. Oleh itu, pembangunan plat dwikutub logam dapat menunjukkan potensi yang tinggi, dan pengubahsuaianya untuk masa depan adalah digalakkan.

Kata kunci: PEMFC; dwikutub plat; kakisan; ujian potentiostatik; plat logam; plat komposit

■1.0 INTRODUCTION

A fuel cell is an electrochemical conversion device that converts chemical energy into electrical energy. When hydrogen and air are supplied, the reaction products are heat and water vapor. The components of fuel cells are an anode, cathode, anode catalyst layer, cathode catalyst layer, electrolyte, and bipolar plate. The different types of fuel cells are the direct methanol fuel cell, proton exchange membrane fuel cell (PEMFC), alkaline fuel cell, phosphoric fuel cell, molten carbonate fuel cell, and solid oxide fuel cell. PEMFC is a good energy source for alternative automotive application. The safe and reliable use of the stacked shape PEMFC has been demonstrated to be by thousands of transportation users. With overall system design efficiency, waste gases, such as carbon dioxide and nitrogen dioxide can be limited to small quantities [1].

The net efficiency of a cell fuel stack is highly dependent on the performance of the bipolar plate, which, in turn, is dependent on the material used and flow field design [2]. A bipolar plate is designed to distribute the fuel and oxidant in the stack, facilitate water management, separate individual cells in the stack, carry the current away from the cell, and facilitate heat management [3]. A bipolar plate, which is the most essential component of PEMFCs, is purposely designed for efficient water and heat management in a fuel cell and for separating fuel cell stacks into a single cell [4]. This component is one of the most expensive in the fuel cell stack and contributes to 80% of the total weight of the stack [5]. The criteria or major constraints for the PEMFC bipolar plate technical design are low cost, ease of gas flow, high electric conductivity (> 100 S/cm), low permeability to gases (H_2 and O_2), high manufacturability, reasonable strength, low weight, low volume, high chemical stability, high corrosion resistance (< 16 μA/cm^2), and low thermal resistance [6]. Thin metallic bipolar plates cost less than the currently used machined graphite bipolar plates. Thin metallic bipolar plates also have reduced weight/volume and perform better than developmental polymer/carbon fiber and graphite composite bipolar plates. However, inadequate corrosion resistance can result in high electrical resistance and contamination of the polymer membrane, which can significantly degrade performance [7].

Previous research reveals several effects of corrosion on PEMFCs. Corrosion will reduce efficiency and form a passive layer that results in increased contact resistance [8]. Metal ions could dissolve into the cell, thus resulting in membrane failure [9]. Corrosion could also decrease the conduction of ionic membrane, consequently affecting the performance of fuel cell stacks [10]. Two categories of materials, namely, metallic and non-metallic bipolar plates, were used in this experiment. Metallic bipolar plates were reported to have the capacity to save 22% of hydrogen gas compared with non-metallic bipolar plates [11]. The objective of the present study is to examine the effect of a corrosive environment on PEMFCs and on the corrosive properties of metal and non-metal part of bipolar plates.

■2.0 EXPERIMENTAL PROCEDURE

The experimental flow chart for this study is shown in Figure 1. The metals used in this study were stainless steel (SS) 316L, aluminum 6061, and titanium. The non-metal materials used were compressed graphite and graphite/CNTs/epoxy nanocomposite. The materials were cut into sample dimensions of 1.0 cm × 1.0 cm (area is 1.0 cm^2). Soldering and cold mounting were used to allow the materials to work as electrodes. The surface roughness of each material was then reduced using carbon carbide papers. The electrical resistance and conductivity of the materials were measured using a digital multimeter [12]. The surface materials were then observed using a microscope before the corrosion test was conducted. Potentiostatic tests were performed to simulate the working conditions of PEMFC [13]. The applied potential was -0.1 V at the anode and 0.6 V at the cathode. The system was purged with O_2. The test temperature was 70 °C, given that the working temperature of PEMFC is approximately 70 °C to 100 °C [14]. The electrolyte used was a 0.5 M H_2SO_4 solution. Electrical resistance and conductivity were again measured after the potentiostatic test was conducted. Effects of corrosion were also studied by measuring the pH of sulfuric acid every three days for 12 days [15]. Finally, the corrosion products were analyzed after 288 hours (12 days) of immersion time using a microscope.

