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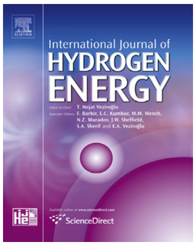

Flexible fuel cell using stiffness-controlled endplate

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ABSTRACT

We investigate the use of stiffness-controlled polydimethylsiloxane (PDMS) endplates with Young's modulus of 7.50×10^5 Pa and 8.68×10^5 Pa for improving the performance of flexible fuel cells. The maximum power densities of stacks with PDMS endplates with Young's modulus of 7.50×10^5 Pa and 8.68×10^5 Pa are 82 $\mathrm{mWcm^{-2}}$ and 117 $\mathrm{mWcm^{-2}}$, respectively. The flexible fuel cells produce a maximum absolute power of 1.053 W (i.e., the power density is 117 $\mathrm{mWcm^2}$) under a bending radius of 15 cm. Interestingly, their impedance spectra reveal that the ohmic and faradaic resistances decrease under the bent condition. Furthermore, the decreased resistance and corresponding performance enhancement are due to the increased compressive force normal to the membrane electrode assembly, which is investigated using a finite element method of stress distribution within the flexible fuel cells. As our experiments show, the faradaic impedance decreases significantly because the bending radius decreases from 36 cm to 15 cm.

Introduction

Demand for portable power sources with high energy density continues to increase as the development, commercialization, and diffusion of portable electronics such as smart phones and laptops increase [1–3]. Current energy sources for portable electronics largely depend upon secondary rechargeable batteries such as lithium-ion batteries; however, secondary rechargeable batteries have limited storage capacities of volumetric and gravimetric energy densities due to the intrinsic properties of materials such as lithium and carbon [4,5]. Since a fuel cell's feature of continuous operation can also eliminate the charging time, which is essential for normal secondary batteries, many researchers are working to improve a fuel cell's energy densities for secondary batteries [1,6–9]. Among various fuel cells, polymer electrolyte fuel cells (PEFCs) have high energy conversion efficiency, are environment friendly, and can even continuously produce DC electric power as long as an equivalent amount of fuel is provided [4,10]. Also,

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recent studies focus mainly on wearable electronic devices, as well as other general portable electronics, all of which require portable bendable and stretchable power sources to be fully flexible electronics [11,12]. Flexible/bendable fuel cells and batteries can be utilized in one of the power sources of bio-related power solutions such a blood glucose sensor and a blood pressure sensor. Recently, the batteries and fuel cells of flexible power sources have been improved. Kwon et al. created a cable-type lithium-ion battery that is fully bendable, practical, and aesthetically pleasing [2]. Tominaka et al. reported that using bendable fuel cells is feasible but the total power (1.9 μW) of the stack was too low to operate real electrical applications [13]. Wheldon et al. did not show the in situ operational characteristics of fuel cells [14]. Hsu et al. reported that bendable fuel cells had relatively low bendability due to a carbon lump that was used as a current collecting layer [15]. The above mentioned studies are still in their infancy.

In a fuel cell operation, except for a performance loss due to mass transport, the fuel cell output voltage associated with drawing current can be described in the following way [4]:

$$V_{cell} = V_{OCV} - \eta_{electrode} - \eta_{ohmic}$$

Here, V_{ocv} represents the ideal voltage calculated using the Nerst equation, and $\eta_{electrode}$ and η_{ohmic} are mainly the overpotentials of the electrode and the electrolyte, respectively. Also, an ohmic loss (i.e., IR overpotential) can be expressed in the following way:

$$\eta_{ohmic} = i(R_{elec} - R_{ionic})$$

Here, η_{ohmic} consists of both electronic (R_{elec}) and ionic (R_{ionic}) resistances within an electrolyte. In particular, R_{elec} and R_{ionic} can be expressed as follows:

$$R = \frac{L}{A\sigma}$$

where L is the path lengths of electrons and ions, A is the cross-sectional area of the path, and σ is the conductivity. Therefore, the resistances commonly depend on the path lengths for moving ions between two electrodes and for minimizing the contact resistance between compartments (i.e., catalyst layer and gas diffusion layer). In particular, previous literature reported deformation (or stiffness) of endplates in fuel cells directly influences on their performances in which the optimization of stiffness and clamping pressure are important parameters of a fuel cell stack [16,17]. Our previous study reported that the decreased resistance and corresponding performance enhancement were due to the increased compressive force normal to the membrane electrode assembly (MEA) [16,18–20]. As shown in Fig. 1A (flat) and Fig. 1B (bent condition), we designed stiffness-controlled polydimethylsiloxane (PDMS) endplates (Young's modulus: 7.50×10^5 Pa → 8.68×10^5 Pa) for increasing the clamping force between two PDMS endplates, and measured 117 $mWcm^{-2}$ at the same bending.

