Effect of starting solution concentration in spray pyrolysis on powder properties and electrochemical electrode performance

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Abstract

Nano-composite powders consisting of Sr-doped SmCoO_3 (SSC) and Sm-doped CeO_2 (SDC) were synthesized by spray pyrolysis using different cation concentration solutions, and the effect of this cation concentration on the electrochemical performance of electrodes fabricated using the powders was investigated. Regardless of the cation concentration, spherical particles consisting of nano-order fine SSC and SDC crystallites were successfully obtained. Although the crystal size of all the synthesized powders was almost the same, the particle size increased with increasing cation concentration. The microstructure of the cathodes fabricated using the nano-composite powders clearly depended on the particle size of the starting powders; the microstructure became coarser with increasing particle size and the original particle shapes partially remained in the cathode network. Also, electrochemical measurements for solid oxide fuel cells with these cathodes revealed that the electrode performance was related to the microstructure. The electrode polarization resistance decreased with decreasing particle size, and a relatively fine microstructure cathode exhibited lower electrode polarization resistance, resulting in a high performance of 1.52 W cm^{-2} at

700 °C. These results indicate that controlling the particle size, as well as controlling the nanostructure within the particles, is crucial to attain high performance electrodes.

Key words: Spray pyrolysis; Nano-composite powder; Particle size distribution; Electrode performance; Solid oxide fuel cell (SOFC)

1. Introduction

High temperature type electrochemical ceramic cells such as fuel cells and electrolysis cells are devices expected to realize high efficiency energy conversion. Although the cell performance primarily depends on the intrinsic characteristics such as conductivity and catalytic activity of the materials used in the cell components, the optimization of cell structure is also essential to maximally utilize the characteristics of the materials. In particular, in the electrode structure in a cell, the electrochemically active region must be designed as large as possible to facilitate electronic, ionic, and gas pathways [1]. The electrode microstructure often dominates overall cell performance. A critical factor determining the electrode microstructure is the properties of the ceramic powder used as raw material for the electrode, for example, particle size distribution, specific surface area, morphology, crystallinity, and sinterability [2–5]. Thus, synthesis of ceramic powders that have superior properties for high performance electrodes has been extensively researched.

Spray pyrolysis is a powder preparation process that can control particle structure at the nano-order level [6–8]. In parallel with synthesizing nano-size

crystallites, submicron-size secondary particles consisting of the crystallites have a narrow size distribution. Changing precursor type used for the atomized solution can also produce various particle morphologies such as hollow, porous, and solid dense structures [9]. In particular, spray pyrolysis can effectively prepare composite powders [10–12]. Simultaneous synthesis of several materials yields particles in which nano-size crystallites of synthesized materials are highly distributed among each other, namely, nano-composite powders. The unique structure of powders prepared by spray pyrolysis leads to fine electrode structure with high surface area and uniform networks, resulting in high performance electrodes in electrochemical ceramic cells [13–21]. Besides the unique structure of the powders, a simple powder preparation process in which a powder can be continually obtained includes only the following three steps: (i) atomization of droplets, (ii) transport of droplets and synthesis into particles in heaters, and (iii) capture of the synthesized powder [6–8]. However, spray pyrolysis is inferior to conventional solid-state synthesis processes and other wet synthesis processes in its powder production rate, defined as the amount of produced powder per specific time [6,14]. Although higher material concentration involved in an atomized solution in spray pyrolysis leads to higher production rate, it affects the properties of the prepared powders [6,8,22]. In particular, the particle size increases with increasing material

concentration. In the case of powder materials used for electrodes, change in particle size often significantly influences the electrode performance, even if the change in size is slight. To achieve high production rate while maintaining powder quality in spray pyrolysis, the relationship between particle size and resulting electrode performance must be clarified.

The present study investigated the relationship between particle size of powders prepared by spray pyrolysis and the electrochemical performance of electrodes fabricated using the powders. In the spray pyrolysis used here, we used ultrasonic vibrators for atomizing droplets to produce fine droplets of uniform size (approximately 1–10 μm) [6,8,18,22,23], and synthesized nano-composite powders consisting of Sr-doped SmCoO_3 (SSC) and Sm-doped CeO_2 (SDC), which are well-known as high performance electrode materials for electrochemical ceramic cells [24–27]. The particle size was controlled by adjusting the cation concentration for SSC-SDC in the starting solution from 0.02 to 0.5 mol L^{-1} . Anode-supported solid oxide fuel cells (SOFCs) with SSC-SDC cathodes using the nano-composite powders were fabricated and then were evaluated in fuel cell mode operation using humidified hydrogen and air.

