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Fabrication and evaluation of a novel wavy Single Chamber Solid Oxide Fuel Cell via in-situ monitoring of curvature evolution

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HIGHLIGHTS

- Uniaxial viscosity of materials using optical method.
- In-situ observation of curvature during co-sintering of multi-layer structure.
- Fabrication of wavy SC-SOFCs using a single step co-sintering process.
- Performance tests, comparison and discussion of both wavy and planar cells.
- Wavy SC-SOFC outperformed planar SC-SOFC under the same operational conditions.

ABSTRACT

Wavy type Single Chamber Solid Oxide Fuel Cells (SC-SOFCs) are beneficial for improved triple phase boundary conditions contributing to higher performance, compared with planar type SC-SOFCs of the same diameter. This study presents a fabrication process for wavy-type, cathode-supported SC-SOFCs with a single fabrication step via co-sintering of a triple-layer structure consisting of NiO/CGO-CGO-LSCF, with a thickness ratio of 1:3:9 respectively. Curvature evolution occurs due to different sintering behaviour of each layer during the co-sintering process. In-situ observation of each layer during the co-sintering process allows for minimisation of mismatched stresses to avoid unnecessary warping and cracking. Bilayers, consisting of NiO/CGO-CGO and CGO-LSCF, are co-sintered at 1200 °C. In-situ observation, to monitor the shrinkage of each material and the curvature evolution of the structures, is performed using a long focus microscope (Infinity K-2). Monitoring curvature behaviour in real time minimised the development of undesired curvature in the triple-layer structure. Performance testing of wavy cell is carried out in a methane-air mixture (CH4:O2 = 1:1). The wavy SC-SOFC generated 0.39 V and 9.7 mW cm \(^{-2}\) at 600 °C, which produced 260% and 540% increments in OCV and in maximum power density, respectively, over the planar SC-SOFC under the same operational conditions.

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1. Introduction

Fuel cell technology is one of several energy technologies that could free society from fossilised carbon energy inputs and so overcoming any technical difficulties with fuel cell fabrication or operation could have huge dividends. Since Single-Chamber Solid Oxide Fuel Cells (SC-SOFCs) were introduced by Prof. Hibino’s group [1–3], many researchers have investigated them primarily due to their inherent advantages such as miniaturisation with simpler structure and reduced manufacturing costs [4–6]. In the operation of SC-SOFCs, single cell or stacks are located in the same gas chamber and exposed to a mixture of fuel (hydrocarbon) and oxidant (air). The design of the fuel cell has inherent simplicity which is aided by having no seals in the fuel cell structure. A wide range of portable electronic devices could benefit from replacing the battery with miniaturized SC-SOFCs. However, the SC-SOFC electrochemical reaction process is based upon a different catalytic selectivity of the electrodes in a gas mixture condition (cathode for oxygen separation and reduction, anode for electrochemical fuel oxidation) compared to conventional dual chamber SOFCs. The selective catalytic reaction rate of SC-SOFC is quite minimal, and engenders a lower fuel utilisation than that of conventional SOFCs, so renders the novel design less attractive. Therefore, it is necessary to increase the effective reaction area for SC-SOFCs in a gas mixture condition,
so as to overcome the main disadvantage of SC-SOFCs of low fuel utilisation and low power density per unit volume. Furthermore, thermo-mechanical instability results in the formation of cracks or delamination between layers which further narrows utilisation rates in a variety of applications. In addition, the multi-step fabrication process, used for conventional SOFCs and SC-SOFCs, is difficult to be commercialised.

To cope with the main issue with SC-SOFCs, namely higher performance, researchers have analysed chemical stability and catalytic performance of electrodes in a range of gas mixture conditions [7–9]. The recent examples have achieved power densities of up to 630 mW cm\(^{-2}\) using anode-supported configurations, with mixing ratios \(R_{\text{mix}}\) of CH\(_4\):O\(_2\) in excess of 1:1 [10]. One effective way to enhance the performance is to increase the number of triple phase boundary (TPB) sites, which elevates the active electrochemical reactions during the operation of the fuel cell. Researchers have also investigated using different ratios of anode functional layers to enhance electrochemical reaction at TPBs [11, 12]. It has been suggested to fabricate a curved SC-SOFC in order to increase the TPB sites and to have a higher effective cell area within the same planar diameter; however, difficulty of fabrication including manufacturing cost and time is one of the main barriers to this suggestion.

