O U R N A L O F

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Fabrication of thin porous electrolyte-supported tubular fuel cells using slip casting

Amir Reza Hanifi^{a,*}, Alireza Torabi^a, Alyssa Shinbine^a, Thomas H. Etsell^a and Partha Sarkar^b

^aDepartment of Chemical & Materials Engineering, University of Alberta, Edmonton, T6G 2V4, Canada ^bCarbon & Energy Management, Alberta Innovates - Technology Futures, Edmonton, T6N 1E4, Canada

In the current research the third generation of tubular solid oxide fuel cells (SOFCs) which is believed to solve the redox cycling problem is introduced and the cell configuration is discussed. This type of ceramic fuel cell consists of a slip cast porous support of approximately 500 μ m thickness coated with a thin dense electrolyte layer both made of calcined YSZ. The porous support can have up to 50% porosity as a result of both the preliminary calcination of YSZ powder and the addition of a pore former. Different parameters that affect the porosity content and thickness of the supports are also studied. It is shown that the short casting time required for high porosity tubes can be controlled by modifying the solid loading of the slip and/or the porosity of the plaster mold. Finally, multiple casting is introduced as a coating method in which the electrolyte layer with the required thickness can be slip cast directly onto the porous support.

Keywords: Slip casting, Fuel cells, Microstructure, Porosity, Yttria Stabilized Zirconia (YSZ).

Introduction

Ceramic fuel cells convert the chemical energy of a fuel to electrical power. The main advantages of this type of fuel cell are their high efficiency, fuel flexibility and minimal contribution to pollution of the environment. SOFCs have captured the interest of many within the scientific community due to these benefits. High oxygen ion conductivity of YSZ (ZrO₂ doped with Y₂O₃) has established this material as one of the most important SOFC materials used in various layers of ceramic cells. Conventional fuel cells are fabricated based on a combination Ni-YSZ (porous anode)/YSZ (dense electrolyte)/LSM (La_{1-x}Sr_xMnO_{3- δ})-YSZ (porous cathode) model [1, 2].

The two main fuel cell designs are planar and tubular configurations [3]. Despite planar fuel cells having a higher power density due to their short current paths, they experience sealing problems [4]. However, even with lower power density tubular fuel cells are advantageous as they do not require sealing, possess improved thermomechanical properties, have higher thermal cycling ability and require less start up/shut down time [5].

The *first generation* of tubular SOFCs was developed in the early 1990's [6]. Due to the relatively high thickness of the dense electrolyte layer (~200 μ m) in this category, the fuel cell has a low power density and high ohmic loss, and thus needs to be operated at high temperatures in order to obtain sufficient power [7].

In order to permit functionality at lower temperatures, *second generation* SOFCs which are anode supported

were developed [8]. The thickness of the electrolyte layer in this type of fuel cell can be as thin as 10 µm, with the thick anode providing the mechanical support. The primary problem faced in the application of anode-supported tubular fuel cells is the effects of redox cycling. During anode oxidation-reduction reactions, Ni oxidizes into NiO, resulting in a volume expansion. This volumetric expansion contributes to the formation of micro-cracks and their propagation within the Ni-YSZ anode support which leads to cell failure [9, 10]. Any accidental oxidation of the anode, mainly caused by a shut down due to maintenance on the system, damages the anode-supported fuel cells.

In order to overcome this issue, the authors developed the concept of a 'Porous Electrolyte-Supported' (PES) tubular SOFC as the *third generation* of SOFCs [11-13]. In the present study, small diameter (\sim 7-10 mm) tubular PES single cells are manufactured using slip casting. It is expected that these YSZ porous supports (\sim 500 µm) coated with a thin dense electrolyte (\sim 10-30 µm) will not have redox cycling related problems. These porous supports can be impregnated with nano-sized Ni anode material and function at low temperatures.

