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A strategy to reduce the impact of tar on a Ni-YSZ anode of solid oxide fuel cells

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Summary

High-temperature raw coke oven gas (COG) is a promising fuel for use in solid oxide fuel cells (SOFCs) because it is rich in both hydrogen (55%-60%) and methane (23%-27%). However, the tar present in COG limits its ability to directly generate power using state-of-art SOFCs because the presence of tar limits the cell's performance and stability. In this work, a strategy is presented in the attempt to reduce the influence of tar on SOFCs by applying a $La_{0.7}Sr_{0.3}MnO_3$ catalyst as a protective layer for the cell. The results showed that 44-g Nm⁻³ toluene had a profoundly negative effect on the performance of a conventional cell, which showed severely reduced performance after only 1.4 hours of exposure to toluene-contaminated hydrogen. In contrast, the catalyst-modified cell showed good stability for at least 110 hours under the same conditions. This work provides a promising route to directly utilize raw COG as an SOFC fuel that is also suitable for biosyngas.

KEYWORDS

coke oven gas (COG), coking resistance, independent catalyst layer, solid oxide fuel cell (SOFC), toluene



1 | INTRODUCTION

Coke production results in the emission of coke oven gas (COG), a mixture of H₂, CH₄, and a small amount of unsaturated hydrocarbons. For every 500 million tons of coke that are produced, 210 billion cubic metres of COG are released as a by-product.¹ Since COG is rich in H₂ and CH₄, it is a promising fuel with a specific heat in the range of 16 720 to 18 810 kJ m⁻³. In the past, COG was often used as a civil gas as a heat source after undergoing a series of cooling and purification processes, such as spraying with an ammonia solution to remove tar. However, during the raw COG cooling process, a large amount of thermal energy is dissipated, which is a huge waste of energy. In recent years, with the exploitation of natural gas, the use of COG as a civil gas has been replaced by natural gas. Therefore, from the viewpoint of environmental issues and energy resources, a new approach to cleanly and efficiently use COG must be identified.

A solid oxide fuel cell (SOFC) is a clean power generation system that has a high efficiency because it directly converts the chemical energy of fuels into electricity. Fuel flexibility is an important advantage of SOFC, and theoretically, any substance that can be oxidized, such as solid carbon,² ammonia,³ carbon monoxide,^{4,5} ethanol,^{6,7} or other hydrocarbons,⁸⁻¹⁰ can be used as a fuel in an SOFC. A high-temperature SOFC (HT-SOFC; higher than 800°C) can directly generate electricity using a high-temperature raw COG after the initial dust removal. However, contaminants such as tar, H₂S, and other hydrocarbons are harmful to the Ni cermet anode of state-of-art SOFCs, and this contamination mainly occurs via carbon deposition and sulfur poisoning.¹¹⁻¹³ Papurello et al¹⁴ reported that tar has a more serious influence on performance than H₂S. Currently, while it is well known that SOFCs severely degrade when fed with tar-contaminated fuels, there is still no feasible way to reduce the influence of tar without changing the SOFC operating conditions, such as high temperature¹⁵ and a high current load.¹¹ Pumiglia et al¹³ observed an aggravated influence of tar on an intermediate-temperature SOFC (IT-SOFC; lower than 800°C). Some extra measures must be taken to remove the influence of tars when developing IT-SOFCs, which helps to reduce the cost and improve the long-term cell performance and reliability.

Tar is a mixture of various aromatic hydrocarbons. When tar-containing fuels are fed into SOFCs that contain a Ni cermet anode, severe carbon deposition occurs via a series of complex chemical reactions, which includes cracking of hydrocarbons (Equation 1) and CO disproportionation (reverse Boudouard reaction, Equation 2). When the cell is running, H_2O and CO_2 are produced from the electrooxidation of fuels (Equations 3)

Novelty Statement

- 1. This paper investigates the effect of 44-g Nm⁻³ (1.07 × 10⁵ ppmv) toluene as a tar model on the performance of solid oxide fuel cell (SOFC) with Ni-based anodes.
- 2. A strategy of reducing the impact of tar on SOFC performance is introduced.
- 3. La_{0.7}Sr_{0.3}MnO₃ (LSM) is applied to the cell as a catalytic layer for toluene oxidation.