In this paper the authors present a novel fabrication method for wavy type SC-SOFCs using co-sintering of multi-layer structure. Compared with typical planar cells, the wavy cell has a higher chemical reaction area due to an increase of effective cell area and so is expected to deliver increased performance per unit diameter compared to planar cells. The shape of the cells can be tailored, subject to curvature development and its manipulation via controlling the sintering conditions, to enhance gas transport in order to enhance gas residual time at electrodes, with the ultimate aim of enhancing the fuel utilisation [13–16]. In addition, the wavy shape allows the cell to absorb thermo-mechanical shock arising from different thermal properties between layers during the redox cycle. The SC-SOFC is a simpler structure than the conventional SOFC. This also applies for the wavy SC-SOFC via co-sintering and leads to a reduction in fabrication steps. Hence if the fuel utilisation and thermo mechanical instabilities can be fully overcome then these wavy type SC-SOFCs could have a wider appeal for a range of portable devices, enabling mass production and commercialisation.

During the sintering process of planar SOFCs, it is well established that a bi-layer structure, consisting of anode and electrolyte layers, is sintered followed by a second sintering step with the cathode layer. The thermo-mechanical behaviour of the anode and electrolyte are similar hence no defects will occur during sintering such as warping, cracking, and delamination. In the second sintering step the cathode layer, which does have different thermo-mechanical properties, shrinks only along the through-thickness direction and thus results in no defects. For a multi-layer structure, co-sintering does result in warping and/or cracking [17–22]. These defects occur due to the different shrinkage rates of the individual layers. The different shrinkage rates result in tensile and compressive stresses being generated at the curved surfaces and result in undesired curvature evolution. This shrinkage behaviour has been delicately monitored throughout this study and an attempt to control the behaviour in order to utilise it and promote a wavy/curved shape has been sought. Consequently, a triple layer structure of thickness ratio 1:3:9 (anode, electrolyte and cathode respectively) was employed to facilitate this curvature evolution in the desired manner. A porous electrolyte (CGO, Gadolinium Doped Ceria) was thus obtained in order to harmonise sintering temperatures for all components, and a cathode (LSCF, Lanthanum Strontium Cobalt Ferrite) supported structure was employed to control the curvature behaviour. It was also a consideration to provide a greater bulk volume of LSCF layer to postpone against deterioration through the anode (NiO/CGO) reduction process prior to the cell test.

The aim of the presented work is to make a more effective wavy type SC-SOFC over a planar SC-SOFC. In order to achieve this aim, the following objectives are set; first, to investigate curvature evolution of bi- and triple-layer structures during co-sintering through in-situ experimental observation; second, to suggest a novel fabrication method for a wavy type SC-SOFC in order to deliver increased electrochemical reaction per unit area; and lastly, to carry out the performance comparison between the wavy and the planar SC-SOFC. Experimental results are presented on shrinkage behaviour of each material followed by the in-situ monitoring of curvature evolution with bi-layer structure. From this triple-layer structure is fabricated so that undesired curvature is minimized during the co-sintering process. Curved triple layer structure can then be fabricated and co-sintered with minimal further curvature (zero-deflection condition). The performance test of wavy type SC-SOFC is presented along with that of planar type including open circuit voltage (OCV) comparison and results are discussed.

2. Experimental procedure

2.1. Materials preparation

Materials used in this study were Ni/CGO for anode, CGO for electrolyte and LSCF for cathode; their specifications are listed in Table 1. Tape-casting process with these materials was carried out with support of Maryland tape-casting company. The thickness of each tape was 20 \(\mu\)m and they were hot pressed at 45 \(^\circ\)C under 5 MPa for 5 min to obtain multi-layer structure. In bi-layer structures, one layer of anode and three layers of electrolyte were laminated for anode-electrolyte structure, and three layers of electrolyte and nine layers of cathode were used for electrolyte-cathode structure. For cathode-supported SC-SOFC fabrication, a triple-layer structure was fabricated with one layer of anode, three layers of electrolyte and nine layers of cathode.

