High power density cell using nanostructured Sr-doped SmCoO₃ and Sm-doped CeO₂ composite powder synthesized by spray pyrolysis

Hiroyuki Shimada ^{a,*}, Toshiaki Yamaguchi ^a, Toshio Suzuki ^a, Hirofumi Sumi ^a, Koichi Hamamoto ^a, Yoshinobu Fujishiro ^a

^a *Inorganic Functional Materials Research Institute, Department of Materials and Chemistry, National Institute of Advanced Industrial Science and Technology (AIST), 2266-98 Anagahora, Shimo-shidami, Moriyama-ku, Nagoya 463-8560, Japan*

*Corresponding author

E-mail: h.shimada@aist.go.jp

Tel: 81-52-736-7581

Fax: 81-52-736-7405

Abstract

High power density solid oxide electrochemical cells were developed using nanostructure-controlled composite powder consisting of Sr-doped SmCoO_3 (SSC) and Sm-doped CeO_2 (SDC) for electrode material. The SSC-SDC nano-composite powder, which was synthesized by spray pyrolysis, had a narrow particle size distribution (D_{10} , D_{50} , and D_{90} of 0.59, 0.71, and 0.94 μm , respectively), and individual particles were spherical, composing of nano-size SSC and SDC fragments (approximately 10–15 nm). The application of the powder to a cathode for an anode-supported solid oxide fuel cell (SOFC) realized extremely fine cathode microstructure and excellent cell performance. The anode-supported SOFC with the SSC-SDC cathode achieved maximum power density of 3.65, 2.44, 1.43, and 0.76 W cm^{-2} at 800, 750, 700, and 650 $^{\circ}\text{C}$, respectively, using humidified H_2 as fuel and air as oxidant. This result could be explained by the extended electrochemically active region in the cathode induced by controlling the structure of the starting powder at the nano-order level.

Key words: Solid oxide fuel cell (SOFC); Spray pyrolysis; Nano-composite powder; High power density; Cathode; Anode-supported cell

1. Introduction

High power density operation in solid oxide electrochemical cells such as fuel cells and electrolysis cells is essential for cost reduction. Anode-supported solid oxide fuel cells (SOFCs) with thin electrolyte (approximately 10 μm thick) are known to realize high fuel cell performance, a power density higher than 1 W cm^{-2} at 800 $^{\circ}\text{C}$ [1–5]. This is due to low ohmic resistance resulting from reducing electrolyte thickness. Thus, the total cell resistance (ohmic + electrode) is dominated by the electrode polarization resistance, especially in the cathode at operating temperatures lower than 800 $^{\circ}\text{C}$. In general, a perovskite-type oxide is used for cathode mixed with an ion-conducting electrolyte material such as ZrO_2 -based or CeO_2 -based oxides to extend electrochemically active region, e.g., the triple-phase boundary (TPB) where electronic/ionic/gas phases are in contact [6–11]. Furthermore, addition of an electrolyte material in a perovskite-type oxide leads to prevent excessive grain growth of the perovskite-type oxide during cathode preparation (sintering), and to match thermal expansion coefficient of the cathode with the electrolyte. Among various perovskite oxides, LnCoO_3 (Ln: lanthanoid)-based oxides are an attractive material for cathode of intermediate-temperature SOFCs (around 700 $^{\circ}\text{C}$) due to its high catalytic activity for oxygen reduction reaction and high electrical conductivity [12]. Although LnCoO_3 -based oxides are sometimes used directly for cathode, a composite of an LnCoO_3 -based oxide and a CeO_2 -based oxide is preferable to use as the cathode material to achieve higher and more stable electrochemical performance during long-term operation.

The microstructure of the composite cathode is crucial to maximize the electrochemical performance of the SOFC. To realize the cathode microstructure with

broadest TPB, it is important to prepare a starting cathode powder with fine structure, and spray pyrolysis is one of effective powder processing methods for controlling the powder structure. Spray pyrolysis can produce fine particles consisting of nano- to submicron-size fragments that are highly distributed within each particle. Many researchers have utilized spray pyrolysis to prepare powders for composite electrodes of SOFCs, and have reported that the powders realized electrodes with fine microstructure [13–21]. Fukui et al. [13] reported successful synthesis of Sr-doped LaMnO_3 (LSM)- Y_2O_3 -stabilized ZrO_2 (YSZ) powder with the mean particle size of about 1 μm and narrow particle size distribution. Hagiwara et al. [16,17] reported that the prepared LSM- Sc_2O_3 -stabilized ZrO_2 (ScSZ) nano-composite powder showed a highly dispersed nanostructure with well-controlled particle size and material composition. Also, they reported that evaluation of the cathode prepared from the LSM-ScSZ nano-composite powder revealed a 50% reduction in the electrode polarization resistance compared to that prepared from conventional simple mixture of LSM-ScSZ composite powder.

