CeO₂-Doped (Co,Mn)₃O₄ Coatings for Protecting Solid Oxide Fuel Cell Interconnect Alloys

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ABSTRACT

Reactive element-doped (Co,Mn)₃O₄ spinel is considered as the most promising coating system to protect ferritic alloys for solid oxide fuel cell interconnect application. In this paper, a CeO₂-doped (Co,Mn)₃O₄ coating was synthesized on a Crofer 22 APU alloy substrate via electrolytic codeposition of a composite layer consisting of a Co matrix and embedded Mn₃O₄/CeO₂ particles, followed by thermal conversion of the deposited layer in air at elevated temperatures. After oxidation at 800°C in air for 250 h, no Cr penetration was detected in both the CeO₂-doped and CeO₂-free spinel coatings. However, CeO₂ doping significantly reduced the Cr₂O₃ scale growth at the coating/substrate interface. An area specific resistance of 8 m² · cm² at 800°C was achieved for the CeO₂-doped coating sample, which was much lower than that of the CeO₂-free coating sample (13 m² · cm²) or the bare substrate (24 m² · cm²) at the same temperature. CeO₂ doping in the spinel coating also improved the performance stability of the anode-supported cell in contact with the alloy interconnect.

1. Introduction

(Co,Mn)₃O₄-base spinel coatings are widely perceived as the best coating system for protecting ferritic interconnect alloys (e.g. Crofer 22 APU) used in intermediate-temperature solid oxide fuel cell (SOFC) stacks, due to its high electrical conductivity, low Cr volatility, and adequate match in coefficient of thermal expansion (CTE) with adjacent cell components [1,2]. Several techniques have been investigated for applying the (Co,Mn)₃O₄ coating on the ferritic alloys, including: (1) screen printing of a spinel powder or an oxide powder mixture, followed by a treatment in a reducing environment and then a re-oxidization treatment [3,4]; (2) spray pyrolysis [5]; (3) thermal spray [6,7]; (4) physical vapor deposition (e.g. sputtering) [8]; (5) sequential electroplating of Co/Mn multilayers, electrodeposition of a Co-Mn alloy layer, or electrocodeposition of a Co-Mn₃O₄ composite layer, followed by thermal conversion [9-11]. Among them, electroplating-based technique is quite attractive, based on the consideration of processing cost, coating quality, and ability to coat the complex-shape interconnect. Furthermore, thermal conversion of the deposited layer to the spinel coating may also be accomplished *in situ* during the stack startup sintering step. Overall, this processing route offers a potentially low-cost approach for application of the (Co,Mn)₃O₄ spinel coatings onto SOFC interconnects with complex geometries and 3-D features.

Even though the (Co,Mn)₃O₄ coatings are capable of blocking Cr evaporation/migration from the ferritic interconnect alloy to the cathode, it still allows oxygen transport to the coating/alloy interface, which can cause continuous Cr₂O₃ scale growth and subsequent electrical resistance increase during long-term thermal exposure of the interconnect [2-4,12,13]. Recently, it has been reported that CeO₂, La₂O₃, or Y₂O₃ doping in the spinel coating can reduce the oxide scale growth rate and improve the scale adhesion [14-17], via the so-called “reactive element

effect” [18,19]. However, the processing techniques used for such reactive element doping are either too expensive or not directly applicable to corrugated SOFC interconnects. Due to the nature of the electrolytic codeposition, various dopants can be readily incorporated into the spinel coating, by adding the relevant metal or metal oxide particles into the plating solution and codepositing these particles into the composite layer. Upon thermal exposure in air, the composite layer can be converted to a spinel layer containing the desired dopant(s).

In this paper, the electrolytic codeposition was explored for the synthesis of both the CeO₂-free and CeO₂-doped (Co,Mn)₃O₄ coatings. Furthermore, the microstructural feature and the performance of these coatings were characterized and the effectiveness of CeO₂ doping in improving the spinel coating performance was critically assessed.