After fabrication by hot pressing, the sintering process was performed with single-layer, bi-layer and triple-layer structures. A heating rate of 1 \(^\circ\)C min\(^{-1}\) was used up to 750 \(^\circ\)C for de-binding and then 3 \(^\circ\)C min\(^{-1}\) up to 1200 \(^\circ\)C. During the sintering process, a long-focus camera (Infinity K-2) was used to monitor shrinkage and curvature evolution at a specific temperature. In this study, sintering process was divided into three parts. Section 2.1.1 covers shrinkage measurement in free sintering and vertical sintering, proposed by Cologna [23] to investigate uniaxial viscosity of each material depending on temperatures. Section 2.1.2 covers the estimation of curvature evolution of multi-layer structure derived from mismatched stresses between layers during co-sintering. Section 2.1.3 covers the fabrication of wavy type SC-SOFC with zero-deflection during co-sintering.

2.1.1. Shrinkage measurement

Rectangular specimens with 4 mm (\(W\)) \times 3 mm (\(L\)) were prepared from single-layer tape of each material and leaned on a vertical wall of alumina substrate for the free sintering process, Fig. 1 (a). During the process, shrinkage in the width direction of the specimen was monitored by optical method, following image pro-

<table>
<thead>
<tr>
<th>Name</th>
<th>Composition</th>
<th>(d_{50} (\mu m))</th>
<th>(S_{\text{BET}} (m^2 g^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/CGO</td>
<td>NiO/40 wt% CGO</td>
<td>0.2</td>
<td>4–8</td>
</tr>
<tr>
<td>CGO</td>
<td>CGO33Gd0.66O2-</td>
<td>0.3</td>
<td>4–8</td>
</tr>
<tr>
<td>LSCF</td>
<td>La0.6Sr0.4Co0.2Fe0.8O3-</td>
<td>1.0</td>
<td>4–8</td>
</tr>
</tbody>
</table>
During co-sintering process, in-situ experimental observation of curvature evolution as a function of temperature was performed with the bi- and triple-layer structures using a long focus microscope (Infinity K-2). Bi-layer structures, consisting of Ni/CGO-CGO and CGO-LSCF, have the same thickness ratio with 1:3, but different in thickness. In addition, curvature evolution of the triple-layer structure was investigated by using an optical method. Although undesired curvature evolution of the specimens occurred during the de-binding process, only the curvature evolution from 900 °C was analysed in this study.

2.1.3. Fabrication of wavy type SC-SOFC

Through co-sintering of bi- and triple-layer structures, the fabrication method of wavy type SC-SOFC was investigated. The specimen, consisting of one layer of anode, three layers of electrolyte and nine layers of cathode was prepared with 35 mm (W) × 35 mm (L) and laid on alumina rods. These rods help the triple-layer structure to be wavy shape during co-sintering process. At 80 °C, pre-shaped triple-layer structure was formed as a wavy type due to binder softening.

2.2. Performance test

After completing the co-sintering of triple-layer structure, current collectors in both wavy and planar cells were coated on anode and cathode using silver (silver conductive paste, Sigma- Aldrich) and allowed for curing process. As shown in Fig. 2, methane-air mixture was passed through all the layers, allowing electrochemical reaction to take place. To avoid the explosion and flammability in the mixture at elevated temperatures, a mixture with a ratio of methane to oxygen (CH4:O2 = 1:1) was the only one supplied for the performance test. Total gas flow rate of the mixture was 600 sccm and the operating temperature was 600 °C. The reduction process of the NiO was carried out at 800 °C for 1 h with a 5% H2/95% N2 mixture at a total flow rate of 500 sccm. Ni meshes (50 mesh, 20 × 20 mm) were arranged as shown in the Fig. 2 (a) and (b), in order to retain contacts with the electrodes throughout the experiments.

3. Results and discussion

3.1. Viscosity of the materials

The shrinkage of the NiO/CGO, CGO and LSCF was analysed using free sintering and vertical sintering, shown in Fig. 3, and the corresponding uniaxial viscosity was calculated from the difference in strain rate. The uniaxial viscosity was measured up to a maximum relative density of 0.7 due to sintering temperature. In comparison of shrinkage between free and vertical sintering, shrinkage rate of free sintering was higher at a specific temperature. It was attributed to tensile stress derived from its own weight during vertical sintering. The relative density was calculated using the shrinkage result of free sintering. After completing the sintering process, the following relative densities were measured: 63.8% for NiO/CGO; 61.2% for CGO; and 63.9% for LSCF by Archimedes method and scanning electron microscopy (SEM) analysis. The uniaxial viscosity of each material was calculated using Eq. (1).

\[ \eta = \frac{\rho g L}{2(\dot{e}_v - \dot{e}_f)} \]  

\( \dot{e}_v \) : strain rate in vertical sintering
\( \dot{e}_f \) : strain rate in free sintering

2.1.2. Curvature evolution

Strip type specimens with 3 mm (W) × 1 mm (L) were cut from the bi- and triple-layer structures and laid on alumina substrate.
ference of shrinkage rate. However, as sintering process is finished before reaching high density, then the viscosity calculated from Eq. (1) is valid and enables an understanding of sintering behaviour for each material.