Different pore formers such as PMMA and graphite had been used so far in order to generate pores inside fuel cell electrodes. It is found that the type, shape and content of pores which change the electrode microstructure influence fuel cell performance significantly [14, 15]. The current research describes the design, fabrication method and physical properties of these porous supports coated with a thin electrolyte. Since there is significant concentration polarization arising from the resistance of the thick anode to gas transport [7], optimizing the electrode microstructure and reducing the porous support thickness can improve fuel cell performance via reduction of both activation and

^{*}Corresponding author:

Tel : +1-780-710-7997 Fax: +1-780-492-2881

E-mail: Hanifi@ualberta.ca

concentration polarization. In this paper, the parameters which affect the porosity and thickness of the porous support are also studied, and the methods to reduce the support thickness as well as to control the slip casting technique are discussed. Finally, a multiple casting method is introduced as a means to directly coat a dense electrolyte onto a porous support while still maintaining excellent interfacial attachment between the layers.

Experimental Procedure

To fabricate YSZ supports, as-received Tosoh YSZ powder (TZ-8Y, 8 mol% Y₂O₃) or YSZ powder calcined at 1300-1500 °C for 3 h was mixed with water at a powder : water ratio of 52 : 48 wt% and milled at 80 rpm for 72 h in a plastic bottle using 5 mm YSZ balls. The weight of the YSZ balls required appeared to be six times the weight of the powder added in order to provide sufficient force for crushing. To stabilize the YSZ suspension for casting, the pH of the slip was set at 4 using diluted 2% HCl acid as a dispersant. For the compositions containing a pore former, graphite (Sigma Aldrich < 325 mesh) was incorporated into the slip following pH adjustment, and the suspension was mixed for 15 minutes before casting. Samples were slip cast as tubes or pellets in plaster molds. In order to create the tubular supports and cell structures, the slip was cast into a tubular plaster mold for a designated time (dependent on the particular experiment), and the excess slip was decanted. Samples were then dried at room temperature for 1 h. In order to determine the physical properties of the tubes, pellets were used instead to increase the accuracy and ease of such measurements. Pellets were cast long enough to be \sim 3 mm thick. Tubes and pellets were then dried at 100 °C in an oven, heated at 700 °C for 1 h to permit graphite to oxidize, and sintered at 1350 °C for 3 h under air in a Carbolite RHF 16/3 box furnace. Bulk density, open porosity and closed porosity of the pellets were calculated based on Archimedes principle, which took into account the dry weight, saturated weight, weight suspended in water and the theoretical density of YSZ $(8 \text{ mol}\% \text{ Y}_2\text{O}_3-6.1 \text{ g/cm}^3)$. Shrinkage and weight loss were calculated via comparing the pellet diameter and weight before and after sintering.

In order to evaluate the effect of plaster mold porosity on the thickness of the tubes, gypsum powder (plaster of Paris, industrial type), product of Georgia-Pacific Company, was mixed with water in ratios of: 1, 1.25, 1.5, 1.75 and 2, which resulted in 50%, 44%, 40%, 36% and 33% porosity, respectively. The appropriate mixture was mixed and cast into a plastic mold and a steel tube/pellet was inserted into the wet mixture. After the initial setting, the steel tube/pellet was removed from the mold and the mold was dried at 60 °C in an oven overnight. The void space formed in the plaster mold after removal of the steel tube/pellet was used for the subsequent casting. The weight of graphite required and the solid loading were calculated using equations (1) and (2), respectively, where $W_{graphite}$, W_{YSZ} and W_{water} are the graphite, YSZ and water mass (g), respectively, ρ_{YSZ} and $\rho_{graphite}$ are the densities of YSZ (~6.1 g/cm³) and graphite (~2.28 g/cm³) and Vol % graphite represents the volume percent of graphite:

$$W graphite = \frac{\left(\frac{WYSZ}{\rho YSZ} \times Vol\% graphite\right) \times \rho praphite}{100 - Vol\% graphite}$$
(1)

$$\% Solid \ Loading = \frac{(WYSZ + Wgraphite) \times 100}{WYSZ + Wgraphite + Wwater}$$
(2)

To measure tube thickness and to study the microstructure of the samples, secondary electron beam SEM images were obtained from gold coated samples using an FEI company XL30 SEM running at 20 kV.

