Effect of cell length on the performance of segmented-in-series solid oxide fuel cells fabricated using decalcomania method

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Segmented-in-series solid oxide fuel cells (SIS-SOFC) have been stacked on all sides of a porous ceramic support using decalcomania method. When cells are stacked using decalcomania method, the cell components do not penetrate into the porous support or neighboring layers, resulting in excellent interfacial bonding. The cell components formed uniform thickness as well. Since the current flows laterally in SIS-SOFC, the cells are prepared having dimensions of 8 and 5 mm in length to minimize their lateral resistance. Subsequent power output characteristics have been studied. As cell length decrease from 8 to 5 mm, the open circuit voltage and maximum power density increase. This is attributed to the lower lateral resistance due to shorter current path. Impedance analysis also shows that ohmic resistances decrease substantially with decreasing cell length.

Key-words: Solid oxide fuel cell, Segmented-in-series, Cell length, Ohmic resistance, Decalcomania paper

1. Introduction

Solid oxide fuel cell (SOFC) has the highest efficiency and better economic potentials among the currently available fuel cell technologies. Therefore SOFC has attracted much interests and many research groups are actively involved in the research.1-6)

Since presently available SOFC technologies can draw up to 1.1 V from a cell, it is necessary to have cells stacked in series to obtain higher voltage. Such design, however, has drawbacks of having a higher volume, complex connections and current leakage due to difficulty in scaling. To overcome such drawbacks, one can have a simple design by stacking cells in series on a support and achieve higher voltage. Segmented-in-series (SIS) development at Rolls-Royce has been employed successfully in many SOFC research7-11) and has been able to produce higher voltage.

Numerical analysis shows that one can obtain close to 1,000 mW·cm⁻² of power density when cell length becomes 1–2 mm. It is reported that redox cycle has better stability as anode thickness decreases.12-14)

Lai et al.12,13) reported that power output improved due to decrease in sheet resistance as LSM cathode thickness increased from 11 to 91 μm when they prepared SIS-SOFC with cell length of 1.4 mm on a single side of a flat-tubular support. They proposed to develop a method to build cell components with uniform thickness on the SIS-SOFC. They also suggested to increase the active cell area and the open circuit voltage (OCV) for better performance of SIS-SOFC.

Pillai et al.14) prepared SIS-SOFC on both sides of a flat-tubular support with active cell width of 1.2–1.3 mm. They reported 0.93 V of OCV per cell and 700 mW·cm⁻² of power density, which is of high values. They, however, reported that the power density from both sides had 5–10% of difference due to non-uniform cell thickness stemming from the irregular shape of the flat-tubular support.

In this study, it is attempted to form cells on all sides of the porous support to increase the effective cell area. To achieve uniform cell thickness, decalcomania method is employed in preparing SIS-SOFC.15-17) To gain higher power output cell lengths of 8 and 5 mm are prepared. The effect on electrochemical properties of the SIS-SOFC is reported.

2. Experimental

The starting materials are NiO (Sumitomo Chem. Co, Japan), YSZ (yttria-stabilized zirconia, TZ8Y, Tosoh Co., Japan) and La₀.₈Sr₀.₂MnO₃ (LSM, Fuel Cell Materials, USA). Anode and anode functional layer (AFL) pastes are prepared with NiO-YSZ and TX-623 (Poongsan Chemical, Korea) organic binder using a paste mixer and 3-roll mill. Cathode and cathode functional layer (CFL) pastes are prepared with LSM and LSM-YSZ, respectively. For each paste, TX-623 organic binder is used. 15 wt% activated carbon is added to both anode and cathode pastes as pore former. The weight ratio of NiO:YSZ and LSM:YSZ are 60:40 and 50:50, respectively. In addition, the weight ratio of the powder to the organic binder is 1:0.5–0.7.

The prepared cell component pastes are printed on decalcomania paper coated with water-soluble adhesion layer. The thickness of the cell components is controlled by the number of printing.

The prepared decalcomania paper printed with cell components is then immersed into water to separate the cell components form the paper. The cell components are laminated on all sides of a porous ceramic support. The support is pre-sintered at 1,100°C for 2 h in air. The SIS-SOFC is prepared by first laminating anode/AFL followed by electrolyte later on the support, then
heat treated at 1,450°C for 4 h in air. CFL cathode layer is laminated after the heat treatment. The SIS-SOFC is completed by heat treatment at 1,250°C for 2 h in air.

The output characteristics of the SIS-SOFC are measured at 750 and 800°C using Potentiostat/Galvanostat (PLZ664WA, KIKUSUI, Japan) in galvano-dynamic mode. 3% humidified H₂ is used as fuel and air is used as oxidant. The electrochemical properties of the SIS-SOFC are measured with an impedance analyzer (SP-300, Bio Logic, France) in the range of 0.5 Hz–500 kHz. FE-SEM (Hitachi, S-800, Japan) is used to observe the surface and cross-section of the cells.

