



Metal-supported solid oxide fuel cell mini-stack with single *in situ* firing at 950 °C[☆]

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ABSTRACT

Metal-supported solid oxide fuel cells (MS-SOFCs) are the most promising type of fuel cells for intermediate temperature range (500 °C – 700 °C) due to their mechanical robustness, high power density and low demand for expensive materials. Nevertheless, fabrication of MS-SOFCs is intrinsically difficult due to necessity to obtain consolidated ceramic and composite layers on the easily oxidizable metal substrate, which often leads to long and multi-stage high temperature firing when using controlled atmosphere firing or to low conductivity when using air firing. This study demonstrated fabrication route, utilizing combination of dry powder deposition method (Aerosol deposition) and magnetron sputtering method, for stacks of MS-SOFCs with single *in situ* firing of all membrane electrode assemblies (MEAs) at 950 °C. The temperature cycling of the stack was conducted with the maximum heating rate 500 °C/hour.

1. Introduction

A solid oxide fuel cell (SOFC) is an electrochemical device that directly converts chemical energy of fuels, such as hydrogen, syngas, methane, etc., into electrical energy [1,2]. As electrical energy generation through electrochemical reactions does not include the necessary step of generating heat energy, it is physically more efficient than electrical energy generation by heat engines [3].

Any SOFC consists of an anode, a cathode, an ion-conducting membrane, and a support. The support is a part that provides mechanical integrity of SOFCs. Using metal supports instead of conventional ceramics promises better mechanical robustness and heat management of SOFC stacks [4–6]. The important property of metal-supported solid oxide fuel cells (MS-SOFCs) is the feasibility of providing sealing of the stacks by welding, which ensures the gas-separation between anode and cathode chambers without high-temperature exposure that is needed when using ceramic-glass sealants. Moreover, the metal weld is much more tolerable to rapid thermal cycles in comparison to ceramic-glass sealants [7].

Nevertheless, MS-SOFCs are associated with complicated fabrication

routes. The porous metal support is undesired to be subjected to high temperatures (≥ 600 °C) in air due to the active formation of oxides [8], therefore high-temperature processing of an anode layer better to be conducted in a low-oxygen environment (4 % hydrogen, vacuum, etc). At the same time, cathode consolidation needs to be conducted in air, as reducing environment leads to partial decomposition of cathodes [9]. Sintering in a low-oxygen environment and at high temperatures (> 1100 °C) leads to nickel oxide reduction and severe nickel coarsening in the anode layer, which can be detrimental to the electrochemical properties of the anode [9,10]. Moreover, the sintering of Ni-based anodes on stainless steel at high temperatures leads to interdiffusion of Ni, Cr, and Fe between the anode and the support, which impairs the performance of the anode layer [8,11]. These requirements lead to complicated and long firing routes that often include a combination of firing in air and in a reducing atmosphere. Therefore, the most optimal way of firing MS-SOFCs would be single *in situ* firing of assembled stacks in a hot box of a SOFC power generation unit where anodes and porous metal substrates can be in reducing or neutral atmosphere and cathodes in air.

There are some proven routes for fabrication of MS-SOFCs. A

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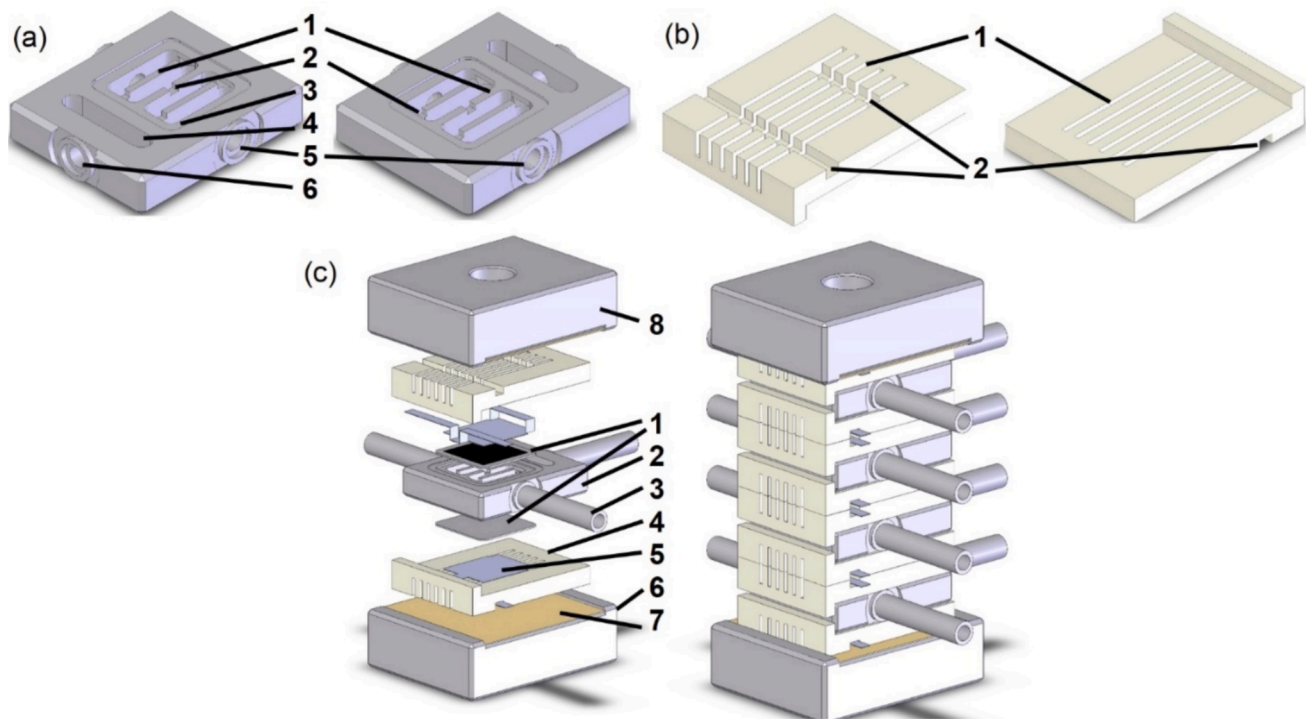


Fig. 1. (a) 3-D geometric models of the monopolar plates of the stack. 1 – current-collecting ribs, 2 – fuel distribution channels, 3 – area for welding of the metal substrate, 4 – main air distribution channels, 5 – opening for gas supply and gas exhaust pipes, 6 – opening for welding of air supply pipe; (b) 3-D geometric models of the alumina plates. 1 – channels for air distribution, 2 – grooves for fixation of a platinum cathode current collecting mesh; (c) 3-D geometric models of the stack with one repeating unit in an exploded state (on the left) and with multiple repeating units in an assembled state (on the right). 1 – metal substrates, 2 – monopolar plates, 3 – pipes, 4 – alumina plates, 5 – cathode platinum current-collecting meshes, 6 – base metal plate, 7 – isolation spacer, 8 – top metal plate.