The configuration of the new generation of tubular SOFCs is schematically illustrated in Fig. 1a. This design consists of a YSZ porous support layer of about 500 μ m coated with a YSZ dense electrolyte layer of about 10-30 μ m. After fabrication and sintering of the basic structure of the fuel cell, a thin layer of cathode of about 20-30 μ m, such as an LSM/YSZ composite, is coated on the surface of the electrolyte and the fuel cell is sintered in air at a temperature between 1100-1200 °C to avoid reactions between LSM and YSZ. Nickel is impregnated inside the porous support until a sufficient loading is achieved (Fig. 1(b)). Then the fuel cell is ready for anode reduction, cell performance testing and redox cycling resistance.

In this study as-received YSZ powder and YSZ calcined at 1300, 1400 or 1500 °C are referred to as "Tosoh YSZ", "CYSZ 1300", "CYSZ 1400" and "CYSZ 1500".

Results and Discussion

Fabrication and properties of the porous supports

Table 1 shows different physical properties of the fabricated tubes. It is found that Tosoh YSZ becomes



Fig. 1. Porous YSZ electrolyte-supported SOFC coated with a dense YSZ and a thin cathode layer: (a) before impregnation with Ni, (b) after impregnation. (schematic).

Table 1	 Physical 	properties of	of the tu	bes made	of different	types
of YSZ.	. CYSZ : C	alcined YSZ	Z, G : G	raphite		

	Bulk	Open	Closed	Shrink-	Weight
Raw Materials Used	(g/cm^3)	Porosity (%)	Porosπy (%)	age (%)	Loss (%)
Tosoh YSZ	5.977	0	2	22	< 0.5
To soh YSZ + 20 vol $\%$ G	5.215	2	12	22	9
CYSZ 1300	5.629	0	7	16	< 0.5
CYSZ 1300 + 10 vol% G	4.857	15	5	15	4.5
CYSZ 1300 + 20 vol% G	4.326	23	6	15	9
CYSZ 1300 + 30 vol% G	3.675	36	4	15	14.5
CYSZ 1300 + 40 vol% G	3.130	46	3	15	20
CYSZ 1400	4.713	21	2	8	< 0.5
CYSZ 1400 + 10 vol% G	4.131	30	2	10	4.5
CYSZ 1400 + 15 vol% G	3.578	39	2	11	7
CYSZ 1400 + 20 vol% G $$	3.173	46	1.5	13	9
CYSZ 1500	4.424	25	2	6	< 0.5
CYSZ 1500 + 10 vol% G	3.331	43	2.5	7	4.5
CYSZ 1500 + 15 vol% G	2.935	50	1.5	9	7
CYSZ 1500 + 20 vol% G	2.664	54	2.5	7	9

dense following sintering at 1350 °C. Even with the addition of 20 vol% graphite as a pore former, it is difficult to generate a porous structure with a significant amount of open pores. Due to the high surface area and sinterability of the YSZ powder, the particles tend to readily sinter to reduce this surface area. However, some pores between the particles are not removed during sintering and become closed pores. Due to the large graphite flakes, pores formed by graphite oxidation are fairly large (1-25 µm), and remain in the structure after sintering. However, they do not possess enough connectivity to form a porous network. Thus, the addition of graphite to the Tosoh YSZ powder only favors the formation of closed pores. To generate pores in the structure, it is crucial to lower the sinterabiliy of the YSZ powder by calcination. This heat treatment leads to growth of YSZ particles. During milling of the calcined powder, broken bonds form and due to the resulting agglomeration of crystals, larger particles with a lower surface area (than the original YSZ powder) appear. This procedure facilitates the formation of porous YSZ structures. The tubes made of CYSZ 1300 still become dense following sintering with some remaining closed pores. Conversely, tubes made of CYSZ 1400 and CYSZ 1500 remain porous even without a graphite addition. However, it is clear that addition of graphite to different calcined powders significantly increases the porosity content. Furthermore, increasing the calcination temperature of YSZ leads to a reduction of closed pores and shrinkage rate of the samples. It appears that graphite does not have a significant effect on the shrinkage. Weight loss recorded in the samples is, as expected, proportional to the graphite