2. Experimental

2.1 Substrate and coating preparation

Crofer 22 APU coupons of 15 mm x 15 mm x 1 mm with a chemical composition of Fe-22Cr-0.45Mn-0.06La-0.1Si-0.12Al-0.08Ti (in wt.%) were used as the substrate for electrolytic codeposition. Test samples were cleaned ultrasonically in water and acetone for 5 min each. After grinding to 400-grit finish, the samples were then etched in a 10% HCl solution for 10 min for improving the adhesion of the deposited layer. After cleansing, the sample was placed vertically between two pure Co anodes which were spaced around 20 mm apart for electroplating. The aqueous plating electrolyte consisted of 300g/L CoSO₄·7H₂O, 50g/L CoCl₂·6H₂O, 15g/L boric acid (as a pH buffer) and 0.3 g/L sodium n-dodecyl sulfate (as a wetting agent). For synthesis of the Co+Mn₃O₄ composite layer, 150 g/L Mn₃O₄ powder (with an average particle size of ~2 μm, from Aldrich) was added to the solution. Additional CeO₂ powder (10 g/L, with an average particle

size of $\sim 0.5 \mu\text{m}$) was further added for synthesis of the $\text{Co}+\text{Mn}_3\text{O}_4+\text{CeO}_2$ composite layer. The plating bath was kept at room temperature and a pH value of around 4, and was agitated continuously by an impeller near the bottom of the container at a speed of 450 rpm. Electroplating was conducted at a current density of 22 mA/cm^2 for 5 min. After deposition, the samples were cleaned, and subsequently they were thermally exposed in static air at 600°C for 6 h and then at 800°C for 4 h to convert the composite layer into the spinel coating. The use of the two-stage thermal conversion procedure was to ensure the formation of a well-adherent spinel coating with a minimum amount of defects in it. The samples were weighed before and after the thermal conversion treatment and the corresponding specific mass gains were calculated.

2.2 Oxidation and electrical resistance testing

After thermal conversion, some of the coated samples were isothermally oxidized in air at 800°C for 250 h. They were weighed before and after oxidation and the specific mass gains after oxidation were obtained. Bare Crofer 22 APU substrate samples were also included in the evaluation for comparison.

Electrical resistance of the oxidized samples was measured using the 2-probe 4-point method at 800°C in air. Two of the oxidized surfaces were first covered with Pt paste over an area of 0.5 cm^2 . Two Pt meshes with two Pt leads attached to each of them were then placed on top of the Pt paste for current collection and voltage measurement. A constant current (I) of 10 mA from a power source was applied to the samples, and the corresponding voltage drop (V) was measured using a digital multimeter. A widely accepted parameter for quantifying the electrical resistance of the oxide scales, area specific resistance (ASR), was reported here. The resistance (R) was calculated according to the Ohm's law, $R=V/2I$. The factor of 2 is used to take into account the

consideration that the resistance is contributed by the oxide scales formed on the both surfaces of the sample. The ASR was then determined as R multiplied by the area covered by Pt (i.e. 0.5 cm^2).

The samples after electro-codeposition, thermal conversion, and isothermal oxidation were characterized by scanning electron microscopy (FEI Quanta 200 FEG) attached with energy dispersive spectroscopy (SEM-EDS). The crystal structures of the coatings were determined by X-ray diffraction (XRD; Rigaku Ultima IV) using $\text{Cu K}\alpha$ radiation.

2.3 In-cell testing

In order to understand how the CeO_2 -free and CeO_2 -doped spinel coatings behave in the realistic SOFC environment with simultaneous oxidation and electric current flow, channeled Crofer 22 APU interconnects were coated and tested in direct contact with the cathode of single cells. The anode-supported anode/electrolyte bilayer with a diameter of 27 mm was purchased from NexTech Materials. In this bilayer, the anode support was a mixture of Ni and yttria-stabilized zirconia (YSZ), while the electrolyte was YSZ. To form a complete single cell, a cathode consisting of a 15- μm $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ (LSM)-YSZ inner layer and a 50- μm LSM outer layer was screen printed onto the electrolyte side of the bilayer, followed by calcination at 1250°C for 2 h. The diameter and active area of the LSM cathode were 18 mm and 2.5 cm^2 , respectively.