In the present study, we focus on the synthesis of Sr-doped SmCoO_3 (SSC) and Sm doped CeO_2 (SDC) nano-composite powder aiming for obtaining an extremely high performance SOFC cathode. SSC is a widely used LnCoO_3 -based oxide for cathode material, and we chose SDC for minimizing the target elements for spray pyrolysis. A key to successfully synthesize nano-composite powder by spray pyrolysis is to select the target elements as few as possible. This realizes easy control of simultaneous synthesis in a sprayed starting solution for obtaining nano-composite powder [18]. In the case of SSC-SDC, it consists of only four metal elements, namely, Sm, Sr, Co, and Ce, suggesting that spray pyrolysis is suitable for obtaining SSC-SDC nano-composite powder. This paper reports the properties of the SSC-SDC nano-composite powder synthesized by spray

pyrolysis and the performance of the SOFCs with cathodes from the powder using an anode-supported configuration with a thin YSZ electrolyte.

2. Experimental

2.1. Powder synthesis by spray pyrolysis

A nano-composite powder was prepared by spray pyrolysis. As shown in Fig. 1, the spray pyrolysis apparatus consisted of an atomizing section, a heating section, and a capture section. The targeted composition was $\text{Sm}_{0.5}\text{Sr}_{0.5}\text{CoO}_{3-\delta}$ (SSC) and $\text{Ce}_{0.8}\text{Sm}_{0.2}\text{O}_{1.9}$ (SDC) at a weight ratio of 70:30. First, a 0.1 mol L^{-1} SSC-SDC nitrate solution was prepared by dissolving 17.485 g of $\text{Sm}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.95% purity, Kanto Chemical Co.), 6.821 g of $\text{Sr}(\text{NO}_3)_2$ (98.0% purity, Kanto Chemical Co.), 18.761 g of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (98.0% purity, Kanto Chemical Co.), and 12.344 g of $\text{Ce}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (98.5% purity, Kanto Chemical Co.) in distilled water to make a total volume of 1000 mL. Then the solution was atomized by ultrasonic atomizers (1.75 MHz) and transported by air (3 L min^{-1}) to the heating section through a quartz tube (1.1 m long and an inner diameter of 52 mm). Three electric furnaces in the heating section were set at 300 °C for dehydration, 700 °C for decomposition, and 900 °C for crystallization from inlet to outlet, respectively. Finally, the synthesized SSC-SDC composite particles were captured by a cyclone and a PTFE filter in the capture section.

2.2. Fabrication of anode-supported cell samples

The anode substrate was a composite of NiO (Sumitomo Metal Mining Co.) and YSZ (8 mol% $\text{Y}_2\text{O}_3\text{-ZrO}_2$, TZ-8YS, Tosoh) at a weight ratio of 60:40. An electrolyte paste, made from YSZ powder (8 mol% $\text{Y}_2\text{O}_3\text{-ZrO}_2$, TZ-8Y, Tosoh), α -terpineol (Kanto Chemical Co.), ethyl cellulose 45 cp (Kishida Chemical Co.), a dispersant, and a plasticizer, was screen-printed onto the anode substrate, and then the electrolyte and substrate were co-sintered at 1350 °C for 3 h in air. An interlayer was prepared to prevent chemical reaction between YSZ and cathode materials [12,22]. An interlayer paste, made from $\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_{1.95}$ (GDC) powder ($40 \text{ m}^2 \text{ g}^{-1}$ in specific surface area, Anan Kasei Co.) and the same admixtures as in the YSZ paste, was screen-printed onto the electrolyte and sintered at 1300 °C for 1 h in air. A cathode paste was prepared using the SSC-SDC nano-composite powder synthesized by spray pyrolysis. The cathode paste was painted on the interlayer and sintered at different temperatures of 900, 950 and 1000 °C for 1 h in air. The effective area of the cathode was 0.283 cm^2 . For current collector, an Au paste ($< 1 \text{ }\mu\text{m}$ thick, Tanaka Kikinzoku Kogyo Co.) was painted on the surface of both the cathode and anode.