3. Results and discussion

Figure 1. shows the schematic of the SIS-SOFC. For cell lengths of 8 mm (Fig. 1(a)) and 5 mm (Fig. 1(b)) before heat treatment, they shrink to 6 and 3.75 mm, respectively after heat treatment. The active cell areas after heat treatment are 6.94 cm² (a) and 4.72 cm² (b). As the cell length shrinks, the laminated area decreases and subsequently there are differences in total power output.

SEM images of the SIS-SOFC after heat treatment are shown in Fig. 2. As shown in the cross-sectional image of the cell in Fig. 2(a), the anode and AFL are indistinguishable as they are made of the same materials. The anode/AFL layer, however, shows uniform thickness of 33.8 μm. The electrolyte, CFL, cathode layers are distinguishable and have uniform thicknesses of 22.5, 5.0 and 35.0 μm, respectively. While the electrolyte (c) shows dense structure, anode/AFL (b) and cathode (d) layers show porous structure. It is reported that the penetration of cell components into the porous structure can cause crack and/or defects, of which can subsequently reduce the cell performance.11) Figure 2(a) shows excellent interfacial bonding. When decalcomania method is used, the cell component layers are stacked in solid layer. Therefore, the cell components do not penetrate into neighboring layers and result in excellent interfacial bonding as demonstrated in the figure.

The OCV for cells with 8 and 5 mm of cell length shows 4.60 and 4.61 V at 800°C, respectively as shown in Fig. 3. The maximum power densities (MPD) for cells with 8 and 5 mm of cell length show 411.9 and 532.2 mW·cm⁻², respectively, at the same temperature. Both OCV and MPD increase with shorter cell length. This result is attributed to the shorter lateral path for current to flow and lower lateral resistance with decreasing cell length. This result agrees well with Zhu et al.13) They reported that power density decreases with increasing effective cell area due to increased current flow path in a planar SOFC. While SIS-SOFC prepared by screen printing on 2 sides of a flat-tubular support shows 5–10% difference in cell performance,14) the results in this study show uniform performance. The uniform output is attributed to the solid layer used in this study, which prevents the cell components penetrating into neighboring interfaces. Therefore, it is concluded that the decalcomania method improves interfacial bonding by minimizing and eliminating cracks and defects in the interfacial areas.

The cell performance is shown in Fig. 4. The maximum power output (MPO) is 2,857 mW for the cell length of 8 mm and 2,510 mW for the cell length of 5 mm at 800°C. The figure shows that the MPO decreases with decreasing cell length. This result is attributed to the decreasing active cell area with decreasing cell dimension.

The impedance analysis, following the procedure proposed by Pillai et al.,14) for SIS-SOFC cell-stacks with cell length of 8 and 5 mm is shown in Fig. 5. For the whole cell-stack impedance, the value where the line crosses the real-axis at high frequency is the ohmic resistance. The arc at low frequency is the polarization resistance. The ohmic resistance decreases to 1.14 Ω·cm² from 1.47 Ω·cm² at 800°C as the cell length decreases from 8 to 5 mm. This is due to the reduced interfacial contact. The polarization resistance also decreases from 2.59 to 1.4 Ω·cm² at 800°C as the cell length decreases. This is attributed to the shortened current path, which results in reduced lateral resistance. For SIS-SOFC fabricated using the decalcomania method, it is concluded that the reduced ohmic and polarization resistances improve its performance.

4. Conclusion

The effect of the cell length on the output performance of SIS-SOFCs fabricated using decalcomania method is studied. When
Fig. 2. SEM images of the 5-cell SIS-SOFC: (a) cross-sectional image of the cell components, (b) microstructure of the anode/AFL layer, (c) microstructure of the electrolyte and (d) microstructure of the cathode.

Fig. 3. Voltage and power density vs. current density of the SIS-SOFCs with cell length of (a) 8 mm and (b) 5 mm at 750 and 800°C. 3% humidified hydrogen is used as fuel and air is used as oxidant.

Fig. 4. Voltage and power output vs. current of the SIS-SOFCs with cell length of (a) 8 mm and (b) 5 mm at 750 and 800°C. 3% humidified hydrogen is used as fuel and air is used as oxidant.
SIS-SOFC is fabricated on all sides of a porous ceramic support, the open circuit voltage and maximum power density increases, while maximum power output decreases, with decreasing cell length. This is attributed to the reduced lateral resistance and active cell area with decreasing cell length. The impedance analysis shows that the ohmic and polarization resistances decrease substantially with decreasing cell length.

It is also found from this study that the SIS-SOFC cell-stack laminated on a porous ceramic support can achieve uniform power output due to uniform component thickness and excellent interfacial bonding when cells are fabricated using decalcomania method.

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