Since the design of the channeled interconnect and the overall cell testing procedures/parameters have been reported in our previous paper [20], only some specific details are given below. The bare and electroplated interconnects were given the standard thermal conversion treatment, prior to being loaded for cell testing. The anode was fitted with an 18-mm diameter Ni mesh, Ni paste, and Pt lead wires for current collection. For the baseline testing, no alloy interconnect was attached to the cell, and the LSM cathode-side current collection was

achieved with Ag mesh/paste, which is widely employed in single cell testing. No contact mesh was applied on the cathode side for the cell testing with the bare or coated alloy interconnect. Instead, prior to the testing, the interconnect side facing the cathode was brushed with a thin layer of Pt paste to improve electrical contact and strain tolerance with the cathode. Note that rather than the typical perovskite contact materials such as $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.5}\text{Mn}_{0.5}\text{O}_3$ (LSCM) [21,22], Pt was utilized as it is more inert and does not react with other cell components/species. The power density of the cell was determined as a function of the test time at a constant cell voltage of 0.7 V. During the test, the flow rates of the fuel ($\text{H}_2+3\%\text{H}_2\text{O}$) on the anode side and the air on the cathode side were maintained at 50 and 500 mL/min, respectively.

3. Results and Discussion

3.1 Microstructures before and after thermal conversion

Figs. 1(a) and (b) show the coating surface morphology and cross-sectional view for the $\text{Co}+\text{Mn}_3\text{O}_4+\text{CeO}_2$ composite-coated samples in the as-deposited condition, respectively. The typical morphology of electroplated Co, with the addition of adsorbed Mn_3O_4 and CeO_2 particles, was observed, as indicated by the arrows in Fig. 1(a). The CeO_2 particles in Fig.1(a) were smaller and appeared slightly brighter than the Mn_3O_4 particles. During electro-codeposition, the Mn_3O_4 and CeO_2 particles became partially adsorbed and then completely embedded by the growing Co layer. From Fig.1(b), the amount of the Mn_3O_4 and CeO_2 particles in the deposited layer was quite significant. Also, since most of the CeO_2 particles were located near the Mn_3O_4 particles, it is difficult to distinguish one from another. EDS analysis of the surface of the as-deposited samples indicated a significant Mn content of 15-20 at.% and a reasonable amount of Ce of 1-2 at.%. The as-deposited coating was about 4- μm thick, and was free of spallation or cracks, Fig. 1(b). In

addition, the Mn_3O_4 particles were relatively evenly dispersed in the layer. The surface morphology and cross-sectional view of the $\text{Co}+\text{Mn}_3\text{O}_4$ composite coating without CeO_2 have been reported earlier [11].

Thermal conversion of the as-deposited $\text{Co}+\text{Mn}_3\text{O}_4$ and $\text{Co}+\text{Mn}_3\text{O}_4+\text{CeO}_2$ composite layers in static air at 600°C for 6 h and 800°C for 4 hr led to the formation of the $(\text{Co},\text{Mn})_3\text{O}_4$ -based coatings, as confirmed by the XRD analysis. The specific mass gains after the initial conversion treatment for the bare and coated samples are listed in Table I. For the bare Crofer 22 APU alloy, the mass gain was small, about $0.02 \text{ mg}/\text{cm}^2$, as a result of the initial oxidation. For the two coated samples, the mass gains were drastically higher, i.e. 0.51 and $0.48 \text{ mg}/\text{cm}^2$ for the CeO_2 -free and CeO_2 -doped $(\text{Co},\text{Mn})_3\text{O}_4$ coatings, respectively. Obviously, the incorporation of oxygen into the coatings during thermal conversion significantly increased the weight of the coated samples. During thermal conversion in air, the Co matrix was oxidized into the Co oxide, which interacted concurrently with the Mn_3O_4 particles to form the $(\text{Co},\text{Mn})_3\text{O}_4$ spinel via solid-state interdiffusion and reaction, as shown in Fig. 2. The small difference in mass gain after thermal conversion for the two coatings was likely due to the variation in initial coating thickness and possibly thickness of the Cr_2O_3 scale formed at the coating/alloy interface during the conversion treatment.

According to Fig. 2, the thickness of the converted coating was $5.1\text{-}5.3 \text{ }\mu\text{m}$, greater than that of the as-deposited ones ($\sim 4 \text{ }\mu\text{m}$), as a result of incorporation of oxygen from the environment. The main microstructural difference between the CeO_2 -free and CeO_2 -doped coating samples was the presence of white particles (indicated by the arrows) in the CeO_2 -doped coating layer in Fig. 2(b), which was identified as CeO_2 , based on the EDS analysis. Apparently, CeO_2 could not be completely dissolved into the spinel during the conversion treatment and thus remained as individual particles. Furthermore, according to the EDS results in both Fig. 2(a) and (b), the

stoichiometry of the $(\text{Co,Mn})_3\text{O}_4$ spinel varied throughout the coating thickness. The existence of a $(\text{Co,Mn})_3\text{O}_4$ spinel solid solution with a changing Co/Mn ratio is consistent with the earlier observation [23] that $\text{Mn}_{1+\delta}\text{Co}_{2-\delta}\text{O}_4$ spinels having $\delta < 0.3$ will generally form a single phase of cubic spinel structure. Furthermore, such compositional non-uniformity can be related to the relatively short duration of the thermal conversion process and subsequently incomplete interdiffusion. It should also be noted that the converted coating layer contained only isolated voids which was much smaller in size than the Mn_3O_4 particles, implying that the diffusion coefficients of the Mn and Co cations in the layer are most likely of the same order of magnitude.