combination of screen-printing and high-temperature sintering (1100–1200 °C) in reducing atmosphere to fabricate an anode layer, gas flow sputtering to deposit a $(\text{Y}_2\text{O}_3)_{0.08}(\text{ZrO}_2)_{0.92}$ (8YSZ) membrane, and magnetron sputtering to deposit a $\text{Gd}_{0.1}\text{Ce}_{0.9}\text{O}_{1.95}$ (GDC) buffer layer was described by Udomsilp et al. [12]. The fabricated SOFCs demonstrated exceptionally high power density around 2 W/cm² at 650 °C. Nevertheless, the maximum firing temperature for this fabrication route (1100–1200 °C) probably does not allow *in situ* firing of the whole cell in a stack as such temperatures are too high for a cathode and also will lead to severe oxidation of metal bipolar plates on the cathode side of the cells.

Ceres Power developed a fabrication route that includes a laser-drilled substrate and all major cell layers deposited by screen-printing with high-temperature sintering in air at a maximum temperature of around 1000 °C [13]. However, it is not clear what kind of technology is used for deposition of YSZ electron-blocking layers [14], as the temperature of 1000 °C is probably too low for obtaining the gas-tight layer deposited by screen-printing. This route has advantages since firing in air can be conducted rapidly and is very suitable for mass production of MS-SOFCs. However, it cannot be ruled out that the obtained microstructures of the anode and GDC membrane layers at 1000 °C are not optimal, which, in combination with the oxide films formed at the anode-metal substrate interface during sintering in air, significantly reduces the total conductivity of the MS-SOFCs.

There were many studies regarding fabrication of MS-SOFCs using plasma spraying technologies [15–19]. These methods allow the fabrication of the entire membrane electrode assembly (MEA) without high-temperature firing steps. However, the electrodes fabricated by these methods usually have undeveloped triple-phase boundaries since resulted layers are characterized by a lamellar structure with a typical size of a gas-tight lamella of several tens of micrometers [18] and the electrolyte membranes fabricated by these methods have high defect concentration and need to be relatively thick to ensure gas tightness,

usually several tens of micrometers [19], which leads to relatively low conductivity of the cells.

This study is a continuation of a series of papers [20,21] directed to develop a fabrication route of MS-SOFC with the desired microstructure of the functional layers that is feasible for mass production with minimal possible firing steps at minimum possible firing temperature. In this study, we demonstrate the fabrication route for the stacks of MS-SOFCs with single *in situ* firing that include the combination of magnetron sputtering (MSP), aerosol deposition method (AD), and screen-printing.

MSP allows the deposition of gas-tight thin membranes without any high-temperature firing steps [22,23], which is essential for the feasibility of one-step firing of the whole MEA.

AD [24–26], also known as vacuum kinetic spraying [27,28], powder aerosol deposition [29,30] provides the opportunity for ceramic, metal, and composite layers formation from dry powders. The layers usually consist of particles less than 100 nm in size [30]. The density of layers can be regulated from almost gas-tight [31] to porous [32] by regulating the properties of initial powders as well as by deposition parameters [31–34]. The absence of liquid between particles leads to a uniform density of the layers, without agglomeration of the nanoparticles, which opens the possibility for formation of the layers with high specific surface area at low consolidation temperatures [35] due to high thermodynamic stimulus and active diffusion between separate nanoparticles.

The absence of organics in the anodes of the MS-SOFCs, relatively low temperatures of the consolidation of the anodes, and initial gas-tightness of the electrolyte membranes provide the opportunity for one-step *in situ* firing of the MEA without major agglomeration of Ni or interdiffusion between the anode and the substrate, which in turn opens the way for production of the MS-SOFC stacks with single high-temperature exposure of all the MEAs in a hot box of a SOFC power generation unit.

In this study, we demonstrated the fabrication procedure of the MS-SOFC mini-stack with single *in situ* firing of all MEAs. Metal substrates