3.2. Curvature evolution of bi- and triple-layer structures

Fig. 4 shows the curvature evolution of bi- and triple-layer structures with increasing temperatures. Even though curvature
evolution occurred during de-binding process, it was subtracted from the total curvature. Therefore, in this study, the curvature evolution of the structures during co-sintering is regarded as curvature derived from sintering behaviour of each material. As shown in Fig. 4, different curvature evolutions were shown depending on composition of the structures [26–32].

Different shrinkage behaviour between layers during co-sintering of the multi-layer structure caused mismatched stress distribution in the structure. In the curvature of NiO/CGO-CGO bi-layer structure, there was no appreciable curvature evolution during co-sintering due to similar properties. But as shrinkage of NiO/CGO layer was higher than CGO layer, the bi-layer structure curved towards NiO/CGO layer at 1200 °C. Similarly, in the CGO-LSCF structure, curvature was directed towards CGO layer after reaching at 1100 °C. Shrinkage of LSCF was higher than CGO up to 1050 °C, and then it was decreased with increasing temperature due to higher shrinkage of CGO. It is reasoned that when a bi- or triple-layer structure was fabricated by hot-pressing, each layer's microstructure (and hence its material properties) could be changed due to factors such as particle rearrangement. During the co-sintering process with a bi-layer structure, relative shrinkage behaviors play an important role compared to its own property. The densification process of CGO with small particles and higher shrinkage rate at 1050 °C was more active than that of LSCF. Once the curvature of a bi-layer was biased towards the CGO layer at elevated temperatures, the tension force against the shrinkage direction was occurring at the LSCF layer, which delayed the densification of LSCF despite the shrinkage being higher than CGO at 1200 °C. With these results, curvature prediction of the triple-layer structure using the sum of curvature evolution of bi-layer structures was estimated and compared with experimental observation, shown in Fig. 5 (NC: NiO/CGO-CGO, CL: CGO-LSCF, NCL: NiO/CGO-CGO-LSCF).

If severe curvature evolution in bi-layer structures occurred due to different shrinkage behaviour during co-sintering, this approach cannot be applied to predict curvature evolution of a triple-layer structure based on bi-layer curvatures. As shown in Fig. 5, the dashed lines show curvature evolution of bi-layers and green solid line is curvature prediction of the triple-layer structure based on bi-layer curvatures. The experimental observations of the triple-layer structure (black solid line) demonstrate good agreement with the curvature prediction based on bi-layer structures. When the sintering temperature reached 1200 °C, there still remained curvature evolution towards NiO/CGO layer, but this curvature was removed during the cooling process resulting in a zero-deflection structure. It is understandable by considering two factors: (a) the temperature of the initial stage of the cooling process was still high enough to greater influence the behaviour of the LSCF layer rather than the other two layers, due to the thermal properties of LSCF, and (b) the higher thermal expansion coefficient (TEC) of LSCF is not stably matched with the TEC of two other layers, so the mismatch would induce further stresses to the whole structure to influence its curvature during the cooling process.

3.3. Fabrication of wavy type SC-SOFC

With a zero-deflection aim for the triple-layer structure, fabrication of wavy type SC-SOFC was carried out using co-sintering
process. At 80 °C, a planar triple-layer structure was transformed to a wavy structure due to binder softening, shown in Fig. 6(a). This pre-shaped structure was heated up to 1200 °C followed by a cooling process rate of 3 °C min⁻¹. Fig. 6(b) shows wavy type SC-SOFC with some curvature evolution but without severe warping, after completing co-sintering and cooling.

Compared with curvature evolution in co-sintering of the planar triple-layer structure, different stress distribution near alumina rods in the wavy structure can be mainly attributed to curvature evolution during co-sintering. Especially, the deformation of the structure on the rods during de-binding process led to non-uniformity of micro structural condition at the early of the co-sintering process. In addition, when fabricating the multi-layer structure by hot pressing, anisotropy might have been induced into the structure during the process. The microstructure of layers in the wavy type SC-SOFC was examined using SEM, shown in Fig. 7.