2. Experimental

2.1. Synthesis of nano-composite powders by spray pyrolysis

The targeted chemical composition of the nano-composite powders 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. Four SSC-SDC aqueous starting solutions with different cation concentration, C (mol L^{-1}), were prepared. First, an aqueous solution was prepared by dissolving 87.43 g of $\text{Sm}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.95% purity, Kanto Chemical Co., Japan), 34.11 g of $\text{Sr}(\text{NO}_3)_2$ (98.0% purity, Kanto Chemical Co., Japan), 93.81 g of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (98.0% purity, Kanto Chemical Co. Japan), and 61.72 g of $\text{Ce}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (98.5% purity, Kanto Chemical Co., Japan) in distilled water to make a total volume of 1000 mL. This solution contained 0.5 mol L^{-1} SSC-SDC in total cation concentration (0.322 mol L^{-1} of SSC and 0.178 mol L^{-1} of SDC), called here 0.5 mol L^{-1} starting solution. Then, part of 0.5 mol L^{-1} starting solution was diluted with distilled water at three different volume ratios of 1:24, 1:4, and 1:1.5 to prepare three different C solutions, namely, 0.02, 0.1, and 0.2 mol L^{-1} starting solutions, respectively.

Nano-composite powders were 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 starting solutions were atomized by three ultrasonic vibrators (1.75 MHz, TDK, Japan) in the atomizing section. During atomization, the water level and temperature of the solutions were kept at 30 mm and 30 °C, respectively, because these parameters affect the size and production rate of atomized droplets [14,21]. The droplets were transported into the heating section through a quartz tube (1.1 m long and an inner diameter of 52 mm) using air as carrier gas at a flow rate of 3 L min⁻¹. The heating section consisted of three serial electric furnaces set at 300, 700, and 900 °C from inlet to outlet, respectively. The droplets were continuously dried, dehydrated, decomposed, reacted, and crystallized in the heating section. Finally, the synthesized SSC-SDC nano-composite powders were captured by a polytetrafluoroethylene (PTFE) membrane filter (0.1 µm pores) in the capture section. These synthesized powders using 0.02, 0.1, 0.2, and 0.5 mol L⁻¹ starting solutions were denoted as SSC-SDC(0.02), SSC-SDC(0.1), SSC-SDC(0.2), and SSC-SDC(0.5), respectively.

2.2. Fabrication of SOFC samples

The SOFC samples were a planar anode-supported type using a NiO-YSZ porous substrate prepared by an extrusion process. The anode substrate was composed of NiO powder (Sumitomo Metal Mining Co., Japan) and YSZ powder (TZ-8YS, Tosoh, Japan) at a weight ratio of 60:40. The detailed fabrication procedure of the anode substrate has been presented elsewhere [28]. An electrolyte paste, prepared by mixing YSZ powder (TZ-8Y, Tosoh, Japan) in α -terpineol (Kanto Chemical Co., Japan) with ethyl cellulose (45 cP, Kishida Chemical Co., Japan), a dispersant, and a plasticizer, was screen-printed on the anode substrate, and then the electrolyte and anode substrate were co-sintered at 1350 °C for 3 h in air. For an interlayer between the electrolyte and cathode, a $\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_{1.95}$ (GDC) paste was prepared by mixing GDC powder (Anan Kasei Co., Japan) and the same admixtures as in the electrolyte paste. The GDC interlayer paste was screen-printed on the electrolyte, and then sintered at 1300 °C for 1 h in air. Four cathode pastes were prepared using the SSC-SDC nano-composite powders synthesized by spray pyrolysis with the same admixtures as in the electrolyte paste. Each cathode paste was painted on the interlayer, and then sintered at 950 °C for 1 h in air. The designed area of the cathode was 0.283 cm². For a current-collection layer, Au paste (< 1 μm thick, Tanaka Kikinzoku Kogyo Co., Japan) was painted on the

surface of the cathode and anode.