and 4), which is beneficial for the internal reforming of hydrocarbons through steam reforming (Equation 5) or dry reforming (Equation 6). These products may interact mutually and generate carbon in various ways.¹⁶

$$C_m H_n \to mC + \frac{n}{2} H_2 \tag{1}$$

$$2CO \rightarrow C + CO_2 \tag{2}$$

$$H_2 + O^{2-} \rightarrow H_2 O + 2e \tag{3}$$

$$CO + O^{2-} \rightarrow CO_2 + 2e \tag{4}$$

$$C_m H_n + m H_2 O \rightarrow m CO + \left(m + \frac{n}{2}\right) H_2$$
 (5)

$$C_m H_n + mCO_2 \rightarrow 2mCO + \frac{n}{2}H_2 \tag{6}$$

The influence of tars on SOFCs has been investigated both theoretically and experimentally,^{11,15} and the research indicates that the degree of carbon deposition is strongly affected by the type and the concentration of tar species,¹⁷⁻²⁰ SOFC operating conditions, and anode materials. Coll et al¹⁷ and Lorente et al^{18,19} reported that lighter tars have a greater tendency to undergo coking than heavier tars and to model this, benzene and toluene have been used as tar models, which have higher carbon deposition than real tars. Therefore, low-molecular-weight tars have been used as representative tars because of their tendency to form carbon deposits.¹⁸ In an experimental study that investigated the impact of tar on SOFC performance, one or several light aromatic compounds including benzene,¹¹ naphthalene,²⁰ and toluene^{13,21} were used as tar models. Anode materials have also been proven to be a key factor to induce carbon deposition. Liu et al²² reported that carbon formation occurred on a Ni-yttria-stabilized zirconia (YSZ) anode when using a biosyngas with a tar content of 6.3 g Nm⁻³. Ni-gadolinium-doped ceria (GDC) WILEY-ENERGY RESEARCH

displayed an improved resistance to carbon deposition when compared with Ni-YSZ, which was attributed to the presence of lattice oxygen in Ce.²³⁻²⁵ Hofmann et al²⁴ observed no C deposits on a Ni-GDC anode when more than 10-g Nm^{-3} tar-contaminated biomass gas was used. Carbon deposition also depends on the operating conditions, and Singh et al¹⁵ and Mermelstein et al¹¹ demonstrated that a high current load, high steam content, and high temperature are favourable for reducing coking through a thermodynamic analysis of a syngas that contained toluene, naphthalene, phenol, and pyrene. Tars, which are mixtures of hydrocarbon complexes, also contain a large amount of chemical energy, as shown by the work of Wu et al,²⁶ which showed that 1.243×10^5 ppmv toluene-containing N₂ can generate an output of 14 mW cm⁻² at 650°C. However, carbon deposition also occurs, which then needs to be removed by blowing oxygen on the anode. As reported from both experimental data and theoretical calculations, a high current load and high O/C ratio is beneficial for coking resistance when feeding cells with tar-contaminated fuels. A common feature between the two methods is the need for oxygen. Tar can usually be completely oxidized^{27,28} into CO₂ or be selectively oxidized into other organic compounds, such as formaldehyde or benzoic acid in the liquid phase.²⁹ A review by Doornkamp and Ponec³⁰ concluded that when some organic compounds are catalytically oxidized by transition metal oxides, the lattice oxygen plays an important role in product formation by promoting the activation of oxygen species and a redox reaction, which is called the "MvK mechanism." Liu indicated that the oxidation of toluene by transition metal oxide catalysts also follows the MvK mechanism.31

Researchers have developed a large number of approaches to reduce the amount of carbon deposition produced from hydrocarbon fuels, which are generally classified into four categories: forming alloys with Ni,³²⁻³⁴ developing new Ni-free metals,^{35,36} modifying the surface of Ni with oxides,³⁷⁻³⁹ and applying a catalyst layer in the anode area.^{35,36} Previous work has indicated that application of a catalyst layer that is catalytically active towards fuel conversion is an effective way to inhibit carbon deposition.⁴⁰ In this paper, using 44-g Nm⁻³ (1.07 × 10⁵ ppmv) toluene as a tar model, the influence of tar on the performance of the state-of-art SOFC is studied. Here, a strategy to reduce the influence of tar is proposed, where La_{0.7}Sr_{0.3}MnO₃ (LSM) is applied as an anodic catalyst layer to pre-oxidize toluene. LSM has been used as a synergistic catalyst for toluene oxidation because manganese oxides have been shown to be good catalysts for toluene oxidization, and lanthanum oxides were reported as good additives. Zhang et al⁴¹ reported that LaMnO₃ had good catalytic behaviour for the oxidation

of toluene. Partially replacing La with Sr produces many oxygen vacancies in LaMnO₃, which can facilitate the adsorption of oxygen and oxidation of the toluene via the MvK mechanism.