content which burns during sintering. Also, the minor amount of weight loss reported (< 0.5%) in graphite free samples corresponds to the removal of chemically absorbed water not released after oven drying as it requires a much higher temperature.

For porous structures as the supports in fuel cells, obtaining thin tubes ($< 500 \mu m$) with sufficient porosity prior to impregnation is desired. After anode impregnation and later reduction, the content of open pores remaining should be about 30-35% to allow sufficient fuel flow inside the anode cermet [16]. High porosity slip cast tubes (above 60%) may not be desirable because of the difficulty that arises in casting and the low mechanical strength associated with such high porosity. The low mechanical strength serves as a limiting factor in handling during various fabrication and impregnation stages. Haslam et al. [17] pointed out that increasing the pore content to a certain extent improves fuel cell performance due to better gas flow and lower polarization but, at high porosity contents, cell performance drops due to removal of active threephase boundary regions.

From our experience, removal of very thin tubes (< 200 μ m) from the plaster mold faces difficulties because of the low green strength and fragility of such samples. Therefore, thicknesses between 200-500 μ m should be the ideal size. The cross section of a tube made of YSZ calcined at 1300 °C, 20 vol % graphite with a thickness of about 560 μ m and its microstructure are shown in Fig. 2(a) and (b), respectively. A variety of pores with different sizes exist in this microstructure which is believed to readily resist redox cycling as the oxidation and reduction cycles of the present anode particles (Ni, Cu, etc.) with the associated volume changes cannot cause the required stress for crack formation and ultimate destruction of the fuel cell.

Based on Table 1, in order to obtain samples with high porosity, the content of graphite as well as the calcination temperature of YSZ should increase. These two parameters, unfortunately, lead to a major increase in tube thickness. To make a thin porous tube (~500 μ m), the casting time must decrease to approximately 10 seconds which may be impractical for the porous support since thickness becomes too time sensitive. Thinner tubes are not only easier to impregnate, but also experience less activation and concentration polarization loss on the anode side.



Fig. 2. (a) Cross section of the tube made of YSZ calcined at $1300 \,^{\circ}$ C, $20 \, \text{vol}\%$ graphite, (b) and the microstructure of the porous support.

Parameters which control the tube thickness

Effect of Graphite Content

In order to study the effect of graphite content on the thickness of supports, graphite was added to suspensions of calcined YSZ in known volume percentages and then the mixtures were slip cast for a constant casting time of 60 seconds in molds of 40% porosity. The YSZ/water ratio in the slips was set at 52:48 wt% and the solid loading varied depending on the graphite content. It can be seen that an increase of graphite content leads to an increase in the tube thickness for different calcined YSZ powders (Fig. 3). This strong, increasing trend in thickness is due to graphite increasing the solid loading and, accordingly, the viscosity of the slip. Since graphite flakes are much larger ($< 25 \mu m$) than the YSZ particles (200-1500 nm), its addition leads to faster solid layer formation and thickening of the tubes. As can be seen in Fig. 3, the combination of increasing the YSZ calcination temperature and graphite content leads to a dramatic increase in tube thickness for suspensions made of CYSZ 1400 and CYSZ 1500. Graphite additions greater than 30 vol% to calcined YSZ suspensions is not recommended because it results in short casting times, difficulty in sample removal, reduced green strength and increased fragility.