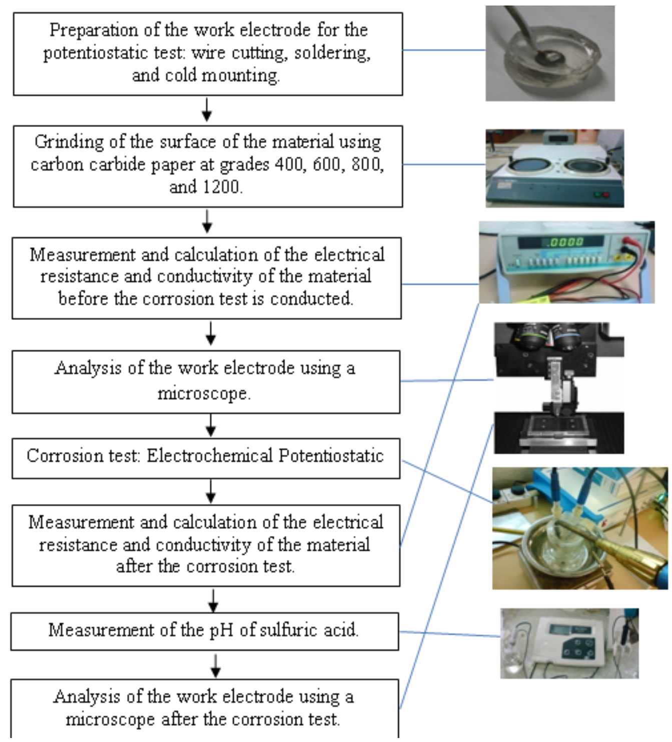


Figure 1 Experimental flow chart

■3.0 RESULTS AND DISCUSSION

Bipolar plates should be highly resistant to corrosion because of the high corrosion potential of the PEMFC environment [16]. The current density of corrosion (mA/cm^2) determined through the potentiostatic test is shown in Figure 2. The graph shows that the current density of aluminum 6061 was the highest, followed by graphite/CNTs/epoxy nanocomposite, compressed graphite, SS 316L, and titanium. From our results, the 0.1750 mA/cm^2 value for aluminum is higher than that obtained when combining the values for SS 316L, titanium, compressed graphite, and graphite/CNTs/epoxy nanocomposite. The same trend is observed in terms of the corrosion rate (mm/Year) of each material, as shown in Figure 3. The graph shows that aluminum 6061 undergoes the most rapid corrosion, followed by graphite/CNTs/epoxy nanocomposite, graphite, SS 316L, and titanium. Based on the law of Faraday [17], the rate of corrosion is proportional to the corrosion's current density. Therefore, the corrosion of aluminum 6061 was proven to be the fastest and the most severe.