2.3. Characterization and measurements

The crystal structure of the synthesized SSC-SDC nano-composite powders was determined using X-ray diffraction (XRD, SmartLab, Rigaku, Japan) at room temperature with Cu K α radiation. The 2θ range in XRD was 20° to 80° and the step size was 0.01°. The crystal size of SSC and SDC was estimated by the Scherrer equation with a Scherrer constant of 0.9. The morphology of the powders and the SOFCs was observed using scanning electron microscopy (SEM, JSM-5600, JEOL, Japan). In particle size distribution measurements, each powder was dispersed in distilled water with sodium hexametaphosphate and then the particle sizes were measured using a laser diffraction particle size analyzer (Microtrack HRA 9320-X100, Nikkiso Co., Japan).

Current-voltage (I - V) measurements and electrochemical impedance spectroscopy (EIS) for the SOFCs were carried out at 700 °C using 3% humidified H₂ fuel at a feed rate of 70 mL min⁻¹ and ambient air as oxidant at a feed rate of 140 mL

min^{-1} . A potentiostat/galvanostat with a frequency response analyzer (Autolab PGSTAT302, Metrohm, Switzerland) was used for these electrochemical measurements.

3. Results and discussion

3.1. Production rate of SSC-SDC nano-composite powders in spray pyrolysis

Fig. 2 shows the production rate of the SSC-SDC nano-composite powders as a function of C . Assuming that the number and size of the transported droplets into the heating section are constant during spray pyrolysis, the production rate is proportional to C . The dashed line in Fig. 2 represents the linearly proportional production rate calculated based on the case using 0.02 mol L^{-1} starting solution for spray pyrolysis assuming a linear increase in production rate over the entire range of the C . The measured production rate increased with increasing C but not linearly over the entire range of C . The production rate using 0.1 mol L^{-1} starting solution was almost the same as the linear production rate, whereas that using 0.2 and 0.5 mol L^{-1} starting solutions was lower. Although the production rate strongly depends on C , it also related to the

total volume of atomized and transported droplets. The mean droplet diameter atomized by ultrasonic vibrator, D_d (μm), is expressed by the Lang's equation [23]:

$$D_d = 0.34 \left(\frac{8\pi\gamma}{\rho f^2} \right)^{1/3} \quad (1)$$

where γ , ρ , and f are the surface tension of the starting solution (mN m^{-1}), the density of the starting solution (kg L^{-1}), and the frequency of the ultrasonic vibrator (MHz), respectively. Higher C leads to higher ρ , resulting in smaller size D_d . Also, γ might vary depending on C . The effect of ρ and γ on the D_d , however, is limited in our C range of $0.02\text{--}0.5 \text{ mol L}^{-1}$. Thus, the lower production rate than the calculated linear production rate in the cases using 0.2 and 0.5 mol L^{-1} starting solutions would be caused by a decrease in the number of the consequently transported particles. After every powder synthesis, almost no particles remained in the quartz tube of the heating section, suggesting that the heated and dried particles could be transported to the capture section regardless of C . We concluded that the main reason for the lower production rate was a decrease in the number of droplets transported into the heating section due to their higher ρ . In particular, relatively large size droplets with high C might not be transported.

3.2. Structural properties of SSC-SDC nano-composite powders synthesized using different cation concentration solutions

The crystal structure of as-prepared SSC-SDC nano-composite powders was confirmed by XRD (Fig. 3). All the powders exhibited peaks at the same 2θ corresponding to either SSC or SDC. These peaks were broad but clearly identified without any impurity phases, suggesting that the powders were successfully synthesized and crystallized. These broad peaks indicate that the crystal size of both SSC and SDC was very small, and the estimated crystal size by the Scherrer equation ranged from 14 to 17 nm for SSC and 12 to 15 nm for SDC. Due to the short synthesis time in the spray pyrolysis process, the SSC and SDC crystallites maintained their small sizes even at high synthesis temperature (900 °C). The crystal sizes of both SSC and SDC were almost the same among all the synthesized powders, suggesting that C does not significantly affect the crystal size of resulting powders in spray pyrolysis.

Fig. 4 shows SEM images of the as-prepared SSC-SDC nano-composite powders. Regardless of C , the particles were spherical with a smooth surface. The particles observed here were much larger than the estimated crystal size (12–17 nm)

from XRD results, indicating that each particle was a secondary particle formed from fine SSC and SDC crystallites. Our previous study focusing on individual particles using TEM observation supports this result [21]. As shown in Fig. 4, the particle size clearly increased with increasing C . Assuming that the particles are spherical and dense, the mean particle diameter, D_p (μm), can be expressed using D_d as follows [29]

$$D_p = D_d \left(\frac{MC}{\rho_p} \right)^{1/3} \quad (2)$$

where M (kg mol^{-1}) and ρ_p (kg L^{-1}) are the molar weight of particle and the density of particle, respectively. Higher C means higher cation concentration in an atomized droplet, which yields a particle after undergoing synthesis in spray pyrolysis. As shown in Eq.2, the particle size therefore increases with increasing C .

