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Performance and characteristics of titanium nitride, chromium nitride, multi-coated stainless steel 304 bipolar plates fabricated through a rubber forming process

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ABSTRACT

The aim of this study is to fabricate SUS304 bipolar plates through a rubber forming process and investigate the characteristics of these bipolar plates with TiN, CrN and CrN/TiN coating layers. SUS304 bipolar plates with a channel depth of more than 0.3 mm are manufactured through a rubber forming process. TiN, CrN and CrN/TiN coating layers are deposited directly on the surface of the bipolar plates. The surface hardness and roughness of the TiN, CrN and CrN/TiN coating layers on the SUS304 bipolar plates are estimated using a nanoindenter and an atomic force microscope (AFM), respectively. The interfacial contact resistance (ICR) is measured on three samples and is found to be 10.2, 26.4 and 23.5 mΩ cm^2 for TiN, CrN and CrN/TiN coating layers, respectively, under a 140 N cm^{-2} compaction force. The corrosion properties are investigated in a proton exchange membrane fuel cell (PEMFC). The TiN coating layer showed a higher corrosion potential and lower corrosion current density than the two other coating layers in both anode and cathode environments. The current densities of a single cell with TiN/SUS304, CrN/SUS304 and CrN/TiN/SUS304 bipolar plates are 0.670, 0.623 and 0.656 mA cm^{-2}, respectively.

Introduction

A fuel cell is a device that changes chemical energy into electrical energy. The fuel composed of hydrogen gas is supplied to the anode, and oxygen from the air is supplied to the cathode for electrochemical bonding. This process continuously generates electricity and water. The fuel cell is used in several fields including transportation, power generation and mobile devices owing to its high efficiency, high current density and other characteristics [1–3]. The proton exchange membrane fuel cell (PEMFC), which is used to supply power to automobiles, offers other advantages such as low operational temperatures (60–90 °C), high power density and

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fast start-up. As a component of the PEMFC stack for a typical passenger car, 400–500 bipolar plates are used. These plates account for about 60–80% of the stack weight and 50% of its volume. Therefore, the bipolar plates must be thin (<1 mm) and light (<1 kg kW^{-1}) [4]. The plates must also have suitable mechanical properties to withstand the compressive forces of stack-clamping. In particular, the cost to fabricate such plates, which represents over 50% of the unit price of a stack, must be reduced in order to realize the economic and commercial value of the PEMFC [5–13]. Therefore, excellent electrical conductivity, heat conductivity, corrosion resistance, low specific gravity, low fabrication cost and other factors play an important role for the materials used in manufacturing bipolar plates [14,15]. Graphite is mainly used for the bipolar plates in the PEMFC because of its excellent corrosion resistance and electrical conductivity. The graphite used in fuel cells has a high production cost owing to the use of mechanical machining methods. High costs are also caused by long lead times for bipolar plate fabrication, which are a result of the brittle characteristics of graphite. Metals such as aluminium, stainless steel and titanium are alternative materials for bipolar plates. In particular, stainless steel has superb mechanical strength, electrical conductivity, surface conductivity, proper corrosion resistance, thermal conductivity and material costs. The optimal process for fabricating stainless steel bipolar plates is through stamping and a rubber forming method [6,16–23]. Jin and Kim [17–19] fabricated stainless steel and titanium bipolar plates using stamping process and reported the optimal parameters for maximum channel depth. Jin et al. [20,21] presented the optimal parameters of rubber forming for fabricating titanium and Al1050 bipolar plates. In addition, they analysed the characteristic of rubber formed titanium coated with TiN film [22]. Jeong et al. [23] suggested the optimal parameters of rubber forming for SUS304 bipolar plate. But the analysis the characteristic of rubber formed SUS304 bipolar plate was not conducted.

Stainless steels will require a protective coating layer to avoid the high likelihood of electrochemical reactions in the aggressive acidic environment of fuel cells, which will result in dissolved metal cations and possible performance degradation of the membrane. TiN is a very common material with a cost effective fabrication process in stainless steel applications for PEMFC bipolar plates owing to its promising corrosion resistance and low film resistivity. TiN coated stainless steel has an excellent corrosion resistance and an improved surface conductivity. CrN films provide a high corrosion protective layer for stainless steel because of a high adhesion force and density [8,24–30]. Yoon et al. [30] deposited CrN/TiN multilayers on stainless steel and examined the electrochemical behaviour of different CrN/TiN coating thickness ratios. These authors commented that a lower surface roughness and higher protective efficiency of the coating were obtained by decreasing the CrN inner layer thickness.

This study aims to examine the characteristics and performance of rubber formed SUS304 bipolar plates with TiN, CrN and CrN/TiN coating layers. This study presents all the process steps for manufacturing bipolar plates from bipolar plate fabrication to the single cell test. The rubber forming process was used to fabricate a SUS304 bipolar plate. This process used a rubber pad instead of a rigid low die, while also improving the channel depth and flatness [20–23]. TiN of 200 nm and CrN films of 200 nm thickness and a CrN/TiN film of 400 nm thickness were deposited on the surface of the formed SUS304 bipolar plates. A nanoindenter was used to analyse the hardness of coated specimens. The surface roughness of coated specimens was measured using AFM. The ICR value, which is directly related to ohmic losses in the PEMFC, between coated specimens and carbon clothes was measured. Hall measuring device was used to measure the electrical conductivity. In order to investigate the corrosion behaviour of the three coating layers, potentiodynamic and potentiostatic polarization experiments were conducted in the operating environment of the PEMFC. Single tests with TiN, CrN and CrN/TiN coated SUS304 bipolar plates were performed in the operating environment of the PEMFC.

Experimental procedures

Apparatus and conditions of rubber forming process for manufacturing SUS304 bipolar plates

A rubber forming process was used to fabricate the SUS304 bipolar plates. The equipment used was composed of a punch, a SUS304 plate, a rubber pad and a container. Fig. 1 shows a schematic of the rubber forming process to fabricate bipolar plates. In the rubber forming process, the rubber pad and SUS304 plate are placed inside the container, after which the punch descends to press the SUS304 plate and the rubber pad together. The even pressure that is applied to the surface of the SUS304 plate provides a repulsive force, through which the SUS304 plate and the rubber pad simultaneously fill the groove in the punch, forming the channels. The speed and pressure of the punch was 300 mm/s and 55 MPa, respectively. The rubber pad had a hardness of Shore A 20 and a thickness of 60 mm [20–23]. A SUS304 plate with thickness of 0.1 mm and size of 100 × 100 mm^2 was prepared in this way. Table 1 shows the physical properties of SUS304. Fig. 2 shows the punch shape with a serpentine channel. The depth and width of the groove are 0.4 mm and 1.2 mm, respectively. The protrusion width was 0.4 mm and the draft angle of the groove was 30°.

Conditions for TiN, CrN and CrN/TiN coatings

TiN, CrN and CrN/TiN films were deposited on rubber formed SUS304 bipolar plates by a DC magnetron sputtering technique. Coatings of TiN and CrN with approximate thickness of 200 nm were deposited of the surface of SUS304 bipolar plates. For CrN/TiN, a 200 nm thick TiN coating was followed by 200 nm thick CrN coating. The total thickness of the CrN/TiN coating layer was about 400 nm and so the thickness ratio of the CrN/TiN layer was 1:1. The target was pure Ti and Cr with 99.995% purity. The distance between the plates and target inside the vacuum chamber was maintained at 100 mm. The base pressure was approximately 1 × 10^{-5} Torr using a rotary pump and a turbo molecule pump. Deposition was carried out at a working pressure below 0.38 Pa. The total power was fixed