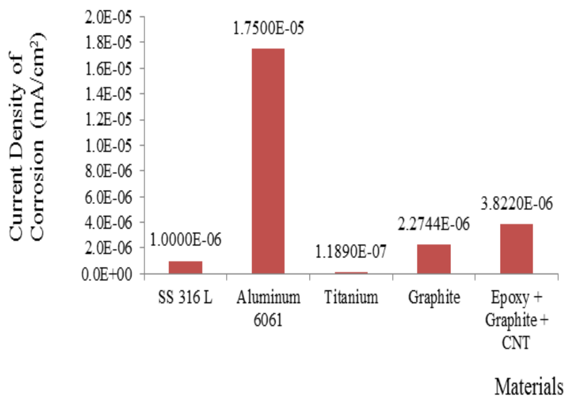


Figure 2 Current density of corrosion (mA/cm^2) for several materials

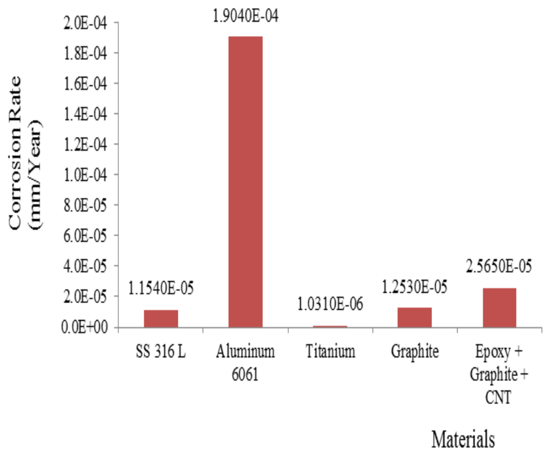


Figure 3 Corrosion rate (mm/Year) for several materials

Figure 4 shows the electrical resistance of the tested materials. Electrical resistance is inversely proportional to electrical conductivity. Electrical conductivity is directly proportional to the current density but inversely proportional to the electric field. Figure 5 shows that electrical conductivity for all materials continuously decreases from the start until the end of the experiment. Aluminum 6061 initially has the best electrical conductivity among all materials but also shows the worst resistance to corrosion because this material was observed to severely corrode during the process. At the end of the experiment, aluminum 6061 has the lowest electrical conductivity, followed by graphite/CNTs/epoxy nanocomposite, compressed graphite, SS 316L, and titanium. Based on the results, this arrangement is appropriate, as described earlier in Figures 3 and 4. Current density decreases during corrosion because of the formation of an oxide layer on the surface, which prevents further corrosion [12]. This oxide layer is passive and has low electrical conductivity, which will increase electrical resistance and cause Ohm's loss.

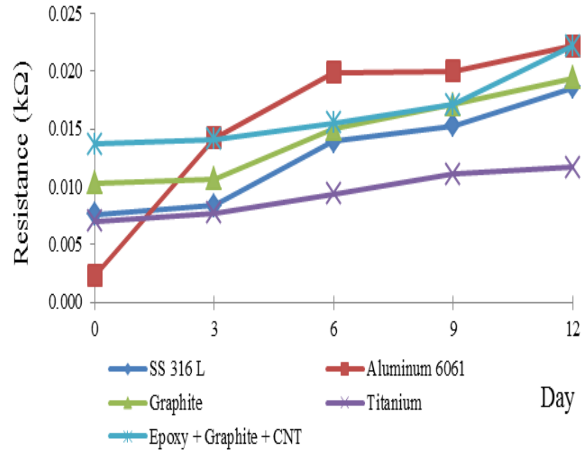


Figure 4 Variation of Electrical resistance of bipolar plate component versus time.

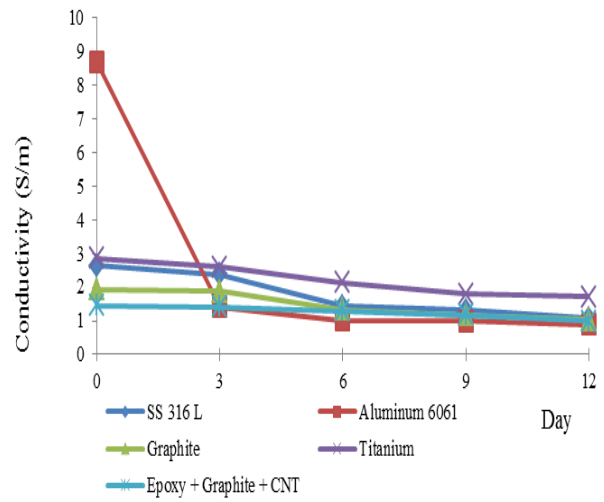


Figure 5 Variation of Electrical conductivity of bipolar plate component versus time.

One factor that contributes to fuel cell corrosion is the pH of the solution. Maintaining a pH of 5 and utilizing an acidic source can prevent bipolar plate corrosion. Metals should not be allowed to come in contact with fuel cell membranes. According to the Nernst equation [18], the pH of sulfuric acid is affected by environmental temperature and the activity of hydrogen ions. The level of pH decreases as the concentration of hydrogen ions increases. An electrochemical process occurs when corrosion starts, which is a chemical reaction that moves electrons from one chemical species to another. A metal atom produces electrons during the oxidation reaction, and these metals then form a positive ion. All electrons produced during oxidation will be transferred to the chemical species, which will undergo a reduction reaction. Metal corrosion in acid solution generates a positive ion containing a high concentration of hydrogen ions, which will undergo a reduction reaction. Figure 6 shows that the pH of sulfuric acid for aluminum 6061 is the lowest at the end of the immersion time, which means that several hydrogen ions in the sulfuric acid facilitated corrosion. Based on Figure 6, aluminum 6061 can be concluded to have undergone the most severe corrosion, followed by graphite/CNTs/epoxy nanocomposite, compressed graphite, SS 316L, and titanium.