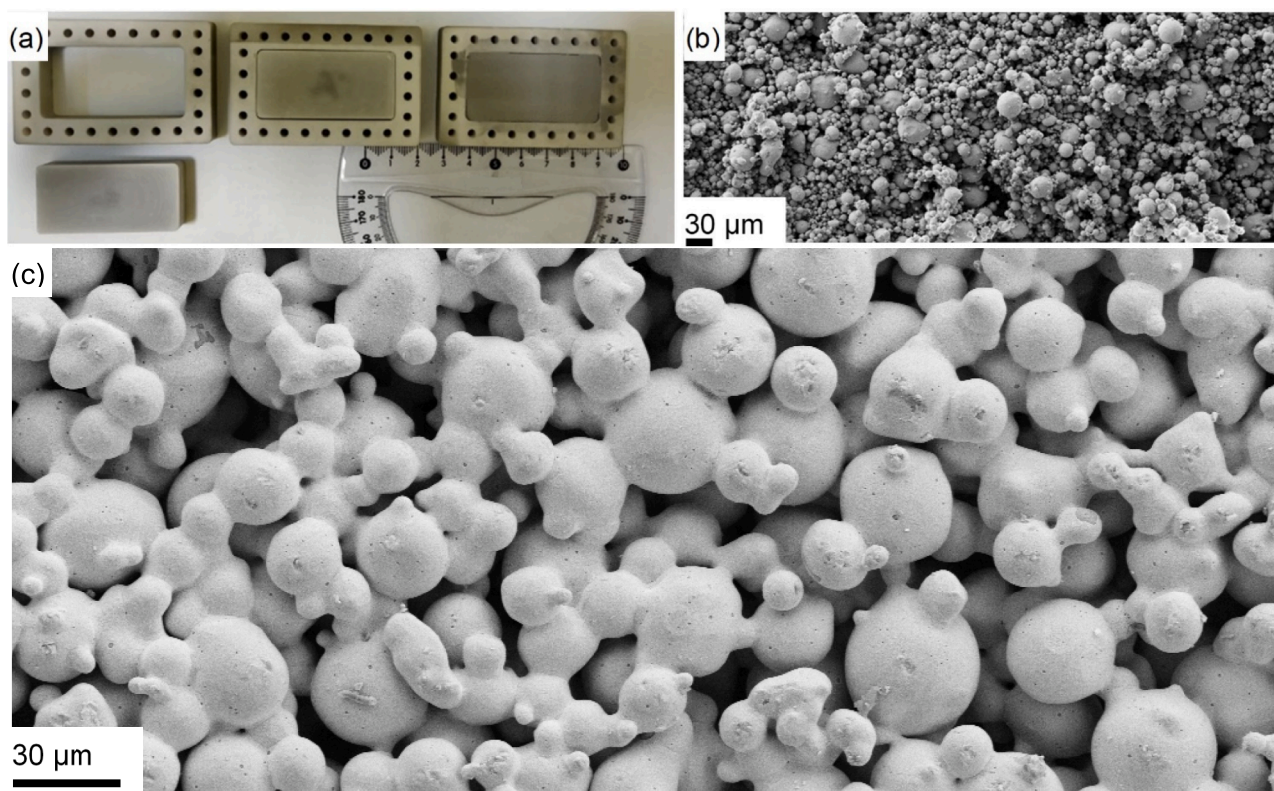


Fig. 2. (a) Alumina dishes for metal powder sintering; (b) SEM image of the metal powder, (c) SEM image of the surface of the metal substrate coated with Ni.

were fabricated from powder by vacuum sintering and welded into monopolar plates by laser welding. MEAs included a Ni/GDC anode layer fabricated by AD, a GDC membrane deposited by MSP, and a LSC cathode layer formed by screen printing. Single *in situ* firing at 950 °C of all MEAs in the mini-stack was conducted during the start-up procedure. The microstructures of the substrates and the functional layers were investigated by scanning electron microscopy (SEM), and the electrochemical characteristics of the stack were investigated by measuring current–voltage dependencies and impedance spectra.

2. Methods

2.1. Investigation methods

Microstructural investigation of the SOFCs and powders was conducted by SEM (Supra 50VP, Zeiss, Germany) with an installed energy dispersive X-ray (EDX) spectrometer (Oxford Instruments, UK). Electrochemical measurements were conducted using a potentiostat/galvanostat/ZRA Reference 3000 (Gamry Instruments, USA), impedance spectra were collected in a frequency range from 0.1 Hz up to 300 kHz at 20 mV voltage amplitude, 10 points per decade.

2.2. Assembling and start-up of the mini-stack

The stack has a monopolar commutation. Fig. 1(a) shows 3-D geometric models of monopolar plates (ISSP, Russia).

The monopolar plates include fuel chambers with current-collecting ribs (1) and fuel distribution channels (2). There is an area around the fuel chambers (3) that is used for welding the metal substrates. The monopolar plates also include main air distribution channels (4). The fuel chambers have two openings for welding of gas supply and gas exhaust pipes (5). These pipes also serve as anode-current collectors. The air distribution channel has one opening for welding of an air supply pipe (6). Fig. 1(b) shows 3-D geometric models of alumina plates (Biruch

Innovation Center, Russia). They spatially separate monopolar plates from each other and distribute air (1) through the cathode. They have grooves (2) for fixation of a platinum cathode current collecting mesh. Fig. 1(c) shows 3-D geometric models of the stack with one repeating unit in an exploded state (on the left) and with multiple repeating units in an assembled state (on the right). The assembly procedure of the stack includes following steps: welding of two metal substrates 20 × 20 mm (1) into monopolar plates 2 by laser welding apparatus C-4 (CNII LOT, Russia), deposition of the anode on both sides of the monopolar plates with welded metal substrates by AD, the deposition of the membrane on both sides of the monopolar plate by MSP, print-screen of the cathode on the membranes, welding of pipes (3) to the monopolar plate, assembling of the monopolar plate with the MEAs between two alumina plates 4 with cathode platinum current-collecting meshes (5) on the base metal plate 6 with an isolation spacer (7), installing a top metal plate on the assembly (8), loading the stack with weight, placing the stack in a furnace.

Metal substrates 25 × 50 mm were made of metal powder AISI430L (New Huarui Group Limited, China) by sintering in vacuum condition in alumina dishes (Biruch Innovation Center, Russia) (Fig. 2(a)).

Fig. 2(b) presents the SEM image of the metal powder. The powder for formation of the substrates was sieved through 50-mesh by ANALYSETTE 3 PRO (Fritsch GmbH, Germany). The sintering of the substrates was conducted at 1100 °C for 1 h under 10^{−5} Torr pressure. The metal substrates were coated with Ni by the electrodeposition method [36] to suppress interdiffusion between the anode and the substrate and increase the conductivity of oxide films that can form on the metal substrate. Fig. 2(c) demonstrates the surface of the metal substrate coated with Ni. The pore size of the substrate ranges from several micrometers up to several tens of micrometers. The substrates were cut into 20 × 20 mm sheets by laser marker MiniMarker 2-M50 (CNII LOT, Russia). The porosity of the substrates was determined by weighting. Fig. 3(a) demonstrates the 25 × 50 mm metal substrates before cutting, the thickness of the substrates is 0.3 ± 0.05 mm, and porosity is 45 ± 5