2.3. Characterization and electrochemical measurements

The crystal structure of the prepared nano-composite powder was characterized using X-ray diffraction (XRD, SmartLab, Rigaku) at room temperature with Cu $\text{K}\alpha$ radiation. Intensities were obtained in the 2θ range between 20° and 80° with a step size of 0.01°. The morphology of the powder prepared by spray pyrolysis and the anode-supported cells was observed using field emission scanning electron microscope (FE-

SEM, JSM-6330F, JEOL) and transmission electron microscopy (TEM, JEM-2100F, JEOL). The distribution of the elements (Co, Sr, Ce, Sm, and O) in the powder was analyzed using energy dispersive X-ray spectroscopy (EDX, JED-2300T) equipped with the TEM. To determine the particle size distribution, the as-prepared powder was dispersed in distilled water with sodium hexametaphosphate and then measured using laser scattering particle size analyzer (Microtrack HRA 9320-X100, Nikkiso Co.). Current-voltage (I - V) measurements and electrochemical impedance spectroscopy (EIS) for the anode-supported cells were performed in a temperature range from 650 to 800 °C using 3% humidified H₂ as fuel at a feed rate of 70 mL min⁻¹ and air as oxidant at a feed rate of 140 mL min⁻¹.

3. Results and discussion

3.1. Structural characteristics of SSC-SDC nano-composite powder

Fig. 2 shows the XRD patterns for the SSC-SDC nano-composite powder prepared by spray pyrolysis. In our spray pyrolysis process, the as-prepared powder was heat-treated up to 900 °C, which is sufficiently higher than the decomposition temperatures of the individual metal nitrates used for the SSC-SDC nitrate solution in order to get rid of remaining metal nitrates that negatively affect the cathode structure and performance [17]. For the as-prepared powder, broad peaks for SSC and SDC were identifiable, indicating that the SSC-SDC nano-composite powder was successfully synthesized. Also, the powder sintered at 950 °C for 1 h in air showed clearly identifiable

sharpened peaks for SSC and SDC without impurity phases. The crystal sizes estimated by the Scherrer equation were approximately 10–15 nm for both SSC and SDC of the as-prepared powder. In general, the crystal size of a powder depends on the synthesis method and sintering temperature. For example, the crystal size of SDC powder prepared by a carbonate co-precipitation method was 12 nm at sintering temperature of 600 °C and increased readily to 100 nm after sintering at 900 °C [23]. Another literature using a carbonate co-precipitation method reported the crystal size of SDC powder was 21 nm at 750 °C [24]. Also, nanocrystalline SSC powders that were synthesized by chelating route and then sintered at 800 °C exhibited a crystal size of 25 nm [25]. Although our powder underwent higher temperature sintering process (900 °C), the crystal size of the powder (10–15 nm) was almost the same as that of the powders prepared by the other methods at lower temperatures. The reason is mainly due to the short sintering time (approximately 8 s in the furnace at 900 °C) in our process. Another possible reason is that the nano-composite structure of SSC and SDC might prevent their grain growth each other.

The FE-SEM images of the as-prepared powder in Fig. 3 clearly reveals spherical particles with an extremely narrow size distribution (measured by laser diffraction), namely, D_{10} , D_{50} , and D_{90} of 0.59, 0.71, and 0.94 μm , respectively. Here, D_{10} , D_{50} , and D_{90} represent the particle diameter such that 10%, 50%, and 90% of cumulative undersize volume, respectively. These results indicate that the shape and size of the particles were well controlled by spray pyrolysis. Previous studies where various composite materials were prepared by spray pyrolysis reported the individual particles were apparently secondary particles consisting of extremely fine fragments [14–17]. This was evident from the broad peaks in the XRD pattern in Fig. 2.

The nanostructure of the as-prepared powder was evaluated in detail by TEM-EDX observation. Fig. 4a shows a cross-sectional TEM image of a particle in the as-prepared powder and Figs. 4b–4e show EDX mappings of constituent elements of SSC-SDC, namely, Co (K α , 6.929 keV), Sr (L α , 1.806 keV), Ce (L α , 4.839 keV), Sm (L α , 5.635 keV), and O (K α , 0.523 keV), respectively. All the elements were detected over the entire cross-section of the particle and overlapped each other. Although the atomic concentration of every element at the surface side of the particle was basically higher than that at the inner side, the distribution of each element seemed different. At the surface side, the concentration of Co and Sr was clearly higher, whereas that of Ce and Sm was slightly higher. Also, the concentration of Ce was higher than that of Co and Sr at the inner side. These results suggest that the particle had a core-shell-like structure where the surface side of the particle was enriched with SSC and SDC and that the inner side was mainly composed of SDC and pores. From these observation, we confirmed that extremely fine crystal fragments of both SSC and SDC that formed the particle were highly dispersed with unique distribution. In conclusion, we successfully synthesized a nanostructured SSC-SDC composite powder by spray pyrolysis for high performance cathode material.