Effect of calcination temperature

For samples of similar solid loading and graphite content, increasing the calcination temperature of the YSZ causes a significant increase in the tube thickness (Fig. 4). While the increase of tube thickness at 10 and 15 vol% graphite follows more or less a linear trend, it seems that at the higher graphite content of 20 vol% the increase is stronger. The increase of tube thickness with respect to an increase of calcination temperature can be explained by much larger particles formed after milling of higher temperature calcined powder. Based on Fig. 3 and 4, it can be seen that an increase of both calcination temperature and graphite content lead to significant increases in tube thickness which is unsuitable for impregnation and fuel cell performance.



Fig. 3. Tube thickness as a function of graphite content at different calcination temperatures.



Fig. 4. Tube thickness as a function of calcination temperature for different graphite contents.



Fig. 5. Tube thickness as a function of casting time.

Therefore, to achieve thin-walled tubes having more than 35% porosity, the tube thickness should be controlled by other techniques which are investigated in later sections.

Effect of casting time

Effect of casting time on tube thickness for suspensions of similar solid loading (52%) and graphite content (10 vol%) but different calcined YSZ is illustrated in Fig. 5. It is obvious that casting time has a direct effect on tube thickness and the longer the casting time, the thicker the tube. Also, the effect of calcination temperature on tube thickness at different casting times is consistent with the former graph since an increase in thickness is experienced with an increase in calcination temperature except for the tube made of CYSZ 1500 and 10 vol% graphite cast for 30 seconds. Based on the least-squares fit (R^2) values, the correlation between casting time and tube thickness follows a relatively linear trend. However, the linearity may not always be apparent, as slip chemistry can be a vital factor in tube thickness and an increase of graphite content may lead to a stronger thickness increase. Based on the information shown in Table 1, tubes made of CYSZ 1300, CYSZ 1400 and CYSZ 1500 and 10 vol% graphite with 15%, 30% and 43% porosity should be cast in 30 seconds or less to achieve viable thicknesses.

Effect of solid loading

In order to increase the casting time of the porous tubes, solid loading of the suspensions, calculated based on eq. (2), was varied from 40-60% and the suspensions were cast for 60 seconds inside the plaster molds of 40% porosity. Fig. 6 depicts the relation between the solid loading and tube thickness as well as open porosity for different YSZ suspensions. It is noted that lowering the solid loading significantly helps to reduce the thickness of the tubes. The level of thickness reduction is ~ 1.5 to 2 times for a 20% reduction in solid loading. This means that, if we consider the effect of casting time to also be linear with respect to tube thickness, a reduction of solid loading from 60% to 40% can increase the casting time by 1.5 to 2 times to realize a similar tube thickness. It is worth noting that the solid loading of the suspension does not affect the content of open pores in the structure. While fabricating thin samples, it is possible to keep the physical properties unaltered. This is due to the fact that the content of open pores in such structures is defined by the type of YSZ powder used as well as the graphite content but not the amount of water. Lowering the solid loading of the suspension further below 40% is expected to produce thinner tubes and further increase the casting time. The thickness increase experienced with an increase in calcination temperature is again observed at fixed solid contents.

Effect of plaster mold porosity

The effect of plaster mold porosity on tube thickness and open porosity has been studied by casting CYSZ 1300 with different contents of graphite for 60 seconds in molds with different porosity contents. Based on Fig. 7, the level of changes in tube thickness upon decreasing mold porosity is slight until 36% mold porosity for 0-20 vol% graphite suspensions; however, further reduction



Fig. 6. Tube thickness and porosity content as a function of solid loading. Hollow symbols show the tube thickness and solid symbols denote the porosity content of each composition.