3.2 Oxidation resistance and area specific electrical resistance

The specific mass gains after the 250-h isothermal oxidation for the bare Crofer 22 APU and samples with the $(\text{Co,Mn})_3\text{O}_4$ and CeO_2 -doped $(\text{Co,Mn})_3\text{O}_4$ coatings were 0.30, 0.28, and 0.20 mg/cm^2 , respectively, as shown in Table I. Fig. 3 shows the cross-sectional views of the samples after oxidation. For the bare Crofer 22 APU, a dense Cr_2O_3 scale of about 2.4 μm was formed, most likely with a very thin, non-uniform $(\text{Mn,Cr})_3\text{O}_4$ spinel layer atop it [24-26], as implied by the increase in Mn near the surface in the EDS scan, Fig. 3(a). For the $(\text{Co,Mn})_3\text{O}_4$ -coated sample, the thickness of the Cr_2O_3 scale was slightly smaller than that on the bare alloy, while with CeO_2 doping the Cr_2O_3 scale thickness was reduced to only 1.3 μm , Table I. As shown in Table I, the thickness of the outer spinel layer was almost identical, around 5.5 - 5.7 μm , which barely increased over that of the thermally-converted coatings.

According to these results, the CeO_2 -free $(\text{Co,Mn})_3\text{O}_4$ coating slightly reduced the specific mass gain compared to the bare substrate. A survey of literature data reveals some controversies regarding the effect of the $(\text{Co,Mn})_3\text{O}_4$ spinel coating on the oxidation rate of interconnect alloys. Depending on the type of substrate alloy, the treatment of substrate surface prior to coating, the

coating process, the spinel stoichiometry, and the oxidation condition, an increase [12,27], decrease [3,4,12,28-30], or no change [31] in the oxidation rate of the metallic interconnect has been reported with the spinel coating. With regard to the oxidation behavior of (Co,Mn)₃O₄-coated Crofer 22 APU, it is generally agreed that the coating reduces the oxidation rate of this alloy as the coating provides some barrier against the oxygen transport to the alloy surface, even though the degree of reduction is debatable. Yang et al. showed that for bare and coated Crofer 22 APU samples which were in touch with the contact layer and exposed to 800°C for 1000 h, the thickness of the Cr₂O₃ scale were about 4.0 and 2.0-2.5 μm, respectively [3]. The oxidation kinetics of both bare substrate and coating sample synthesized by electrophoretic deposition obeyed the parabolic law and the parabolic rate constant was reduced 1-2 orders of magnitude with the spinel coating [29]. On the other hand, Zhang et al. found that the Crofer 22 APU alloy with the electroplated Co-Mn spinel coating had the same mass gain as the bare substrate after 1400-h oxidation at 750°C [31]. The effectiveness of the coating is apparently also a function of the Mn content in the spinel. For example, for a Co₃O₄ spinel coating without the Mn addition, the reduction in oxidation rate was not significant [30]. These different results might be related to the formation kinetics of the Co-Cr spinel subscale between the Cr₂O₃ scale and the surface spinel layer [32], which has been postulated to significantly affect the oxygen diffusion to the metal-scale interface [12,13]. With the coating composition under the specific oxidation condition in this study, the CeO₂-free spinel coating can reduce the oxidation rate of the Crofer 22 APU alloy, while its effectiveness is moderate.