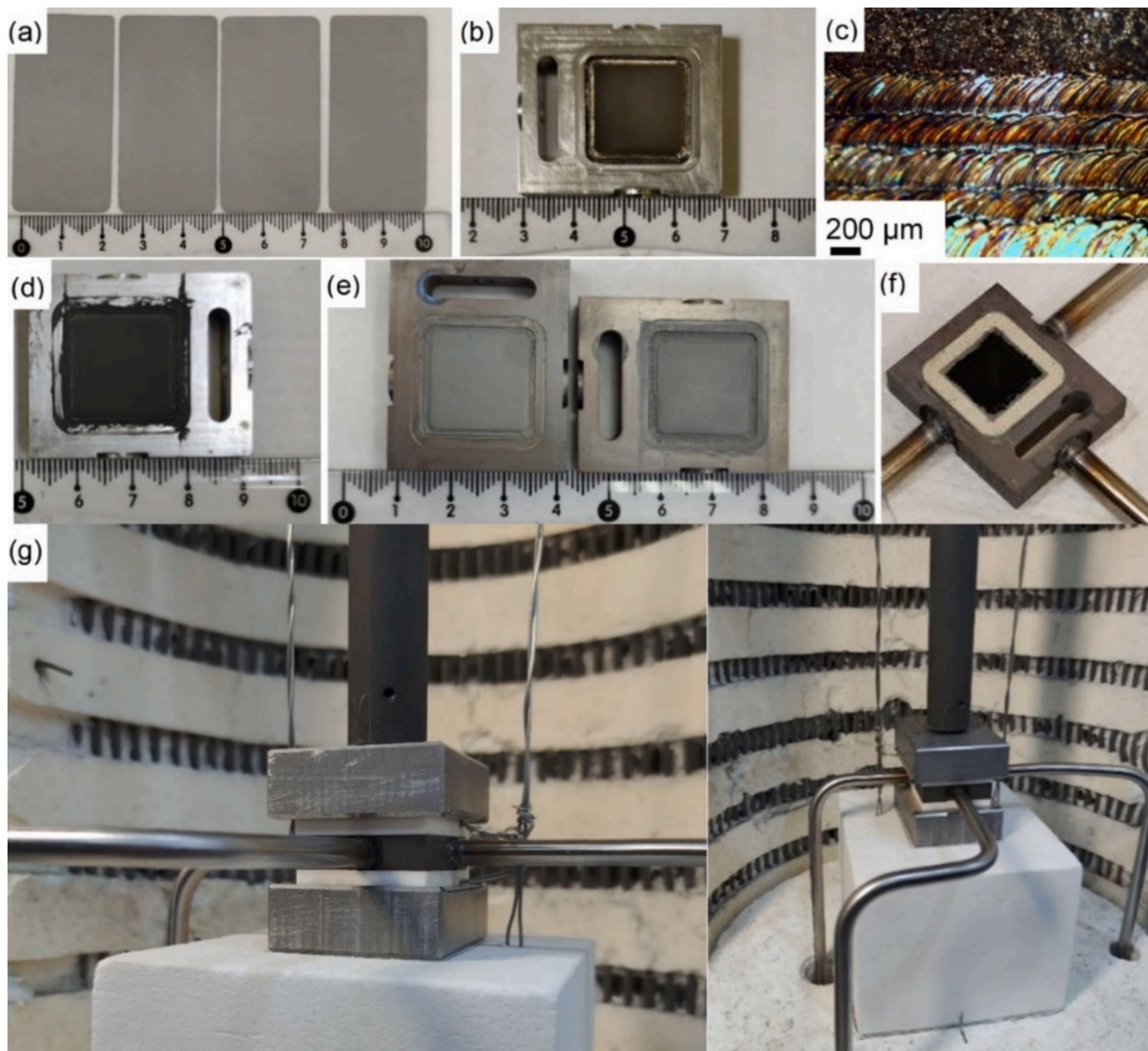


Fig. 3. (a) Metal substrates 25×50 mm; (b) Monopolar plate with welded metal substrates; (c) Image of the weld; (d) Monopolar plate after deposition of the Ni/GDC anode; (e) Monopolar plate after deposition of the Ni/GDC anode and GDC membrane (f) Monopolar plate with the cathode applied and the compression gasket placed; (g) Assembled mini-stack.

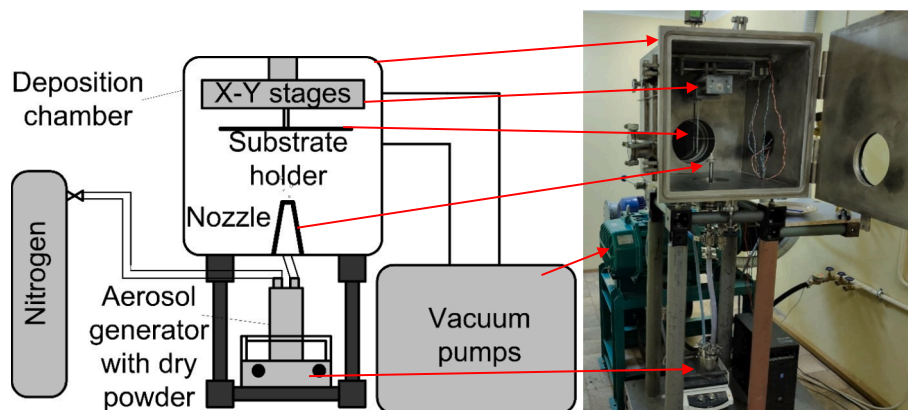


Fig. 4. General schematic diagram of an AD setup and a photo of the AD equipment used in this study.

% Fig. 3(b) shows the monopolar plate with welded metal substrates 20×20 mm that were coated with Ni. Fig. 3(c) shows an image of the weld, the weld consists of 5 lines that intersect with each other at about

50 %. The closer a weld line was to the edge of the substrate, the more intense a laser beam was made, which provided gradual difference in thickness, which was beneficial for gas tightness. The Ni/GDC anode