2 | EXPERIMENTAL SECTION

2.1 | Powders

NiO, YSZ, polyvinyl butyral (PVB), and graphite were commercially available products. LSM and $Ba_{0.5}Sr_{0.5}$ $Co_{0.8}Fe_{0.2}O_3$ (BSCF) powders were synthesized by a method involving a combined ethylenediaminetetraacetic acid (EDTA)–citric acid (CA) complex.⁴⁰ Sm_{0.2}Ce_{0.8}O_{1.9} (SDC) powders were prepared via a hydrothermal process.⁴² The structures of as-sintered and in situ-reduced LSM were analysed by X-ray diffraction (XRD).

2.2 | The preparation and characterization of a double-layered catalyst slice

LSM samples were copressed with the Al_2O_3 substrate to form a double-layered slice in a detailed procedure described as follows. A 0.2-g substrate powder (a uniform mixture of Al_2O_3 , PVB, and graphite at a mass ratio of 40:6:3) was pressed at 144 MPa in a steel mould (13-mm diameter). Then a 0.04-g catalyst powder (a mixture of LSM, PVB, and graphite at a mass ratio of 24:5:2) was covered over the substrate for a second pressing at 240 MPa and heat-treated at 900°C for 4 hours.

Pore properties of the catalyst slice were tested using N2 adsorption/desorption isothermal experiments at - -196 °C after degassing for 24 hours. A Micromeritics ASAP-2460 M automated pore size distribution and surface area analyser (Micromeritics, USA) was used to obtain the specific surface area and the pore size distributions, which were analyzedanalysed using the multiple-point Brunauer-Emmett-Teller (BET) method and the Barrett-Joyner-Halenda (BJH) method, respectively.

2.3 | Cell fabrication

The anode-supported cell was fabricated by first ball milling the NiO, YSZ, PVB, and graphite (at a weight ratio of 30:20:5:3) in ethanol at 400 rpm for 1 hour. After evaporation, 0.43 g of this anode powder was placed into a steel mould and then pressed at 100 MPa. YSZ (0.21 g) powder was sprayed onto the anode surface to form an electrolyte layer by copressing it at 180 MPa. The bilayered half-cell was coheated at 1400°C for 5 hours, and then a thin-film SDC buffer layer was deposited onto the YSZ electrolyte layer via a wet powder spraying technique. Next, the cathode BSCF-SDC (at a mass ratio of 7:3) was spray-coated onto the SDC layer, followed by cofiring at 900°C for 2 hours to obtain a cathode with an effective area of 0.48 cm². The catalyst slice and cell were attached in sequence on the top of the quartz test tube using silver paste with the catalyst layer on the anode side.

2.4 | Experimental set-up and reactor

Toluene vapour was introduced into H_2 by bubbling. The vapour pressure of toluene P_{Tol} (mm Hg) at a given temperature was calculated using the Antoine equation, which is as following formulas 7 and 8.^{1,26} Mass concentration of toluene vapour M_{Tol} (g Nm⁻³) was obtained from volume fraction of toluene $\nu\%$ (formula 9).

$$\log_{10}^{P_{Tol}} = A - \frac{B}{t+C},\tag{7}$$

$$\nu\% = \frac{P_{Tol}^*}{P},\tag{8}$$

$$M_{Tol} = \nu\% \times \frac{92}{22.4}.$$
 (9)

Here, *P* represents the vapour pressure of the hydrogen generator, *t* represents the temperature, and *A*, *B*, and *C* are the Antoine coefficients specific to toluene, corresponding to 6.95 464, 1341.8, and 219.482, respectively. A H₂ stream

with a constant flow rate (80 mL min⁻¹) was bubbled in sequence through distilled water and liquid toluene at room temperature to obtain 44 g Nm⁻³ (1.07×10^5 ppmv) toluene-contaminated H₂ fuel for the wet conditions used in this study.