On the other hand, with CeO₂ doping in the spinel coating, the oxidation rate decreased significantly, with about 30% reduction in specific mass gain after the isothermal exposure, as indicated in Table 1. Correspondingly, the Cr₂O₃ scale thickness was reduced from about 2.4 μm

to only 1.3 μm . Similar results have been reported for the $(\text{Co,Mn})_3\text{O}_4$ coatings with the CeO_2 , La_2O_3 , or Y_2O_3 addition [14-16] as well as the Co_3O_4 coatings with the CeO_2 addition [30], and has been attributed to the reactive element effect. It should be noted that the white particles indicated by the arrows in Fig. 3(c) were again CeO_2 . Obviously, the solubility of CeO_2 in the spinel is limited, as has been reported earlier [14,30]. From the EDS line scans in Fig. 3, no detectable chromium penetrated through the spinel layer after the 250-h oxidation for the two coated samples. Also, the Mn concentration gradient was greatly decreased compared to the thermally-converted coatings, due to the additional interdiffusion of Mn and Co cations in the coatings during the extended exposure at 800°C. From Fig. 3, it can also be seen that there were some voids in the oxidized coating layer, the size of which was considerably larger than those in the as-converted coatings shown in Fig. 2. This is a result of the void coalescence during the thermal exposure to reduce the overall surface energy associated with the voids as well as additional void formation due to further interdiffusion within the coating and between the coating/substrate. It should be noted that such voids are typically observed in the thermally-converted spinel coatings, and they are not detrimental to the coating protectiveness as long as they are not interconnected.

The measured ASR values at 800°C in air for these oxidized samples are also listed in Table I. The ASR includes the resistances of the coating and the Cr_2O_3 scale as well as the contact resistance between the surface oxide and the Pt electrode. At 800°C, the bare substrate had a moderate scale ASR of $24 \text{ m}\Omega\cdot\text{cm}^2$, while the $(\text{Co,Mn})_3\text{O}_4$ coated sample had a much lower ASR of $13 \text{ m}\Omega\cdot\text{cm}^2$, which likely was due to the reduction in contact resistance with the presence of the highly-conductive spinel layer [33]. Moreover, with the addition of CeO_2 in the spinel layer, the ASR of the oxide scale was further reduced to $8 \text{ m}\Omega\cdot\text{cm}^2$, which is among the lowest values of

ASR reported for SOFC interconnect coatings on Cr_2O_3 -forming alloys [24-26,33-36]. The significant reduction in ASR with the CeO_2 -doped coating could be attributed to the smaller thickness of the Cr_2O_3 layer, which is much more electrically resistive than the spinel.

3.3 In-cell performance stability

In-cell testing results shown in Fig. 4 further confirmed the superior performance of the CeO_2 -doped $(\text{Co,Mn})_3\text{O}_4$ spinel coating in protecting the ferritic interconnect alloy. The baseline data was obtained from a cell without any alloy interconnect placed on the cathode side. The baseline cell performance increased initially (the so-called “burn-in” period [10,20,37]). Such “burn-in” behavior could be related to the LSM cathode material and possible migration/deposition of noble metal paste into the cathode. Afterwards, the cell performance was reasonably stable. The cell with the bare Crofer 22 APU attached to it, on the other hand, exhibited a continuous and significant drop in the **cell power density**, due to Cr transport and subsequent cathode poisoning as well as the electrical resistance increase with continuous oxidation of the interconnect alloy. Such drop in **power density** was not observed for the cell in contact with the interconnect coated with the CeO_2 -free or CeO_2 -doped spinel, as both coatings eliminated the Cr evaporation from the alloy substrate. Furthermore, the cell in contact with the CeO_2 -doped spinel coated interconnect achieved a **more stable power output** during the 250-h cell operation, compared to that in contact with the CeO_2 -free spinel coating. The addition of CeO_2 in the coating further slowed down the Cr_2O_3 scale growth, resulting in less electrical resistance increase and therefore more stable **cell power output**.

4. Conclusions

The electro-codeposition technique was successfully utilized to synthesize the CeO₂-doped (Co,Mn)₃O₄ spinel layer for SOFC interconnect coating application. CeO₂ doping was achieved by electrolytically codepositing a composite layer of Co+Mn₃O₄+CeO₂ onto the alloy substrate and subsequently thermally converting this layer into the CeO₂-doped spinel coating. While both the CeO₂-free and CeO₂-doped spinel coatings were effective in blocking the Cr diffusion/migration after oxidation at 800°C in air for 250 h, CeO₂ doping significantly reduced the Cr₂O₃ scale growth. An area specific resistance of 8 m · cm² at 800°C was achieved for the CeO₂-doped coating sample after oxidation, which was much lower than that of the CeO₂-free coating sample or the bare substrate. CeO₂ doping in the spinel coating also improved the cell performance stability.