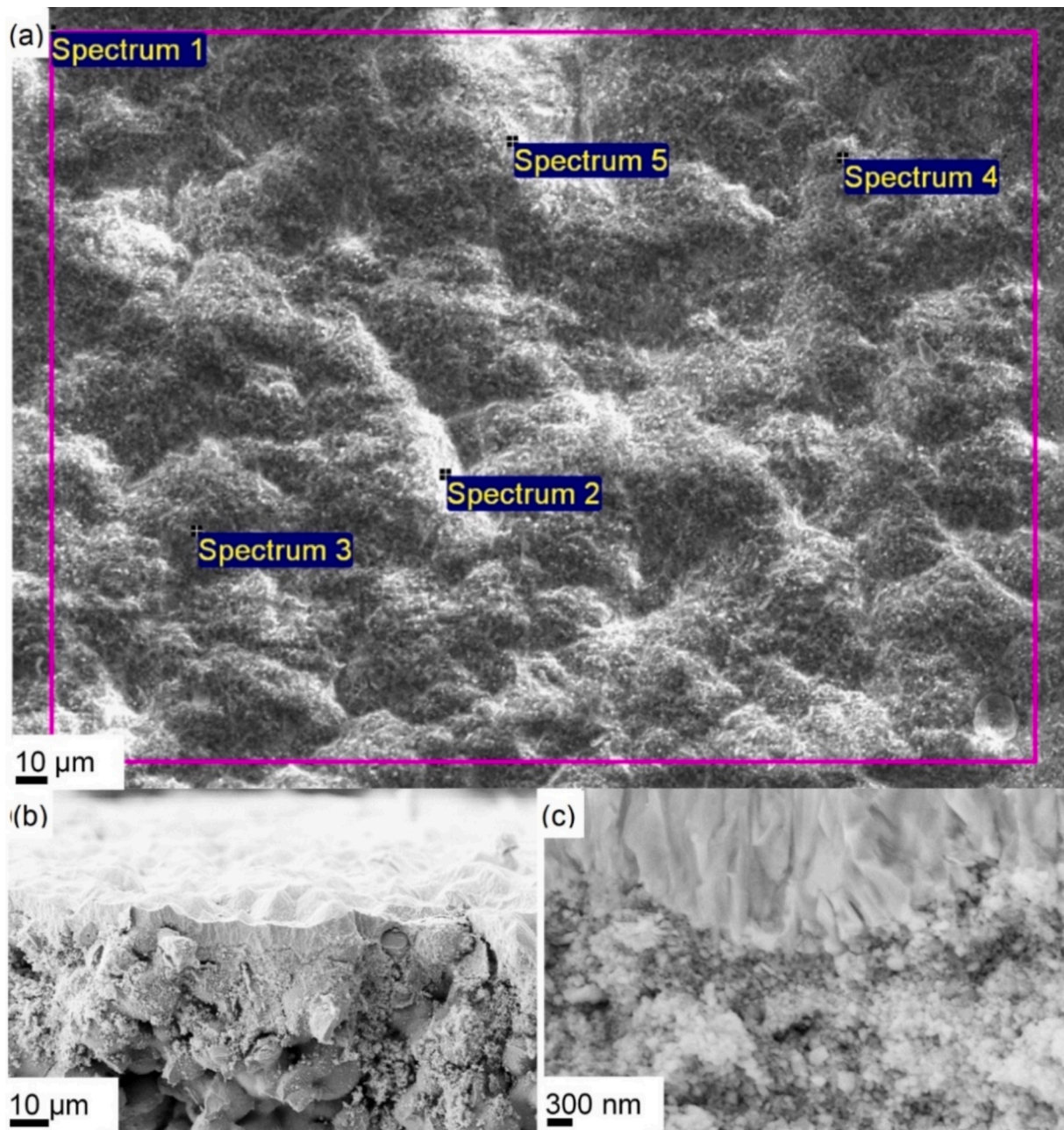


Fig. 5. (a) SEM image of the surface of the Ni/GDC anode layer; (b) SEM image of the cross-section of the half-cell; (c) Interface between the Ni/GDC anode and the GDC membrane.

Table 1
Results of the EDX analysis of the anode layer.

Spectrum	Ni, wt%	Ce, wt%	Gd, wt%	Ni/GDC, wt% (calculated)
1	48	46	6	43/57
2	49	45	6	44/56
3	53	42	5	49/51
4	55	40	5	50/50
5	48	46	6	43/57

functional layers were deposited by AD from Ni (IEP, UB RAS, Russia) and GDC (Kceracell, South Korea) powders (50/50 wt%).

Fig. 4 demonstrates the general schematic diagram of an AD setup and a photo of the AD equipment used in this study. The dry powder is placed in an aerosol generator with a steel cylinder and a vibrating table. Nitrogen gas flows into the aerosol generator and mixes with the

powder. The aerosol flows to a nozzle and accelerates toward a substrate. Vacuum pumps provide low pressure (100–1000 Pa) in a deposition chamber.

The deposition parameters and microstructure of the used powders were described elsewhere [21]. Fig. 3(d) shows the monopolar plate after deposition of the Ni/GDC anode. The GDC membranes were deposited on the anode by magnetron sputtering of a $\text{Ce}_{0.8}\text{Gd}_{0.2}$ target (Girmet Ltd., Russia) without any intermediate firing steps. The deposition parameters were described elsewhere [21]. Fig. 3(e) shows the monopolar plate after deposition of the GDC membrane. The anode deposition took place only on the porous metal substrate, whereas the membrane deposition was conducted on the whole area of the monopolar plate. The active area of the anode on one side of the monopolar plate is about 18×18 mm. Fig. 3(f) shows the monopolar plate with the $(\text{La}_{0.80}\text{Sr}_{0.20})_{0.95}\text{CoO}_{3-\delta}$ (LSC) cathode applied by screen-printing and a compression gasket placed. Though the compression gasket is not

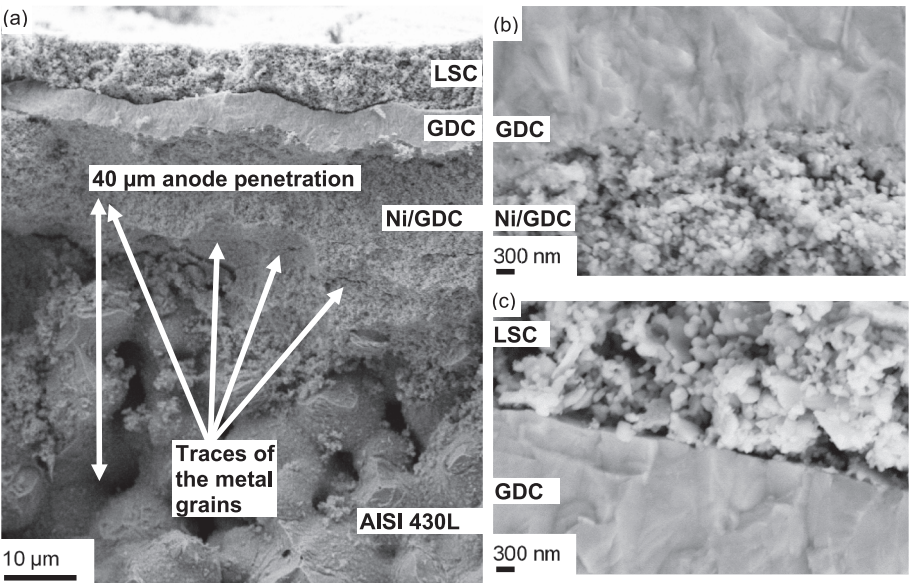


Fig. 6. SEM images of a MSC after *in situ* firing at 950 °C (a) cross-section of the whole MEA, (b) anode-membrane interface, (c) cathode-membrane interface.