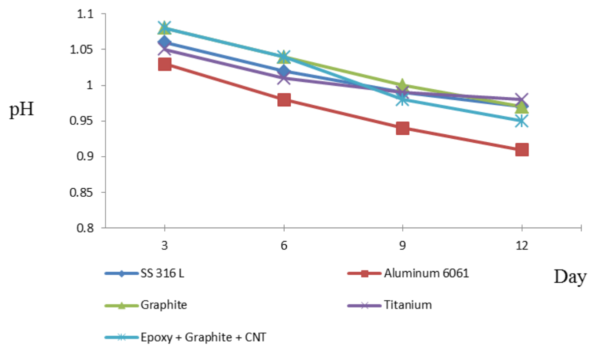


Figure 6 Variation of pH measurement of bipolar plate component versus time

Figure 7 shows the surface microstructure of the studied materials. The surfaces of SS 316L, aluminum 6061, and titanium coarsened after corrosion. This roughness resulted from the presence of oxidation products, which were not spread evenly. The change in surface morphology for compressed graphite and graphite/CNTs/epoxy nanocomposite is insignificant. Pitting corrosion occurred in SS 316L, aluminum 6061, and titanium. Small holes can be observed on the outside surface because of the damage to the local passive film. As gravity naturally grows into the hole, the concentrations and density of sulfuric acid will be higher at the end of the hole, thus inducing more impact in terms of pitting corrosion. The surface morphology of aluminum is coarsest because it contains several small holes on its surface and because it undergoes the most severe corrosion among the five materials. Graphite/CNTs/epoxy nanocomposite and compressed graphite showed no considerable changes on the surface because their properties differ from those of metal.

4.0 CONCLUSION

Electrical conductivity was successfully used to predict the corrosion of a bipolar plate in PEMFC. Results from the observations on electrical conductivity, potentiostatic, pH of sulfuric acid, and microscope showed that metallic bipolar plates made of aluminum 6061 underwent the most rapid and severe corrosion. Non-metal bipolar plates made of such materials as compressed graphite and graphite/CNTs/epoxy nanocomposite did not undergo severe corrosion because of their chemical properties, composition, and microstructure. Among the three metals, titanium underwent the least corrosion. Nevertheless, given the high price of titanium in the market, the selection of SS 316 as the metallic bipolar plate for PEMFC can be the most cost effective because of its longer life compared with other metals.

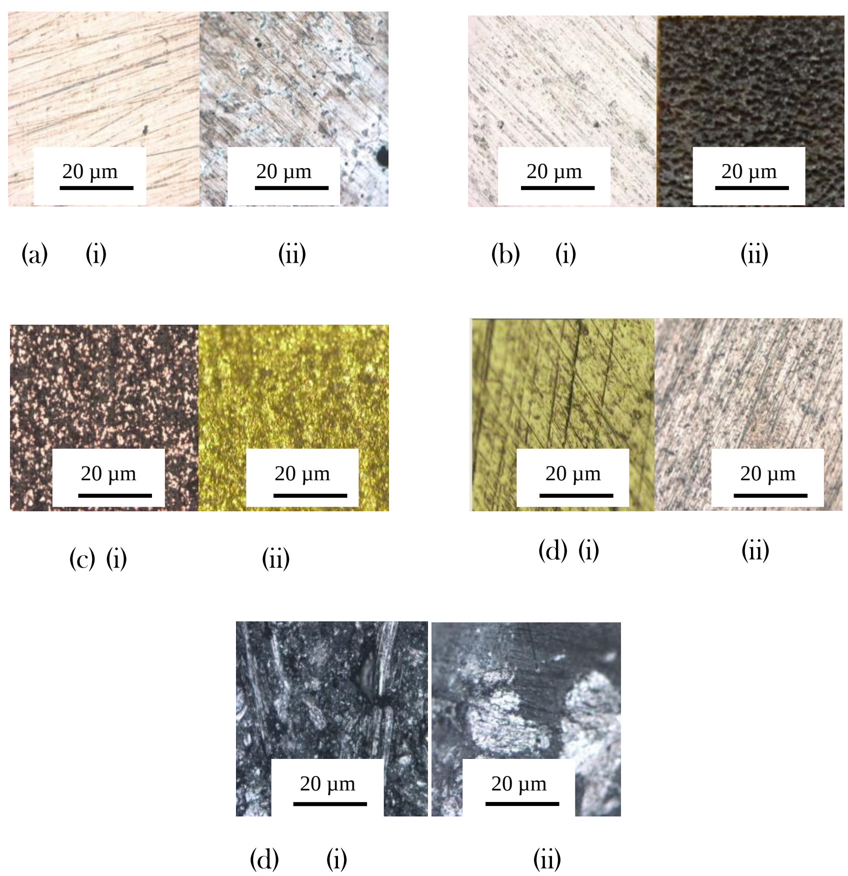


Figure 7 Surface morphology before and after corrosion for a) SS 316L; b) Aluminum 6061; c) Graphite; d) Titanium; e) Epoxy + Graphite + CNT at i) before and ii) after 12 days

Acknowledgement

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