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The cell was packed in a high-temperature furnace and heated to the required temperature at a heating rate of 5°C min⁻¹. Two H₂ streams (with and without tar contaminant) were individually bubbled through water into the cell in which the H₂O content was about 3% estimated by saturated vapour pressure at room temperature. The test temperatures ranged from 800°C to 600°C at 50°C intervals using the ambient air as the cathode gas. Prior to tests, the cell was reduced in situ for at least 2 hours at 700°C until the open circuit voltage (OCV) value stabilized.

An Ivium electrochemical workstation was used to obtain the electrochemical performances, and electrochemical impedance spectroscopy (EIS) at OCV were tested from 10^6 to 0.1 Hz with an amplitude of 10 mV.

3 | RESULTS AND DISCUSSION

3.1 | Physical characterization of catalysts

The LSM catalysts were synthesized by a sol-gel method and were calcined at 1100°C for 2 hours in an ambient air atmosphere. XRD patterns indicated a typical perovskite structure for the sintered LSM (Figure 1), which agrees with results from a reported paper.⁴³ LSM has an average particle size of 27 nm that was calculated based on the half width of the 2 θ peak at 32.64° using the Scherrer equation. In addition, the structure of the in



FIGURE 1 X-ray patterns of as-sintered and in situ-reduced La_{0.7}Sr_{0.3}MnO₃ (LSM)

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situ-reduced catalyst was explored because an anode catalyst for fuel conversion will be located in a reducing atmosphere. Experiments indicated that treating the LSM powder in hydrogen for 2 hours at 800°C caused the collapse of the perovskite structure, and LSM was indexed to $Sr_{1.5}La_{0.5}MnO_4$ (PDF: 83-1898), Mn_2O_3 (PDF: 24-0508), and LaMnO_{3.26} (PDF: 50-0299). Manganese oxides and LaMnO₃ have been shown to be good catalysts for toluene oxidization.^{27,28,41,44} Oxygen vacancies produced by replacing La with Sr facilitates the adsorption of oxygen and the oxidation of toluene. Therefore, LSM is expected to be active for toluene oxidation under typical SOFC operating conditions.

3.2 | Characterization of LSM-modified cell

The test set-up and the microstructures of the cells are shown in Figure 2. The porous catalyst slice is separated from the cell by a 110- μ m substrate layer and an 80- μ m catalyst layer, in order to prevent cell damage because of the different thermal expansion coefficients of the cell materials and catalyst. A densified electrolyte bilayer with thicknesses of 13.6- μ m YSZ, 1.15- μ m SDC, and 10- μ m BSCF was observed.

To ensure that the fuel gas reaches the anode, the catalyst layer must be porous, and there is a strong correlation between catalytic activity and pore properties. The pore properties of the as-prepared and the reduced LSM catalyst layers were investigated using N_2 adsorption/desorption (Table 1), which showed that the catalyst layers had similar pore properties. Compared with the as-prepared samples, the reduced samples had slightly smaller surface areas, while the average pore size was slightly larger, with no clear change in the pore volume. A typical type H3 hysteresis loop indicated a mesoporous structure with seam-type nanopores whose average pore size was approximately 13.4 nm.

3.3 | Electrochemical performance

3.3.1 | Conventional cell with a Ni-YSZ anode fed with 44-g Nm^{-3} toluene-contaminated wet H_2 fuel

The influence of toluene on the electrochemical performance of SOFC was investigated using 44 -g Nm⁻³ toluene-contaminated H₂ and excluding the influence of other carbonaceous species. Figure 3A and 3B shows the I-V(P) performance and EIS of cells operated on clean wet H₂ and toluene-contaminated H₂ at 800°C, respectively. The presence of toluene significantly reduced the



(B)



FIGURE 2 A, Illustration of the fuel cell test set-up. B, The crosssectional microstructures of the yttria-stabilized zirconia (YSZ)– $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC) electrolyte bilayer and the $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_3$ (BSCF) cathode layer [Colour figure can be viewed at wileyonlinelibrary.com]

electrochemical performance of the cell, as shown by the decrease in the peak power density (PPD) from 1.251 to 0.996 W cm⁻². The cell fed with clean H₂ had an OCV of 1.05 V, which is near a theoretical Nernst potential, indicating the presence of a dense electrolyte layer. When toluene is added, the OCV showed a slight increase of 0.05 V, which is consistent with other reports that have investigated hydrocarbon fuels.⁴⁰ Cell polarization involves the activation polarization of the electrode, ohmic polarization, and concentration difference polarization from mass transfer. Activation polarization of the electrode is used to overcome the electrochemical potential barrier, which is reflected with low current densities.