Similar to the SEM observation results, the particle size distribution measured by laser diffraction of each as-prepared SSC-SDC nano-composite powder in Fig. 5 clearly shows that the particle size increases with increasing C ; the median diameter, D_{50} , of SSC-SDC(0.02), SSC-SDC(0.1), SSC-SDC(0.2), and SSC-SDC(0.5), was 0.71, 1.24, 1.36, and 1.54 μm , respectively. The powders synthesized by spray pyrolysis with ultrasonic vibrators generally have a very narrow particle size distribution because D_d can be controlled by the atomizing frequency, typically according to Eq. 1. The

synthesized powders in the present study exhibited a narrow particle size distribution, although higher C led to a slightly broader distribution probably due to a portion of particularly large and heavy droplets not being transported by carrier gas.

Fig. 6 shows the particle sizes as a function of C . D_{10} and D_{90} represent the particle diameters at 10% and 90% of cumulative volume of particles less than the particle diameter. Particle diameters, D_{10} , D_{50} , and D_{90} all increased with increasing C and their increasing slopes were almost the same. According to Eq. 2, the increase in particle diameter is proportional to the cube root of C (i.e., $C^{1/3}$). However, the slope in the C range of 0.1–0.5 mol L⁻¹ was less than 1/3, namely, 0.132 for D_{50} , whereas that of 0.02–0.1 mol L⁻¹ was 0.348 for D_{50} , which is approximately 1/3. This result suggests that D_d decreased at the high C of 0.2 and 0.5 mol L⁻¹. Wang et al. [22] reported that actual D_d properties depend on C , and thus concluded that particle size cannot be precisely predicted on the assumption of a constant D_d for different C . Another reason for the lower slope is the droplet transport efficiency by carrier gas. The droplets have a distribution in size, although the distribution range is narrow after spray pyrolysis with an ultrasonic vibrator. As described above, when C was 0.2 and 0.5 mol L⁻¹, relatively large droplets within the size distributions might be too heavy to be transported into the heating section, resulting in the slope value less than 1/3.

Table 1 summarizes the structural properties of four synthesized SSC-SDC nano-composite powders using different C . For all the powders, extremely fine SSC and SDC crystallites formed spherical particles. Although the crystal size of every powder was almost the same, the particle size increased with increasing C . The particle sizes of SSC-SDC(0.2) and SSC-SDC(0.5) were smaller than that expected based on the relationship between the D_p and C (Eq.2) due to a decrease in the size of the atomized and transported droplets. This result coincides with the production rate of the powders.

3.3. Microstructure of cathodes using SSC-SDC nano-composite powders

Using the synthesized SSC-SDC nano-composite powders for the cathode material, planar anode-supported SOFCs were fabricated. Fig. 7 shows a cross-sectional SEM image of a representative SOFC sample with SSC-SDC cathode fabricated using SSC-SDC(0.1). The SEM observation was carried after the electrochemical measurements using H_2 fuel, and thus the anode of the SOFC had reduced NiO to Ni before the SEM observation. The thicknesses of the SSC-SDC cathode, GDC interlayer, YSZ electrolyte, and Ni-YSZ anode were approximately 25 μm , 3 μm , 8 μm , and 0.55

mm, respectively. The other SOFCs using different nano-composite powders had thickness similar to that of the SOFC shown in Fig. 7 (data not shown). Our SOFCs had a typical anode-supported structure, namely, porous cathode and anode, dense electrolyte, and thin interlayer.

Fig. 8 shows SEM images of the cross-section of the SSC-SDC cathodes fabricated using nano-composite powders, called here as SSC-SDC(0.02) cathode, SSC-SDC(0.1) cathode, SSC-SDC(0.2) cathode, and SSC-SDC(0.5) cathode, respectively. The cathode microstructure apparently depended on the powder used for the cathode. When the powder with the smallest particle size was used, namely, SSC-SDC(0.02), the resulting microstructure of the SSC-SDC(0.02) cathode was very fine. The cathode microstructure became coarser with increasing particle size. The diameter of the network stems in the cathodes depended on the particle size because the particles became necked and also connected to each other during cathode sintering. In particular, the particles in the SSC-SDC(0.2) and SSC-SDC(0.5) cathodes evidently remained spherical and were almost the same size as the original particles in their networks. Typically, the grain size and surface area of cathodes using nano-composite powders as starting material are not determined simply by the size of secondary particles, but in many cases also by the subordinate nanostructure consisting of crystallites in individual

particles [10,13,17,20,21]. However, difference in particle size at the microstructure level significantly affected the resulting cathode structure. These results suggest that control of the particle structure at both the nano-order and micro-order levels is essential to achieve an extremely fine electrode structure.