3.2. *Microstructure of SSC-SDC cathodes*

Our anode-supported cell had an SSC-SDC cathode fabricated using the prepared SSC-SDC nano-composite powder. Figs. 5a and 5b show FE-SEM images of the cross-section of the anode-supported cell after electrochemical measurements. The observed thicknesses were approximately 10 μm , 4 μm , 6 μm , and 0.55 mm for the SSC-SDC

cathode, GDC interlayer, YSZ electrolyte, and Ni-YSZ anode, respectively. The cathode, interlayer, and electrolyte were deposited on the porous anode substrate (Fig. 5a), and the electrolyte was sufficiently densified to prevent gas cross leakage (Fig. 5b).

Figs. 5c–5e show FE-SEM images of the SSC-SDC cathodes sintered at different temperatures (900–1000 °C for 1 h). Even in the case of sintering at 900 °C that was the same temperature as the as-prepared powder underwent, the cathode exhibited the different structure from the powder because of difference in sintering time. The powder was sintered at 900 °C for only 8 s in the spray pyrolysis apparatus, whereas the cathode sintering time was 1 h. This further sintering of the cathode grew the grains of SSC and SDC. As shown in these images, all the SSC-SDC cathodes had very fine microstructure, although the grain size of SSC and GDC slightly increased with increasing sintering temperature. The approximate grain size of 200–400 nm sintered at 900 °C grew up to that of 300–600 nm sintered at 1000 °C. These observed grain sizes of the cathodes were smaller than the particle size of the as-prepared powder ($D_{50} = 0.71 \mu\text{m}$), indicating that the nano-composite structure in the particles affected the resulting network structures of the cathodes through the further sintering process. The individual particles consisted of SSC and SDC nano-size crystal fragments and also involved a lot of nano-size small pores because the dehydration and decomposition processes in spray pyrolysis certainly produced pores in the particle. In the cathode sintering process, the grains of SSC and SDC grew and constructed a porous structure in the particles, resulting in fine network structure with the small grain size. The similar results were observed in previous studies [15,16,18]. These phenomena are due to the unique nano-composite powder structure controlled by spray pyrolysis. The porosity of the cathodes was designed to be approximately 40 vol.% and the pores to be uniformly distributed within the cathodes to

obtain good gas diffusion property. In addition, highly distribution of both SSC and SDC was expected in the cathode using the composite powder because their distribution had been controlled at the nano-order level at the powder synthesis stage by spray pyrolysis. The fine distribution of pores, SSC, and SDC is expected to be resulted in an increase in the electrochemically active region.

3.3 Electrochemical performance of anode-supported cells with SSC-SDC cathodes

Fig. 6 shows the I - V characteristics and the corresponding power densities at different temperatures for the anode-supported cell with the cathode fabricated using the SSC-SDC nano-composite powder when 3% humidified H_2 was used as fuel and air was used as oxidant. Here, the cathode sintered at 950 °C was representatively shown. Note that the actual cell temperature is generally higher than the measured temperature in I - V measurements because of heat generation due to the internal resistance of a cell. We therefore closely located a thermocouple to the cell for temperature measurement, namely, at the cathode side with a clearance of approximately 1 mm from the cell surface to measure cell temperature as accurately as possible. As shown in Fig. 6, the measured open-circuit voltages (OCVs) at each temperature were almost similar to the theoretical values, indicating gas tightness of the YSZ electrolyte. This cell achieved high power density of 2.45, 1.65, 1.02, and 0.57 $W\ cm^{-2}$ under an operating voltage of 0.75 V at operating temperatures of 800, 750, 700, and 650 °C, respectively, and reached a respective maximum power density, P_{max} , of 3.65, 2.44, 1.43, and 0.76 $W\ cm^{-2}$.

Fig. 7 shows P_{max} for the anode-supported cells with the cathodes sintered at different temperatures (900, 950, and 1000 °C). P_{max} for all the cells increased with

increasing operation temperature. In general, higher temperature sintering leads to a decrease in the specific surface area within a cathode due to grain growth, whereas it enhances electronic and ionic conductivities to construct networks. When the cathode was sintered at 950 °C, $P_{\max}$ exhibited the highest value among these three cells, indicating that the optimum sintering temperature is 950 °C for the SSC-SDC cathode proposed in the present study.