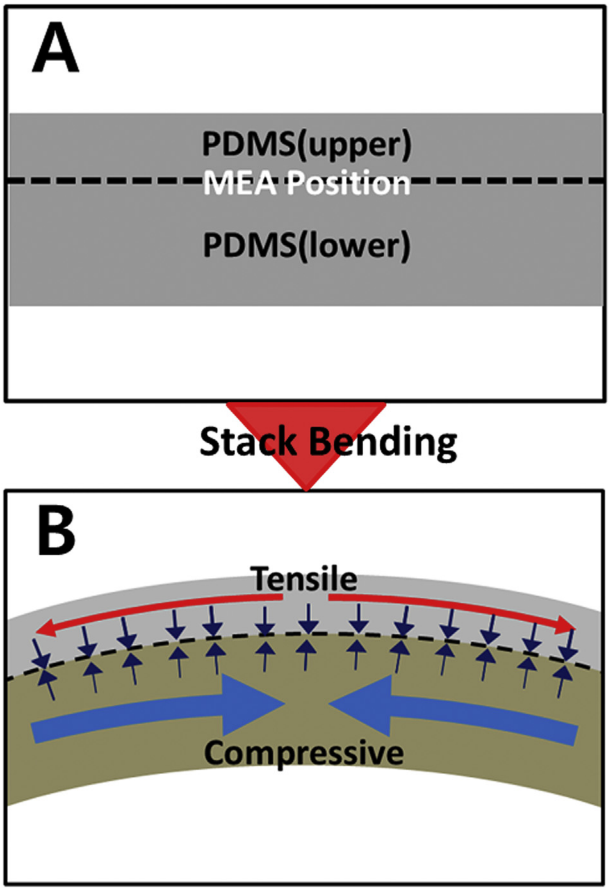

Fig. 1 – Internal stress schematics of bendable fuel cells; (A) original stacks and (B) bent stacks.

Experimental

First, the PDMS layer was mixed with a curing agent in a stainless steel mold where the anode and the cathode flow channels were machined to feature the channels on the PDMS endplates. The mixing ratios of the PDMS and the curing agent were 10:1 (Young's modulus: 7.50×10^5 Pa) and 5:1 (Young's modulus: 8.68×10^5 Pa) [21]. Then, the mold was heated at 70 °C for 4 h to solidify the PDMS. As shown in Fig. 2, the dimensions of the cross-sectional areas of the flow channels in the anode and cathode PDMS endplates were 1 (W) × 1 (H) mm^2 and 2 (W) × 1 (H) mm^2, respectively. The thicknesses of the asymmetric PDMS pads are 6 mm (anode) and 4 mm (cathode). Fig. 3A and B describe the process of fabricating Ag nanowires (NWs) as current collectors on the PDMS endplate. The Ag NWs were fabricated using conventional polyol synthesis. As shown in Fig. 3C, a successive multi-step growth (SMG) method was used to increase the length of the Ag NWs so they can be used as stable current collectors under various bent conditions [22]. Since our study focuses mainly on the scheme of the bendable fuel cell, we excluded the details of fabricating Ag NWs from our explanation. These details were discussed in our previous studies [18,20,22]. Fig. 3D shows the bent stack whose bending radius was 15 cm. An MEA (0.45 $mgcm^{-2}$ Pt/C loading, Fuel Cell Power Inc., Korea) with an active area of 3 × 3 cm^2 was attached to the center of the anode PDMS endplate using polypropylene tape (3M, USA). The thicknesses of the Nafion™ 212 membrane and carbon paper electrodes were 50 μm and 350 μm, respectively. This