Acknowledgement

This research was financially supported by the National Science Foundation under Grant #CMMI-1362680. Additional support was provided by the Center for Manufacturing Research, Tennessee Technological University.

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Figure Captions:

Fig. 1 Surface morphology (a) and cross-sectional view (b) of a $\text{Co}+\text{Mn}_3\text{O}_4+\text{CeO}_2$ coating on Crofer 22 APU in the as-deposited condition. The Mn_3O_4 particles were indicated by the arrows in these figures. The CeO_2 particles, as also pointed by the arrows, appeared slightly brighter than the Mn_3O_4 particles in Fig. 1(a).

Fig. 2 Cross-sectional view with EDS line scan overlaid on the image of the samples after thermal conversion: (a) with the $(\text{Co},\text{Mn})_3\text{O}_4$ coating and (b) with the CeO_2 -doped $(\text{Co},\text{Mn})_3\text{O}_4$ coating. The CeO_2 particles are pointed by the arrows in Fig. 2(b).

Fig. 3 Cross-sectional view with EDS line scan overlaid on the image of the samples after isothermal oxidation in air at 800°C for 250 h: (a) bare Crofer 22 APU; (b) with the $(\text{Co},\text{Mn})_3\text{O}_4$ coating; and (c) with the CeO_2 -doped $(\text{Co},\text{Mn})_3\text{O}_4$ coating.

Fig. 4 Performance stability of the anode-supported cells at 800°C at a constant voltage output of 0.7 V: (a) with no interconnect placed on the cathode side (baseline); (b) with the bare Crofer 22 APU interconnect; (c) with the $(\text{Co},\text{Mn})_3\text{O}_4$ -coated interconnect and (d) with the CeO_2 -doped $(\text{Co},\text{Mn})_3\text{O}_4$ -coated interconnect. The flow rates of the fuel ($\text{H}_2+3\%\text{H}_2\text{O}$) on the anode side and the air on the cathode side were 50 and 500 mL/min, respectively.

Table I Specific mass gain, thickness of the oxide layers formed on the alloy surface, and oxide scale ASR at 800°C after isothermal oxidation in air at 800°C for 250 h for the bare and coated samples. Specific mass gain after the thermal conversion treatment for each sample was also included for comparison.

Coating/Alloy	Specific Mass Gain (mg/cm ²) after Conversion	Specific Mass Gain (mg/cm ²) after oxidation	Layer Thickness (μm)		ASR at 800°C (mΩ·cm ²)
			Spinel	Cr ₂ O ₃	
Bare Crofer 22 APU	0.02	0.30	Thin (Mn,Cr) ₃ O ₄	2.4	24
(Co,Mn) ₃ O ₄	0.51	0.28	5.7	2.2	13
CeO ₂ -doped (Co,Mn) ₃ O ₄	0.48	0.20	5.5	1.3	8

Fig. 1 Surface morphology (a) and cross-sectional view (b) of a $\text{Co}+\text{Mn}_3\text{O}_4+\text{CeO}_2$ coating on Crofer 22 APU in the as-deposited condition. The Mn_3O_4 particles were indicated by the arrows in these figures. The CeO_2 particles, as also pointed by the arrows, appeared slightly brighter than the Mn_3O_4 particles in Fig. 1(a).

Fig. 2 Cross-sectional view with EDS line scan overlaid on the image of the samples after thermal conversion: (a) with the (Co,Mn)₃O₄ coating and (b) with the CeO₂-doped (Co,Mn)₃O₄ coating. The CeO₂ particles are pointed by the arrows in Fig. 2(b).

Fig. 3 Cross-sectional view with EDS line scan overlaid on the image of the samples after isothermal oxidation in air at 800°C for 250 h: (a) bare Crofer 22 APU; (b) with the (Co,Mn)₃O₄ coating; and (c) with the CeO₂-doped (Co,Mn)₃O₄ coating.

Fig. 4 Performance stability of the anode-supported cells at 800°C at a constant voltage output of 0.7 V: (a) with no interconnect placed on the cathode side (baseline); (b) with the bare Crofer 22 APU interconnect; (c) with the (Co,Mn)₃O₄-coated interconnect and (d) with the CeO₂-doped (Co,Mn)₃O₄-coated interconnect. The flow rates of the fuel (H₂+3%H₂O) on the anode side and the air on the cathode side were 50 and 500 mL/min, respectively.