Fig. 7. Tube thickness and porosity content as a function of porosity of the plaster molds. Hollow symbols show the tube thickness and solid symbols denote the porosity content of each composition.

to 33% causes a significant reduction in tube thickness. As well, for the suspension of CYSZ 1300 and 30 vol% graphite, a decrease in thickness is noticed earlier at 40% mold porosity. The reduction of tube thickness versus reduction of mold porosity can be attributed to the fact that less porous plaster molds have a lower capability for absorbing the water. This, in turn, decelerates the procedure of drying and solid formation of the tubes. It also appears that mold porosity has no effect on tube porosity and only affects the speed of tube formation. Other parameters that can reduce the rate of water absorption by the mold and tube thickness include pre-wetting the mold via misting with water or using a plaster mold immediately after a sample removal (from a casting). However, these options may not be predictable or reproducible in the context of thickness control.

A blend of α - and β -hemihydrate is normally used in molding applications to achieve a highly absorptive plaster with greater strength and hardness [18]. The former phase is less water absorptive but is mechanically stronger in contrast to the latter. Another possible procedure for reducing the tube thickness is to slip cast the tubes inside molds richer in the α -hemihydrate phase compared with the β -hemihydrate. This is expected to decelerate the water absorbance process and prolong the slip casting time.

Coating of the dense electrolyte using a multiple casting technique

In order to coat a thin electrolyte layer on the porous support, slips were prepared using CYSZ 1300 at different solid loadings. This powder is a potential material for fabrication of the dense electrolyte as the bodies made from this slip become dense after sintering at 1350 °C. Immediately after removal of the porous support slip, the electrolyte slip is cast for a brief time and the remaining slip is poured out. This quick casting method enables a thin-walled electrolyte layer to form inside the outer support. When the electrolyte layer is cast, the water in the slip is Fabrication of thin porous electrolyte-supported tubular fuel cells using slip casting



Fig. 8. Secondary electron beam SEM images showing the interface between the porous support and the electrolyte: (a) SI = 40%, t = 5 S, (b) SI = 20%, t = 5 S, (c) SI = 40%, t = 1 S, (d) SI = 20%, t = 1 S. SI : solid loading, t : casting time.

absorbed by the porous layer and a new thin-walled layer results. Following drying and co-sintering, a dense electrolyte appears attached to the porous support. Figure 8 shows SEM images of porous supports made of CYSZ 1300, 20 vol% graphite coated with YSZ slips with solid loadings of 40% and 20% cast for two different times. When the electrolyte layers made of 40% and 20% solid are cast for 5 seconds, thicknesses of 12 µm and 10 µm appear (Fig. 8(a) and (b)). As well, these microstructures depict the excellent interfacial attachment between the electrolyte and the porous support. No cracks or defects in the electrolyte were apparent, which signifies no gas penetration. In order to achieve thinner electrolytes, a 40% solid loading slip was cast for 1 second which resulted in an electrolyte with a thickness of 9 μ m and the slip with a solid loading of 20% produces an electrolyte layer of $\sim 6 \,\mu m$ (Fig. 8(c) and (d). The latter electrolyte layer does not have a uniform structure and undesirable fractures are present. Therefore, it is not recommended to use low solid loading slips (20% or less) and a short casting time for coating the electrolyte.

Using multiple casting, it is possible to fabricate complex structures with desired thicknesses making this technique potentially very useful and versatile for fabrication of fuel cells. However, it should be noted that this coating method can only be used for monolithic ceramic pieces in which the former substrate was also formed by slip casting. This is because the whole body must undergo cosintering. The shrinkage rate of the two layers should be matched to avoid crack formation and breakage of the samples during sintering. This is the reason the 1300 °C calcined YSZ is used instead of Tosoh YSZ powder for the electrolyte coating. Leng et al. [19] had a similar experience as they were unable to coat a dense electrolyte using nano-sized YSZ (50-60 nm) on a Ni/YSZ anode. However, they managed to coat the electrolyte with larger YSZ particles $(0.5 \,\mu\text{m})$ on the anode. They attributed this to a significant difference in sintering kinetics between the nano-sized YSZ and Ni/YSZ anode.