For comparison, $P_{\max}$ for anode-supported cells with SSC-based cathodes and either YSZ electrolyte or ScSZ electrolyte reported in recent literatures [26–32] are listed in Table 1. Note that higher power density have been achieved with higher conductive electrolytes such as CeO₂-based oxides and LaGaO₃-based oxides [33–35]. In terms of the OCV, however, these electrolytes could not reach the theoretical value because they showed the electronic conductivity in the high temperature range (> 500 °C), indicating a decrease in energy conversion efficiency of SOFCs. Thus, we selected YSZ for the electrolyte material in the present study to achieve high power density with high OCV and compared with the cells using YSZ or ScSZ electrolytes here. As shown in Table 1, our cell exhibited an outstanding performance. The thickness of the YSZ electrolyte of our cell (6 μm) was similar to that of the other cells. Also, our cell did not include any catalytic functional layers at the anode side. The superior performance of our cell was therefore mainly attributed to the cathode performance, indicating that the proposed SSC-SDC cathode is one of the candidate materials to realize high power density SOFCs.

Fig. 8 shows the impedance spectra for the anode-supported cell using 3% humidified H₂ as fuel and air as oxidant in a frequency range of 1 MHz to 0.1 Hz. The ohmic resistance, R_{ohm} , was determined by the intercept on the real axis at the higher frequency side, and electrode polarization resistance, R_p , was determined by the

difference between the two intercepts at the lower and higher frequency sides. Note that R_p was the sum of the cathode and anode polarization resistances. To evaluate the cathode performance separately, three-electrode measurements using a reference electrode is required. However, in the anode-supported cell configuration (asymmetric configuration of anode and cathode), the three-electrode measurements is essentially impossible because the measurements requires a symmetric placement of cathode and anode to use reference electrodes [36–38]. Thus we simply evaluated R_p here.

The I - V and EIS results are summarized in Table 2. At all temperatures, the impedance spectra under the OCV condition (Fig. 8a) demonstrated high R_p in a low frequency range (< 10 Hz), where the concentration polarization resistance is generally detected. This high R_p was considered to be due to a change in O_2 partial pressure at the anode side by the applied alternating current in EIS. R_p at 0.75 V (Fig. 8b) was much lower than that at OCV (Fig. 8a) because the O_2 partial pressure at the anode side had increased due to transported oxide ions across the electrolyte during fuel cell operation. In general, the sum of R_{ohm} and R_p , denoted as R_t , under operating condition represents cell performance. The low R_p observed at 0.75 V (Table 2) therefore indicated high performance of the SSC-SDC cathode. In particular, extremely low R_p , that was lower than R_{ohm} , was achieved above 700 °C, even though R_p involved anode polarization resistance with cathode polarization resistance.

As shown in the electrochemical measurement results (Figs. 6–8 and Table 2), our anode-supported cells showed excellent performance. Also, the comparison with the previously reported results (Table 1) suggested that the higher performance of our cells was due to the cathode, particularly due to cathode microstructure. In general, SSC-based cathodes are sintered at approximately 900–1000 °C to construct the network structure

[26,29,30,32], although lower temperature ($< 850\text{ }^{\circ}\text{C}$) is favorable to maintain high specific surface area of a cathode [27,28,31]. In our cathodes fabricated using the SSC-SDC nano-composite powder, highly dispersed nano-size SSC and SDC fragments prevented excessive grain growth in the particles even at sintering temperature of $950\text{ }^{\circ}\text{C}$. Also, the individual particles connected each other, constructing the sufficient networks to achieve high electronic and ionic conductivity. The nano-composite powder realized electrode structure control at two phases, namely, nano-order level in the particles and micro-order level between the particles, yielding the broad active region with electronic and ionic conduction networks maintaining porous structure for sufficient gas diffusion in the cathodes.

In the present study, anode-supported cell configuration was used to achieve higher power density and to exhibit the impact of using our proposed cathodes. As described above, three-electrode measurements using an electrode-supported symmetrical cells enable to evaluate in more detail cathode performance. Also, long-term stability is essential for cost reduction of SOFCs besides high power density. Our future work will therefore include three-electrode measurements and long-term stability test. Although further experimental measurements and discussion are needed to clarify the detailed cathode characteristics, the present study suggests that controlling the nanostructure of composite powder is an effective method to realize fine electrode structure and high performance cathodes.