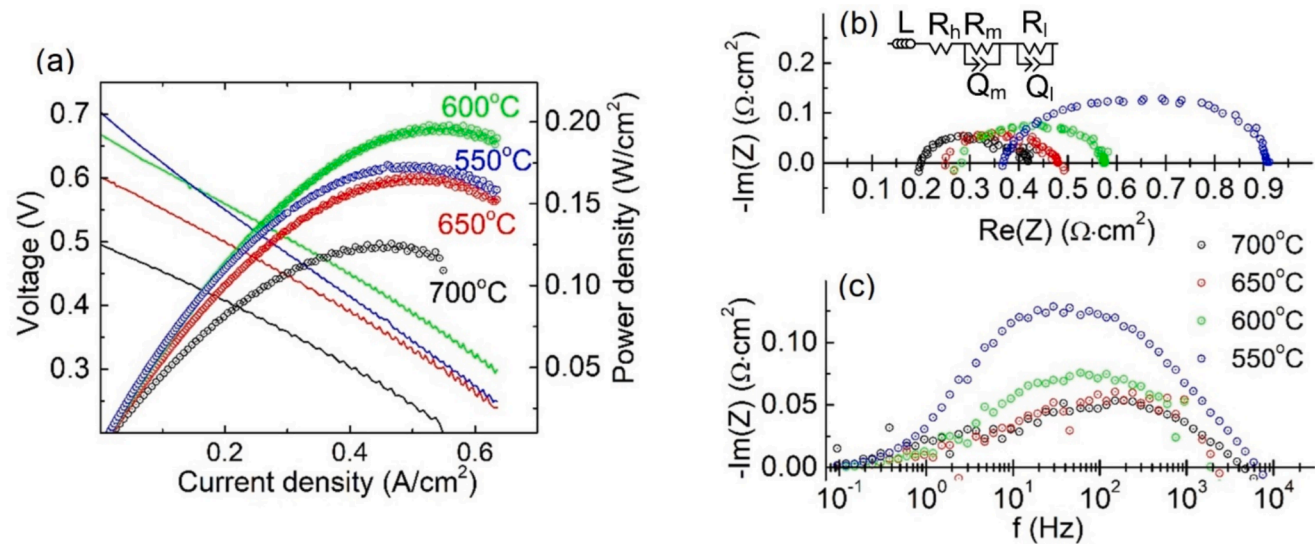


Fig. 7. (a) Current-voltage dependencies of the mini-stack. The active area of the cathode 3.92 cm² ; (b) Impedance hodographs and equivalent circuit scheme; (c) Bode-plots of the imaginary impedance for the stack at open circuit conditions.

Table 2
Results of the equivalent circuit analysis of the impedance hodographs of the stack.

Temperature, °C	Ohmic losses, Ω × cm ²	Total losses, Ω × cm ²
700	0.19	0.42
650	0.24	0.48
600	0.25	0.58
550	0.35	0.91

necessary in the stack, it was used to decrease the probability of gas leakages through the weld. The active area of the cathode on one side of the monopolar plate is about 14 × 14 mm, which gives the total active area of the mini-stack equal to 3.92 cm². Fig. 3(g) shows the assembled mini-stack. All functional layers were fired during a startup procedure of the mini-stack. The stack was heated up to 950 °C at 30 °C/hour rate. During the start-up, nitrogen was supplied to the anode chamber at a 50

Table 3
Parameters of the temperature cycling of the stack.

N ^o of a cycle	Heating rate, °C/hour	Max. T, °C	Cooling rate, °C/hour	Min. T, °C
1	30	950	30	550
2	40	550	40	200
3	150	550	150	200
4	300	550	with furnace	25
5–10	500	550	with furnace	25

ml/min rate, and air was supplied to the cathode chamber at a 200 ml/min rate. The stack was held at 950 °C for an hour, after that it was cooled to 700 °C at a 30 °C/hour rate. When the stack cooled down to 700 °C, the anode gas was changed to a mixture of hydrogen (50 ml/min) and nitrogen (90 ml/min). All electrochemical measurements were conducted at these gas flows.

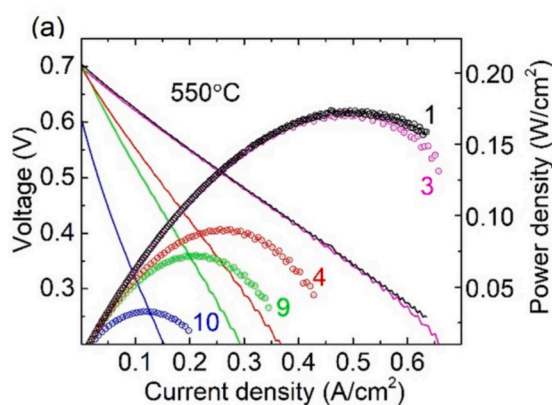


Fig. 8. (a) Current-voltage dependencies of the stack after some of the temperature (redox) cycles; (b) Impedance hodographs; (c) Bode-plots of the imaginary impedance of the stack at open circuit conditions after some of the cycles.

Table 4

Results of the equivalent circuit analysis of the impedance hodographs of the stack after some of the cycles.

N ^o of a cycle	Ohmic losses, $\Omega \times \text{cm}^2$	Total losses, $\Omega \times \text{cm}^2$
1	0.35	0.91
4	0.59	1.76
9	0.62	1.94

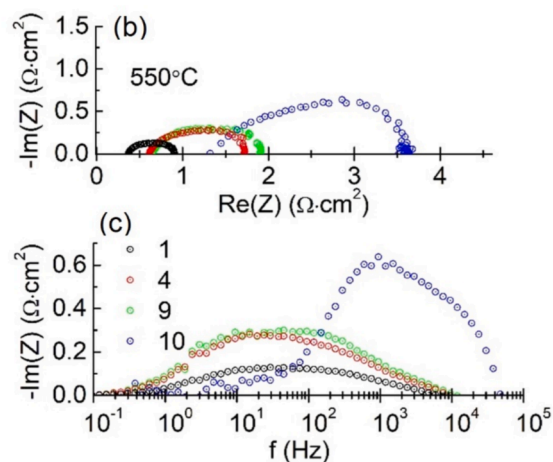
3. Results and discussion

3.1. Microstructural investigation of the MSCs

Fig. 5(a) demonstrates the backscattered electron SEM image of the surface of the anode layer deposited on the metal substrate with areas from which information for EDX analysis was collected. The anode layer fully covers and substantially flattens the surface of the substrate, which makes it suitable for subsequent membrane deposition by magnetron sputtering. Results of the EDX analysis are presented in Table 1, the Ni/GDC ratio was calculated from the stoichiometry. The Ni content is in the range from 43 wt% to 50 wt%, the average ratio of Ni/GDC is 43/57 wt%, which is in the applicable range of functional Ni/GDC anodes [37]. The difference between Ni/GDC ratio in the layer and in the composite powder probably comes from the difference in aerodynamic properties of the Ni and GDC powders.

Fig. 5(b) demonstrates the secondary electron SEM image of a cross-section of a half-cell with the Ni/GDC anode deposited by AD on the metal substrate and the GDC membrane deposited by MSP on the unsintered anode. The anode layer penetrates the substrate up to 40 μm , whereas the thickness of the anode layer relative to the tops of the metal grains can be down to submicron, which makes delamination of the anode layer from the substrate highly unlikely due to high contact surface area.