Cathode material can be coated on the surface of the electrolyte and sintered prior to anode impregnation. An alternative to the coated cathode layer is a thin porous layer coated on the electrolyte with required thickness and porosity using multiple casting which then can be used for impregnation of the cathode material. When nano-size anode and cathode materials are impregnated into their respective separate layers, the cell performance should improve.

Impregnation of Ni inside the porous supports of planar fuel cells has been studied by several researchers [16, 20]. It is known that both connected Ni and dispersed particles promote catalytic activity on the anode side while electrons can move only through the connected nano-particles [21]. The thickness of the porous layer used for impregnation in earlier studies is much lower compared with the currently developed porous support, since they were mainly electrolyte supported. Therefore, impregnation of the developed structures might be challenging. Busawon et al. [16] found that, after 12 wt% Ni impregnation, Ni/YSZ cermet showed a conductivity of about 360 S cm⁻¹ at room temperature which is similar to other anode materials. If a similar Ni loading is considered as the target for impregnation of the tubular fuel cells, then it is possible to calculate the volume of the infiltrated Ni and hence the remaining open porosity in the tube. Table 2 shows the open porosity content of different tubes after impregnation by a similar content of Ni (15 wt% NiO or when reduced ~12 wt% Ni). Comparing Tables 1 and 2, there is a reduction of ~7-13% in open porosity following NiO impregnation or ~4-7% after the reduction into Ni particles. Therefore, if a minimum 30% porosity is considered as sufficient to allow gas flow inside the porous structure, then the potential candidates for use as porous supports can be selected. For 1300 °C

 Table 2. Open porosity content of the support tubes after impregnation with NiO or reduced Ni

Raw Material Used	Open Porosity after 15 wt % NiO Impregnation (%)	Open Porosity after Ni Reduction (%)
CYSZ 1300 + 10 vol% G	2	8
CYSZ 1300 + 20 vol% G	12	16
CYSZ 1300 + 30 vol% G	26	30
CYSZ 1300 + 40 vol% G	38	41
CYSZ 1400	9	14
CYSZ 1400 + 10 vol% G	19	24
CYSZ 1400 + 15 vol% G	30	33
CYSZ 1400 + 20 vol% G	38	41
CYSZ 1500	13	18
CYSZ 1500 + 10 vol% G	34	38
CYSZ 1500 + 15 vol% G	42	45
CYSZ 1500 + 20 vol% G	47	50

calcined YSZ samples, at least 30% graphite is necessary to allow gas flow, while for the 1400 °C and 1500 °C groups, a minimum 15% and 10% graphite is required, respectively. However, these porous supports have different pore sizes due to the effects of calcination temperature and graphite content. Pores formed by CYSZ 1400 and CYSZ 1500 are in the range of 1-2 μ m, while pores formed by graphite can be as large as 25 μ m. This difference in pore size distribution, as well as content and morphology may affect the impregnation process as well as fuel flow in the anode cermet and hence cell performance. This topic is the next subject of our current research.

Conclusions

The new design for the third generation of tubular SOFCs was described and the method of fabrication of YSZ porous supports coated with a thin dense electrolyte was discussed. It was found that, in order to generate high porosity YSZ support layers, it is essential to increase the graphite content and the calcination temperature of YSZ. However, increasing these parameters thickened the porous support which is undesirable. To achieve a porous support with a viable thickness, a short casting time was required, which would make the slip casting procedure difficult to handle and control. In order to achieve high porosity thin layers, lowering the solid loading of the YSZ suspension in conjunction with using plaster molds with low amounts of porosity (~33%) can significantly improve the slip casting time. Finally, it was found that multiple casting is a useful and simple technique for fabrication of monolithic tubes that consist of both a porous layer and a dense electrolyte.

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