4. Conclusions

Anode-supported SOFCs with cathodes using an SSC-SDC nano-composite powder synthesized by spray pyrolysis was investigated. The SSC-SDC nano-composite powder was submicron-size spherical particles with a narrow size distribution (D_{10} , D_{50} , and D_{90} of 0.59, 0.71, and 0.94 μm , respectively). Also, the individual particles were secondary particles consisting of nano-size crystal fragments (approximately 10–15 nm). These results indicate that the structural properties of the particles were successfully controlled by spray pyrolysis. By using this nano-composite powder for cathode material, the resulting SSC-SDC cathodes exhibited extremely fine microstructure where SSC, SDC, and pores were highly distributed, suggesting the broad electrochemically active region. All the anode-supported SOFCs with the SSC-SDC cathodes sintered at different temperatures achieved high power densities; in particular, that sintered at 950 $^{\circ}\text{C}$ exhibited the highest values, i.e., 3.65, 2.44, 1.43, and 0.76 W cm^{-2} at 800, 750, 700, and 650 $^{\circ}\text{C}$, respectively, using humidified H_2 as fuel and air as oxidant. EIS results revealed that these measured high power densities were due to a low electrode polarization resistance. These results suggest that controlling the electrode microstructure at the powder material stage is an effective method to achieve high performance electrodes.

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Tables

Table 1

Summary of maximum power density $P_{\max}$ for anode-supported cells with SSC-based cathodes and ZrO₂-based electrolytes reported in previous studies.

Components				$P_{\max}$ (W cm ⁻²)	Ref.
Cathode	Interlayer	Electrolyte	Anode		
SSC-SDC	GDC	YSZ (6 μ m)	Ni-YSZ	2.44 (750 °C)	This study
SSC-SDC	SDC	YSZ (5 μ m)	Ni-YSZ	0.46 (800 °C)	[26]
SSC-SDC	—	ScSZ (10 μ m)	Ni-SDC	0.66 (700 °C)	[27]
SSC-SDC	—	YSZ (15 μ m)	Ni-YSZ	1.21 (750 °C)	[28]
SSC-GDC	GDC	YSZ (10 μ m)	Ni-YSZ	1.24 (780 °C, 0.8V)	[29]
SSC-SDC	SDC	YSZ (2 μ m)	Ni-YSZ	1.19 (750 °C)	[30]
SSC-SDC	SDC	YSZ (7 μ m)	Ni-YSZ	1.50 (750 °C)	[31]
SSC-SDC	SDC	YSZ (6 μ m)	Ni-YSZ	1.15 (750 °C)	[32]

Table 2

Summary of electrochemical measurement results for our anode-supported cell with SSC-SDC cathode sintered at 950 °C.

Temperature (°C)	I - V characteristics		EIS results at 0.75 V		
	OCV (V)	$P_{\max}$ (W cm ⁻²)	R_{ohm} (m Ω cm ²)	R_p (m Ω cm ²)	R_t (m Ω cm ²)
800	1.083	3.65	52	28	80
750	1.093	2.44	74	52	126
700	1.103	1.43	108	107	215
650	1.111	0.76	167	229	396

Figure captions

Fig. 1

Schematic of spray pyrolysis apparatus used in the present study.

Fig. 2

XRD patterns for SSC-SDC nano-composite powder (as-prepared sample and sintered sample at 950 °C for 1 h).

Fig. 3

FE-SEM images of as-prepared SSC-SDC nano-composite powder at (a) low magnification and (b) high magnification.

Fig. 4

TEM-EDX images of as-prepared SSC-SDC nano-composite powder: (a) TEM image, (b) Co-K α mapping, (c) Sr-L α mapping, (d) Ce-L α mapping, (e) Sm-L α mapping, and (f) O-K α mapping.

Fig. 5

FE-SEM images of cross-section of anode-supported cells: (a) overview of a cell and (b) cathode/interlayer/electrolyte interface; SSC-SDC cathodes sintered at (c) 900 °C, (d) 950 °C, and (e) 1000 °C.

Fig. 6

I - V characteristics for anode-supported cell with SSC-SDC cathode sintered at 950 °C.

Fig. 7

Maximum power densities $P_{\max}$ for anode-supported cells with SSC-SDC cathodes sintered at 900–1000 °C for 1 h as a function of operating temperature.

Fig. 8

Impedance spectra for anode-supported cell with SSC-SDC cathode sintered at 950 °C under (a) OCV condition and (b) operating condition at 0.75 V.

Fig.1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8b