Fig. 5(c) shows the secondary electron SEM image with a higher magnification of the interface between the anode and membrane. GDC electrolyte, that is present in the anode, provide nuclei for growth of the GDC membrane that is being deposited by magnetron sputtering, which makes strong adhesion between the membrane and the anode even before sintering. The thickness of the deposited GDC membrane is $5 \pm 2 \mu\text{m}$. There is no obvious delamination of the membrane from the anode after the preparation of the cross-section, which indicates good adhesion even before sintering. The structure of the membrane is gas-tight, which provides an opportunity for *in situ* firing under different oxygen partial pressures for the anode and the cathode sides of the cell. The anode layer consists of particles less than 100 nm in size. The small size of particles



and relatively high density make consolidation temperatures relatively low due to high thermodynamic stimulus and high rate of diffusion.

Fig. 6(a) presents SEM images of a MSC with Ni/GDC anode, GDC membrane, and LSC cathode after *in situ* firing at 950 °C. The pore size of the anode layer before sintering is about several tens of nanometers. These pores coalesce after sintering and grow to the size of up to several hundreds of nanometers (Fig. 6(b)). There are visible bonds between the anode layer and the membrane, which ensures good adhesion and conductivity of the interface. The penetration of the anode layer up to 40 μm and the traces of the metal grains in the cross-section of the anode layer indicate a large contact area, which is essential for withstanding high mechanical stress. The thickness of the LSC cathode layer is 5 – 10 μm , and the pore size is up to about a micrometer (Fig. 6(c)). The partial delamination of the cathode layer happened during the preparation of the cross-section due to the high ductility of the metal substrate.

3.2. Electrochemical investigation of the mini-stack

Fig. 7(a) shows current–voltage dependencies of the mini-stack. Due to the high electron conductivity of the GDC membrane in the reducing atmosphere [38–40], values of open circuit voltage (OCV) are significantly lower than standard values at about $1.05 \pm 0.05 \text{ V}$. According to Duncan et al. [40], measured OCV values indicate an effective GDC membrane thickness of less than two micrometers, which probably indicates column structure, defects in the magnetron-deposited GDC membrane, or gas cross leakage due to defects in the substrate weld joint. The strong temperature dependence of OCV indicates high electronic conductivity of the membrane, which proofs its significant reduction. The ionic and electronic conductivities of the MEAs increase with increasing temperature, which increases the maximum power density. However, the OCV drastically decreases with increasing temperature due to the high electronic conductivity of the GDC membrane in a reducing atmosphere, which decreases the maximum power density. These two competing factors resulted in the existence of the optimum temperature of around 600 °C in terms of maximum power density, which was 0.2 W/cm^2 . Fig. 7(b–c) demonstrates impedance hodographs and bode-plots of the imaginary impedance of the stack at open circuit conditions. The impedance data was analyzed using the equivalent circuit method. The data fitting was performed using an equivalent circuit LRh(RmQm)(RlQl) (Fig. 7(b)), where L – inductor; Rh, Rm, Rl – resistors; Qm, Ql – constant phase elements. The results of the equivalent circuit analysis are presented in Table 2.

The total losses of the stack are about 0.42 – 0.91 $\Omega \times \text{cm}^2$ in the temperature range of 700 – 550 °C. The ohmic losses are about 0.19 – 0.35 $\Omega \times \text{cm}^2$. These values of resistance are at the lower limit of

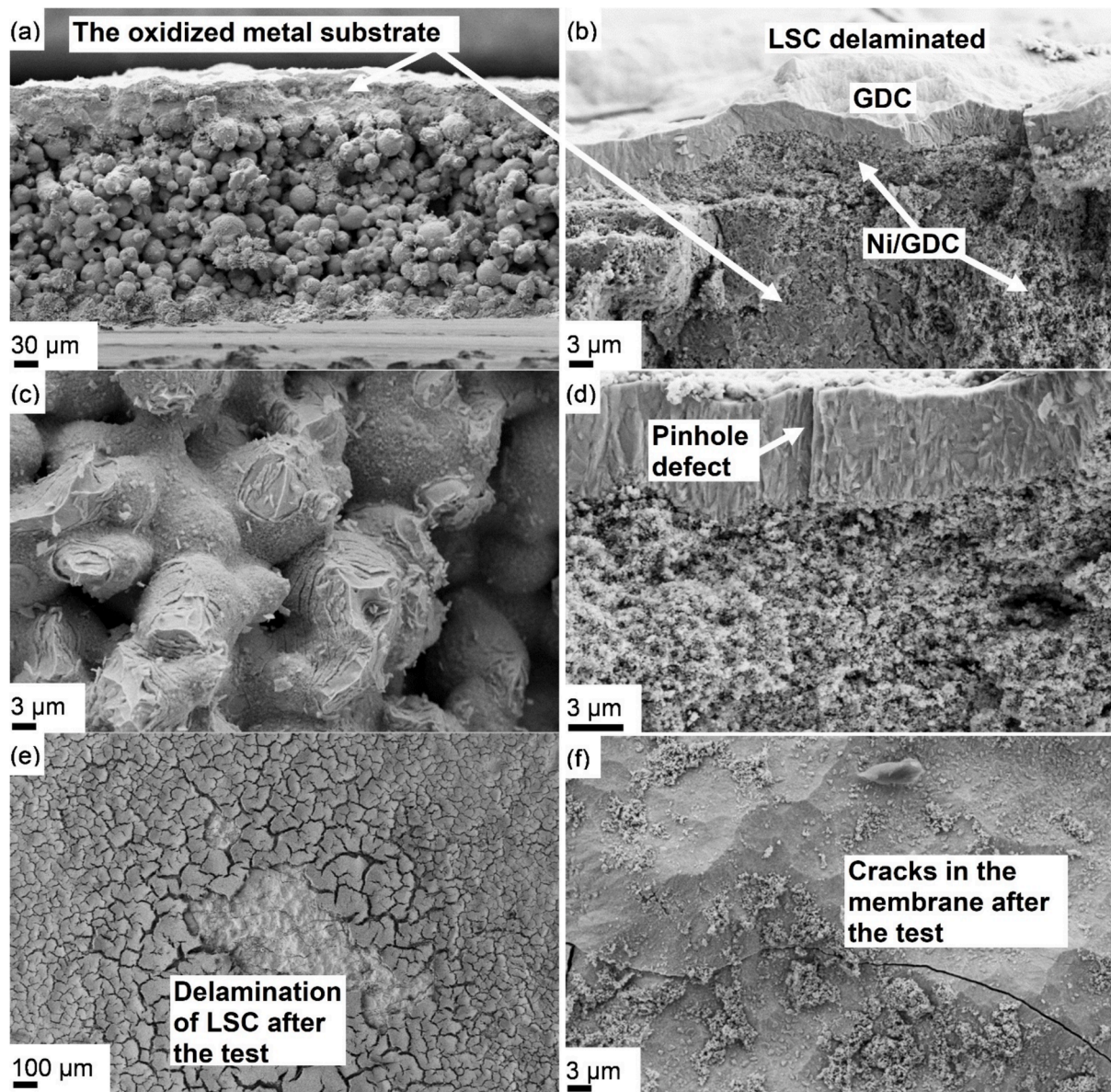


Fig. 9. SEM images of the microstructure of the MSC of the mini-stack after the test (a) The whole cross-section of the cell, (b) Cross-section of the area near the MEA, (c) Cross-section of the metal grains at about 0.15 mm depth from the substrate surface, (d) Cross-section of the anode and the membrane, (e) Surface of the cathode layer, (f) Surface of the membrane.