3.4. Performance of SOFCs with cathodes using SSC-SDC nano-composite powders

In electrochemical measurements, the SOFCs with the different SSC-SDC cathodes were evaluated at an operating temperature of 700 °C using 3% humidified H₂ as fuel and ambient air as oxidant. Because all components of the SOFCs were designed the same except the cathodes, only the cathodes caused the difference in electrochemical performance. Fig. 9 shows the *I-V* characteristics for the SOFCs. The best performance was achieved by the SOFC with the SSC-SDC(0.1) cathode, with its maximum power density reaching 1.52 W cm⁻². The power densities of the SOFCs with the SSC-SDC(0.2) and SSC-SDC(0.5) cathodes were lower than that with the SSC-SDC(0.1), because of their relatively coarse microstructures. Also, in the case of the SSC-SDC(0.02) cathode, the SOFC exhibited a lower power density, although this

cathode had finest microstructure as observed by SEM (Fig. 8a). Based on the powder properties and the cathode microstructure, we had expected the highest performance to be achieved by the SSC-SDC(0.02) cathode. The unexpected result that this cathode was not the highest performer might be due to peeling of the cathode layer from the interlayer surface. Cathode sintering progresses with grain growth and decreasing small pores, yielding attraction between each grain. In cases of using very fine powders, the attraction becomes stronger, possibly resulting in peeling of a cathode layer.

3.5. Dependence of electrode performance on particle size of nano-composite powders used for starting electrode material

To evaluate electrode performance of the SOFCs, EIS were performed under a typical fuel cell operating condition at 0.75 V. Fig. 10 shows the impedance spectra for the SOFCs with the different SSC-SDC cathodes. In the impedance spectra, the intercept of the real axis at the higher frequency side represents the ohmic resistance, R_{ohm} , and the difference between the two intercepts at the lower and higher frequency sides represents the electrode polarization resistance, R_p , which includes both the

cathode and anode polarization resistances. The sum of R_{ohm} and R_p is the total cell resistance, R_t .

Fig. 11 shows the dependence of the area-specific resistances of the SOFCs on D_{50} of the SSC-SDC nano-composite powders. R_{ohm} of every SOFC was almost the same, indicating that the difference in cathode microstructure (Fig. 8) did not influence the conductivity of the cathodes. In the cases of high catalytic active material such as SSC-SDC, because the electrochemical reaction occurs only near the cathode/interlayer (or cathode/electrolyte) interface, ionic conductive networks of SDC generally do not significantly extend the electrochemically active region. Also, SSC, which was the main material of our cathodes (70 wt.%), essentially has a high electronic conductivity [30,31]. R_{ohm} therefore did not depend on the cathode microstructure and mainly represented the bulk resistance of the electrolyte and interlayer, which were commonly used in our SOFCs. On the other hand, R_p depended on D_{50} . Similar to the tendency of I - V characteristics, R_p decreased with decreasing D_{50} to 1.25 μm (SSC-SDC(0.1)), although R_p at $D_{50} = 0.71 \mu\text{m}$ (SSC-SDC(0.02)) increased probably due to partial peeling of the cathode layer. The peeling is considered a problem in the fabrication process of the cathode layer and can be minimized by optimizing the cathode slurry, painting method, and sintering temperature. In addition, due to its having the finest

cathode microstructure among the cathodes studied here (Fig. 8a), an SOFC with an optimized SSC-SDC(0.02) cathode is expected to have a similar or lower R_p compared to that with the SSC-SDC(0.1) cathode. These results indicate that, besides the fine nanostructure within the individual particles, the small particle size of the nano-composite powders is crucial for electrode performance. The synergistic effect of controlling both the nanostructure and microstructure during the powder stage yields an extremely fine electrode with a large electrochemically active region. Even though the use of low C to produce small particles leads to low powder production rate, it is effective for achieving high performance electrochemical electrodes.