TABLE 1 Pore properties of the catalyst before and after reduction

	Specific Surface Area, m ² g ⁻¹	Pore Volume, cm ³ g ⁻¹	Average Pore Size, nm
As-prepared LSM	59.5	0.19	12.6
Reduced LSM	54.1	0.18	13.4

Abbreviation: LSM, La_{0.7}Sr_{0.3}MnO₃.



FIGURE 3 The comparison of A, I-V(P) curves and B, electrochemical impedance spectroscopies (EIS) of cells fed with clean and toluene-contaminated H_2 at 800°C [Colour figure can be viewed at wileyonlinelibrary.com]

In this work, the activation polarization from the cathode was identical because the cathode material was the same, which meant that the change in the activation polarization came mainly from the anode. The slope of the voltage drop reflects the resistance, with a larger slope indicating a higher resistance.⁸ Accordingly, the slope of the voltage drops of the two cells at lower current

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densities was calculated from Figure 3A. The slope values for the two cells fed with toluene-contaminated H₂ and clean H₂ were 0.57 and 0.42, respectively. These values indicate that toluene addition increases the resistance of the anode activation, which corresponds to the higher activation energy of toluene compared with H₂. The EIS at OCV in Figure 3B shows similar resistance between the cells before and after toluene contamination (0.12 Ω cm²) $(R_{o} \text{ is the high-frequency x-axis intercept of the curve}).$ However, the polarization impedance, $R_{\rm p}$, which is the x-axis intercept difference of the curve, was significantly influenced by toluene. The polarization resistance value increased from 0.31 to more than 0.8 Ω cm², and the large change in the low-frequency resistance (for example, 100, 10, and 1 Hz) reveals that toluene has a negative effect on mass transfer.¹³ The up-trending line of the EIS at low frequencies clearly indicates a diffusion-



FIGURE 4 The comparison of (A) I-V(P) curves and (B) electrochemical impedance spectroscopies (EIS) of $La_{0.7}Sr_{0.3}MnO_3$ (LSM)//Ni-yttria-stabilized zirconia (YSZ) fed with clean wet H₂ and 44-g Nm⁻³ toluene-contaminated H₂ at 800°C [Colour figure can be viewed at wileyonlinelibrary.com]

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controlled electrode process, which is related to gas diffusion, adsorption, and dissociation. Papurello et al reported that toluene had a greater influence on the low-frequency resistance, which is related to fuel diffusion at the anode. They explained this observation by noting that the number of active sites on the anode decreased due to carbon deposition and the adsorption/desorption of toluene on the active sites.^{14,45}

3.3.2 | Catalyst-modified cells with a Ni-YSZ anode fed with 44-g Nm^{-3} toluene-contaminated wet H_2 fuel

Carbon deposition caused by toluene has been shown to have a negative influence on cell performance, so the LSM catalyst was loaded onto the Ni-YSZ anode to reform/oxidize toluene into less coking-prone intermediates. Electrochemical performances were tested for the catalyst-modified cell (named as LSM//Ni-YSZ), which was fed with clean wet H_2 and 44-g Nm^{-3} toluenecontaminated wet H_2 fuel. The corresponding I-V(P) curves and EIS at 800°C are shown in Figure 4, which show that the addition of toluene caused a decrease in the cell performances of LSM//Ni-YSZ because of the influence of toluene. Despite this decrease, the cell showed an improved performance compared with the blank cell (Ni-YSZ) with the LSM//Ni-YSZ displaying a PPD of 1.127 W cm⁻², which was higher than that of the Ni-YSZ with 0.996 W cm^{-2} (Figure 3A). This shows that application of LSM can be used to reduce the negative impact of toluene. When the fuel gas is changed from



FIGURE 5 Time-dependent voltage of $La_{0.7}Sr_{0.3}MnO_3$ (LSM)// Ni-yttria-stabilized zirconia (YSZ) and Ni-YSZ at a constant current of 300 mA at 800°C using 44-g Nm⁻³ toluene-contaminated wet H₂ fuel [Colour figure can be viewed at wileyonlinelibrary.com]