the values for MS-SOFC in literature [15,41–43] indicating sufficient consolidation of the functional layers and the absence of low-conducting oxide films on the anode-metal substrate interface. The polarization resistance and its contribution to the impedance increase with cooling due to a reduction of the catalytical activity of the electrodes. Minor contribution to the impedance of the cell at frequencies less than 1 Hz mostly associated with gas-transport losses [44–46] probably indicates the high level of gas permeability of the metal substrate and the electrodes.

The temperature cycling of the mini-stack was conducted. The parameters of the cycling are provided in Table 3. Hydrogen was present in the anode chamber only at temperatures equal to or higher than 550 °C. The maximum heating rate was equal to 500 °C/hour. Fig. 8(a) shows current–voltage dependencies of the stack after some of the cycles. Fig. 8 (b–c) depicts impedance hodographs and bode-plots of the imaginary impedance of the stack at OCV conditions after some of the cycles.

The results of the equivalent circuit analysis are presented in Table 4. OCV stays at 0.7 V until the 10th cycle, which indicates mechanical

stability of the cell structure especially of the magnetron sputtered GDC membrane. The increase of resistivity at the heating rates higher than 150 °C/hour is probably caused by the partial delamination of the cathode due to the high thermal expansion coefficient of the LSC in comparison to the other layers of the stack [47,48]. The drop of OCV after the 10th cycle is accompanied by the drastic change in the imaginary component of the impedance, which indicates the strong change in the microstructure of the cells that can be caused by the formation of macro defects due to temperature cycling.

3.3. Post-test microstructure analysis of the MSC of the mini-stack

Fig. 9 demonstrates SEM images of the microstructure of the MSC of the mini-stack after the test. Fig. 9(a–b) shows that the part of the metal substrate close to the MEA oxidized to a depth of about 30 μm. The oxidation probably happened due to the air leakage through the cracks in the membrane (Fig. 9(f)) that formed in large numbers after the 10th temperature cycle. Ni/GDC anode stays porous even after Ni oxidation

(Fig. 9(b),(d)), which allows it to be separated visually from the oxidized metal substrate (Fig. 9(b)). The strong oxidation of the anode layer and the upper part of the metal substrate is probably the cause of the drastic change in the imaginary component of the impedance described in the previous section (Fig. 8(c)).

Fig. 9(c) demonstrates the metal substrate at about 0.15 mm level from the surface. The metal grains look weakly oxidized and have relatively thick unoxidized necks of up to 10 μm in diameter, which indicates no significant oxidation of the metal substrate during *in situ* firing at 950 °C in nitrogen and promises high ductility of the substrate.

Fig. 9(e) demonstrates the surface of the LSC cathode layer after the test. The LSC was very cracked and had macro defects due to delamination, which probably decreased the effective power density of the stack. The adhesion of the LSC was relatively weak as it delaminated during the cross-section preparation (Fig. 9(b)). Therefore, if the cathode application technique is improved, the MSCs' performance can be expected to increase further.

Fig. 9(d) demonstrates that thin defects were present in the membrane, which could be a reason for pinholes and led to lower than expected initial OCV of the stack. Deposition of a multi-layered membrane with an electron-blocking layer will probably resolve not only the problem of electron leakage but also the problem of the pinholes.

4. Conclusions

The metal-supported SOFC mini-stack with single *in situ* firing of MEAs at 950 °C was fabricated. The MEAs consisted of the porous metal substrate welded in the metal plate and sequentially applied Ni/GDC anode, GDC membrane, and LSC cathode. The combination of AD and magnetron sputtering methods allowed minimization of the number of firing steps and equalization of all firing temperatures to the sintering temperature of the LSC cathode layer which is usually the minimal firing temperature of all layers in a MEA.

The maximum power density of 0.2 W/cm² was achieved at 600 °C. The OCV of the mini-stack with single-layered GDC membrane ($5 \pm 2 \mu\text{m}$) was 0.7 – 0.5 V in the temperature range 550 – 700 °C. The low values of OCV were explained by the high electronic conductivity of GDC in a reducing atmosphere.

The temperature cycling of the mini-stack was conducted. The values of resistance of the cells at OCV condition (total $0.42 - 0.91 \Omega \times \text{cm}^2$, ohmic $0.19 - 0.35 \Omega \times \text{cm}^2$ at 550 – 700 °C) are at the lower limit of the values for MS-SOFC in the literature indicating sufficient consolidation of the functional layers and the absence of low-conducting oxide films on the anode-metal substrate interface. The stability of the cell structure was demonstrated even at the maximum heating rate of 500 °C/hour.

The fabricated mini-stack is a preliminary step towards the fabrication of MS-SOFC systems with single *in situ* firing of all MEAs. The main direction for improving the performance of the MS-SOFCs is blocking the electron current through the GDC membrane, for example, by a thin layer of 8YSZ, which will be implemented in further studies.

CRedit authorship contribution statement

I.S. Erilin: Writing – original draft, Investigation, Data curation. **I.N. Burmistrov:** Writing – review & editing, Methodology, Investigation, Data curation. **E.A. Smolyanskiy:** Investigation, Data curation. **A.A. Solov'yev:** Methodology, Investigation, Data curation. **O.V. Pikalov:** Investigation. **M.N. Levin:** Methodology, Conceptualization. **S.I. Bredikhin:** Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Glossary

Abbreviation

SOFC: Solid oxide fuel cell
 MS-SOFC: Metal-supported solid oxide fuel cell
 MEA: Membrane electrode assembly
 OCV: Open circuit voltage
 AD: Aerosol deposition method
 MSP: Magnetron sputtering method
 YSZ: Yttria Stabilized Zirconia
 8YSZ: 8% Yttria Stabilized Zirconia
 GDC: Gadolinium-doped ceria
 LSCF: Lanthanum strontium cobalt ferrite
 LSC: Lanthanum strontium cobalt
 SEM: Scanning electron microscopy
 EDX: Energy-dispersive X-ray spectroscopy