It is shown that all layers have porous structure with relative density of 0.7 and the structure has a 175 ± 2 μm total thickness (16 μm for anode, 37 μm for electrolyte, and 122 μm for cathode). In addition, the pore size of LSCF is larger than the pore sizes in others. As it is well known that the sintering temperature of cathode material is lower than that of anode or electrolyte material, LSCF with coarse green particle was used to match the final porosity of each material after co-sintering. The images are evidently showing the similarity between two cells’ microstructure, in particular with respect to average component thickness and average pore size. Interestingly, there are small level of differences in microstructure of wavy cell, i.e. anode layer thickness and anode porosities between Fig. 7a–c, where images were taken from the convex area, flat area and concave area respectively. These subtle differences were generated during the co-sintering process (anode layer was compressed in Fig. 7a whilst the same layer was under tensile stress in c), and so can contribute to the variation of gas flow and fuel to oxygen ratios locally.

3.4. Performance test and comparison with planar cell

A polarisation curve was obtained at 600 °C, shown in Fig. 8. The OCV and maximum power density of the wavy SC-SOFC were measured as 0.39 V and 9.7 mW cm⁻² under the condition of methane-air mixture (Rmix = 1), whereas the planar SC-SOFC generated 0.15 V and 1.8 mW cm⁻².

It is well known that performance of SC-SOFC is sensitive to the operational conditions [9,33], particularly to temperature and to the fuel-to-air ratio. In comparison with the planar cell, given the same operational conditions, the wavy cell demonstrates significant gains in terms of OCV (by 260%) and the maximum power density (by 540%). The higher maximum power density from the wavy SC-SOFC over the planar SC-SOFC may be attributable to the fact that wavy cell has 7.1% higher effective cell area for a given area defined by the cell perimeter (geometric projected area). In addition, the performance difference can be explained that the cell shapes influenced gas flow through the wavy cell. A wavy shape could lead to an increase in gas flow, enhancing the effective gas diffusion. The vortex of the gas flow from wavy shape may increase transportation rate between the reactant and product gases, delivering increased utilisation rate of TPBs. Thereby enhanced transportation rate of gases due to different microscopic structures at the interfaces of the wavy cell may help provide higher performance. The difference in OCV obtained is of interest as there are fewer variables in play, and demonstrates a significant advantage for the wavy cell given that the same conditions and lack of optimisation are applicable. It is known that the OCV of SC-SOFCs is highly subjective to fuel to oxygen ratios, total & local flow rates, microstructure, operating temperature, and favoured reactions [33–35]. Some researchers have investigated the local transport characteristics inside curved SOFC, such as the gas concentration distribution, the overpotential distribution, and the current density distribution, showing a different pattern with that of a planar SOFC [33–37]. Furthermore, compared to the planar cells, the wavy cell should have different pore shape, orientation and interconnectivity influenced by the induced stress developed on each component during co-sintering, particularly at around the point of centraflexure where stress concentration could have occurred to elevate such microstructural differences [38–40]. Whilst these can address the superior performance of the wavy cell to a certain degree, the OCV of both the SC-SOFCs, and particularly the planar cell, is still lower than that reported from literature [4,8] and therefore merits investigation, even accounting for the special sensitivity of SC-SOFCs to non-optimised operational conditions. The ramifications of employing a cathode supported cell with a porous electrolyte structure should be considered. The effectiveness of perovskite-based mixed ionic and electronic conductor (MIEC) mechanisms are dependent on the lattice structure (number of electrons and electron holes for electronic conductivity, vs interstitial sites and lattice vacancies for oxygen separation and reduction), partial pressure gradient and, in the single chamber configuration case, selectivity of the cathode for the oxygen reduction reaction (ORR) step [41]. The use of a relatively thick cathode layer suggests
a high contribution to area-specific resistance from oxygen ion transport through the cathode itself. Whilst the exact contribution will have to be determined by further investigation via material and electrochemical characterisations, it also suggests that the cathode supported cell may add a significant bulk diffusion retardation, although research suggests LSCF oxygen reduction may be a surface-exchange limited process [42,43]. Moreover, the use of a hydrogen reduction process may have impacted the obtained OCV overall. It is known that cathode selectivity plays a major role in establishing OCV as the anode is not acknowledged to be as favourable to fuel oxidation as would be ideal [8,11]. It is therefore imperative that the perovskite phase be retained in the cathode whilst the anode reduction process is taking place. In SC-SOFC, LSCF is susceptible to reduction, particularly under hydrogen reducing atmospheres, and a high degree of reduction/destruction of the perovskite phase has been observed [44,45], as with other perovskite-based cathodes, which would impair the oxygen reduction reaction. This may also favour LSCF to be more catalytically active for oxidation of fuel (both partial oxidation, and direct electrochemical oxidation) [46], and further reduce the OCV with a low oxygen partial pressure on the cathode side. The use of silver as a current collector and adhesive for mesh may have distorted the cell operation, and can impede the function of the anode; in particular, its catalytic activity towards free oxygen reduction can dominate the cell OCV and current, which will be described by the net partial pressure gradient across the membranes. The greater bulk volume of LCSF of the wavy cell (7.1% × 9 layers for 57% greater volume with the same planar area) may have provided an additional buffer against this tendency. As a result of the above, it may be proposed that another reason for the low OCV in both cells could be that, at low oxygen partial pressures, the CGO electrolyte demonstrates significant electronic conductivity [47], which provides an electronic pathway from the MIEC cathode to the Ni-CGO anode when cathode oxygen partial pressure is low, and may therefore cause short circuiting, which manifests voltage loss at open circuit condition itself. Thus, further investigation is required to identify suitable anode reduction conditions, the ideal mixing ratios for the preferable reactions to occur, and optimisation of the above for the given geometries. In addition, electrochemical and material characterisations should be performed to validate the exact causes of the difference in performance. Overall, the obtained performance output is far less than reported values obtained out of cells from other sources, predominantly of anode-supported or electrolyte-supported types [2,4,48–50], whereupon OCV starts from 0.6 to 0.8 V, and maximum power densities are in excess of 400 mW cm$^{-2}$. Hence, it is apparent that other configurations and operating conditions ($R_{\text{mix}} > 1$) deserve further investigation in terms of obtaining higher output. Future work is involved in applying this co-sintering method to derive wavy and planar structures based on the use of a composite cathode material.