FIGURE 6 Scanning electron microscopy (SEM) micrographs of the Ni-YSZ anode surface from the top view: A, a freshly prepared anode; B, post-mortem morphology of the anode of Ni-yttria-stabilized zirconia (YSZ); and C, post-mortem morphology of the anode of La_{0.7}Sr_{0.3}MnO₃ (LSM)//Ni-YSZ. Energy-dispersive X-ray (EDX) analysis of the anode surface is given

clean wet H_2 to toluene-contaminated wet H_2 , an increase in the total resistance of the LSM//Ni-YSZ was observed, especially the polarization resistance. Compared with the blank Ni-YSZ cell fuelled with toluene-contaminated wet H_2 , the LSM//Ni-YSZ cell exhibited a much lower capacitive character and lower polarization resistance. The EIS also revealed an up-trending line at frequencies lower than 1 Hz, indicating a large diffusion resistance, which indicates that, while the application of the catalyst reduces the influence of toluene, it cannot completely eliminate it.

3.4 | Discharge stability in a galvanostatic mode when feeding the cell with 44-g $\rm Nm^{-3}$ toluene-contaminated wet $\rm H_2$ fuel

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Using 44-g Nm^{-3} toluene-contaminated wet H₂ fuel, the discharge stability in a galvanostatic mode was tested for LSM//Ni-YSZ and Ni-YSZ cells (Figure 5). The cell voltage as a function of time was recorded at constant current of 300 mA at 800°C. The LSM//Ni-YSZ cell showed relatively stable operation over a period of approximately 110 hours with only a slight degradation



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in voltage. The average amplitude of the voltage drop for LSM//Ni-YSZ was 0.052 mV h⁻¹, while Ni-YSZ showed a cell voltage drop from 0.8 to 0 V in 1.4 hours, which is likely due to rapid coking on the Ni-YSZ anode.²⁴ These results indicate that application of the LSM improves the coking resistance and cell stability.

3.5 | Post-mortem microstructural characterization of cells

Pre-mortem and post-mortem morphologies were tested for Ni-YSZ and LSM//Ni-YSZ to verify that the improvement in the coking resistance was caused by the LSM catalyst layer. Figure 6A shows the porous morphology of a fresh in situ-reduced anode surface. After being exposed to toluene-contaminated H₂ for 1.4 hours, the anode morphology of Ni-YSZ (Figure 6B) shows the presence of a large amount of flocculent species. The anode surface morphology of LSM//Ni-YSZ exhibited sintering to some extent with fewer pores. Figure 7 shows the surface morphologies of the LSM catalysts before and after the aging test in toluene-contaminated H₂ fuel, and the surface showed some sintering with a coarsening particle size.

The energy-dispersive X-ray (EDX) analysis was performed on both the anode surfaces and catalyst surfaces to provide information about carbon deposition. As seen in Figure 6B, the carbon content of the Ni-YSZ anode surface without the catalyst reached 89.66 at% after the aging test, which is in agreement with the flocculation observed on the surface. The carbon content of the anode surface for LSM//Ni-YSZ greatly decreased and had a mean value of 11.72 at% (Figure 6C), while the carbon content of the fresh anode surface was determined to be approximately 13.97 at% (Figure 6A), which is likely due to the presence of residual carbon from pore maker or pollution. Similarly, the carbon content of the catalyst surface after the aging test was nearly identical to that of a fresh surface (Figure 7). Combined, these results show that application of the LSM catalyst greatly reduces the influence of toluene and improves the coking resistance of Ni-based anodes.

4 | CONCLUSION

In this work, the influence of a model tar compound (toluene) on the performance of SOFCs containing a Ni-YSZ anode is experimentally explored. The results indicated that 44-g Nm^{-3} toluene caused a rapid decrease in the performance of the SOFC, along with an increase in the polarization resistance. A strategy to reduce the influence of tar is suggested by loading a protective and catalytic layer of a perovskite complex, LSM, on the anode to reform/oxidize toluene into less coking-prone intermediates. The results demonstrate that applying the catalyst to the anode reduces the influence of toluene on the cell performance under identical conditions. Aging tests in a galvanostatic mode indicated that application of the LSM greatly improved the stability of an SOFC and allowed it to operate for more than 110 hours with 44-g Nm⁻³ toluene-contaminated H₂. The cell without the catalyst layer severely degraded after 1.4 hours under the same conditions because of the severe carbon deposition, which was shown by scanning electron microscopy (SEM) and EDX. Post-mortem microstructural analysis demonstrated no obvious carbon deposition on either the catalyst surface or the anode surface of the catalystmodified cell.

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