4. Conclusions

The present study investigated the effects of the cation concentration of the starting solution in spray pyrolysis on the properties of the resulting nano-composite powder and of electrochemical electrodes fabricated using this powder. Regardless of the cation concentration, spherical particles consisting of nano-order SSC and SDC crystallites were successfully synthesized. The crystal sizes of SSC and SDC were

almost the same regardless of the cation concentration, whereas the particle size increased with increasing cation concentration. Although in theory the increase in particle size should be proportional to the cube root of cation concentration, the measured sizes of particles prepared using high cation concentration solutions (0.2 and 0.5 mol L⁻¹) were smaller than the predicted sizes, due to a decrease in size of the droplets. The relatively large droplets with high cation concentration might not be transported into the heating section due to their higher density. This agreed with the dependence of powder production rate on the cation concentration, namely, non-proportional increase in powder production rate with increasing cation concentration. The microstructure of the cathodes using the SSC-SDC nano-composite powders was influenced by the particle size, and the electrode performance clearly depended on the microstructure. The microstructure significantly changed from fine to coarse as the particle size increased. The diameter of the network stems in the cathodes depended on the particle size, and the original particle shapes partially remained in the network. In electrochemical measurements, the electrode polarization resistance decreased with decreasing particle size. A fine microstructure cathode using SSC-SDC(0.1) exhibited a very low electrode polarization resistance due to the extended electrochemically active region, resulting in a high performance of 1.52 W cm⁻² at 700 °C in SOFC operation. In

the case of using nano-composite powders, the resulting electrode structure is generally related to the subordinate nanostructure within individual particles. In conclusion, control of the particle structure at both the nano-order and micro-order levels is essential to achieve extremely fine structured electrodes that have high performance.

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Tables

Table 1

Crystal and particle sizes of SSC-SDC nano-composite powders synthesized by spray pyrolysis.

Sample	Concentration (mol L ⁻¹)	Production rate (g h ⁻¹)	Crystal size (nm)		Particle size (μm)		
			SSC	SDC	<i>D</i> ₁₀	<i>D</i> ₅₀	<i>D</i> ₉₀
SSC-SDC(0.02)	0.02	0.19	17	15	0.49	0.71	1.07
SSC-SDC(0.1)	0.1	1.01	14	12	0.86	1.25	2.13
SSC-SDC(0.2)	0.2	1.65	15	12	0.92	1.36	2.46
SSC-SDC(0.5)	0.5	2.29	16	13	1.03	1.54	2.88

Figure captions

Fig. 1

Schematic of spray pyrolysis apparatus.

Fig. 2

Production rate of SSC-SDC nano-composite powders as a function of cation concentration of starting solution C .

Fig. 3

XRD patterns for SSC-SDC nano-composite powders synthesized using different cation concentration solutions C .

Fig. 4

SEM images of SSC-SDC nano-composite powders synthesized using different cation concentration solutions C : (a) SSC-SDC(0.02), (b) SSC-SDC(0.1), (c) SSC-SDC(0.2), and (d) SSC-SDC(0.5).

Fig. 5

Particle size distribution of SSC-SDC nano-composite powders synthesized using different cation concentration solutions: (a) SSC-SDC(0.02), (b) SSC-SDC(0.1), (c) SSC-SDC(0.2), and (d) SSC-SDC(0.5).

Fig. 6

Particle sizes (D_{10} , D_{50} , and D_{90}) of SSC-SDC nano-composite powders as a function of cation concentration of starting solution C .

Fig. 7

SEM image of cross-section of anode-supported SOFC with cathode fabricated using SSC-SDC(0.1).

Fig. 8

SEM images of cross-section of cathodes fabricated using (a) SSC-SDC(0.02), (b) SSC-SDC(0.1), SSC-SDC(0.2), and SSC-SDC(0.5).

Fig. 9

I-V characteristics for anode-supported SOFCs with different cathodes fabricated using SSC-SDC nano-composite powders at 700 °C using 3% humidified H₂ and air.

Fig. 10

Impedance spectra for anode-supported SOFCs with different cathodes fabricated using SSC-SDC nano-composite powders at 700 °C using 3% humidified H₂ and air under operating voltage of 0.75 V.

Fig. 11

Area-specific resistances of anode-supported SOFCs as a function of particle size D_{50} of SSC-SDC nano-composite powders.

Figure(s)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

I-V
700 C

Fig. 9

Fig. 10

Fig. 11

Graphical Abstract