4. Conclusions

The authors have fabricated higher output wavy type SC-SOFCs, using triple layer structure, based on a careful study of the co-sintering fabrication process. The performance of these fuel cells has been compared with that of a planar SC-SOFC. The different shrinkage behaviour between layers during co-sintering results in curvature evolution in the multi-layer structure. This evolution was monitored experimentally using an optical method. Through in-situ monitoring of curvature evolution of bi-layer structures enabled the authors to predict the curvature of a triple-layer structure during co-sintering with the aim of fabricating zero-deflection
structure and this was verified by experimental results. Utilising the outcome from the optical observation study, wavy and planar SC-SOFCs are fabricated via single process, co-sintering process. As far as the authors are aware the work presented here is the only successful demonstration of fabricating a wavy SC-SOFC via single sintering process. During the co-sintering process, it was shown that wavy type SC-SOFC was well-fabricated without severe warping after co-sintering process. In addition, this study successfully addresses the prediction of the macro-scale response of wavy cells and shows curvature prediction of a triple-layer structure is feasible based on the bi-layer curvature results. In the comparison for performance, the OCV and maximum power density of the wavy SC-SOFC were 0.39 V and 9.7 mW cm\(^{-2}\) at 600 °C, 2.6 times higher OCV and 5.4 times higher maximum power density than the planar cell. The wavy dimension influences the increase of the effective cell area in the unit diameter, and enhances the effective gas diffusion paths that both are contributing to higher performance. It is believed that the higher output is also attributed by the different microstructure of components caused by the induced stress during co-sintering. The higher output of wavy SC-SOFC over planar SC-SOFCs is consistent with literature results reported, and the comparison of performance shows that curvature of SC-SOFC can significantly influence the output, and so it is expected that different curvature, probably with an even higher effective cell area for a given projected area, may deliver even higher output over the samples used in this study. It is also apparent that an anode-supported or electrolyte-supported configuration needs to be investigated for securing the findings of superiority of a wavy cell over a planar cell. It can also serve to verify the viability of the single step co-sintering approach to fabricating single chamber SOFCs, for both planar and wavy structures. The suggested co-sintering process may open a new production process that can deliver curvature customised SC-SOFCs and such cells would be useful for powering mobile or portable electronic devices, e.g. micro UAVs (Unmanned Aerial Vehicle), where high crashworthiness is required.

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