Chromium Poisoning of Neodymium Nickelate (Nd$_2$NiO$_4$) Cathodes for Solid Oxide Fuel Cells

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ABSTRACT

In this study, we investigated the long-term stability of Nd$_2$NiO$_4$ solid oxide fuel cell (SOFC) cathodes to evaluate their chromium poisoning tolerance. Symmetrical cells consisting of Nd$_2$NiO$_4$ electrodes and a yttria-stabilized zirconia electrolyte were fabricated and the cell potential and polarization resistance were measured at 850 °C in the presence of gaseous chromium species for 800 h. Up to 500 h of operation, the cell potential remained constant at 500 mV/cm$^2$. However, it increased slightly over the operation duration of 500-800 h. No appreciable increase was observed in the polarization resistance of the Nd$_2$NiO$_4$ cathode during the entire operation of 800 h. Physicochemical examinations revealed that the gaseous chromium species did not form chromium-related contamination not only in the Nd$_2$NiO$_4$ cathode but also at the cathode/electrolyte interface. The results demonstrated that Nd$_2$NiO$_4$ is resistant to chromium poisoning, and hence is a potential alternative to standard perovskite cathodes.

Key words : Nd$_2$NiO$_4$, Chromium poisoning, Solid oxide fuel cells, Impedance spectra, Long-term stability

1. Introduction

High-temperature solid oxide fuel cells (SOFCs) have several advantages over polymer electrolyte membrane fuel cells, which operate at low temperatures.$^5$ SOFCs exhibit multi-fuel capability, i.e., carbon monoxide or hydrocarbons can be directly supplied to the fuel electrode.$^8$ The operating temperature of SOFCs is 600–800°C. FCs with a high operating temperature exhibit high energy generation efficiency, particularly when they are coupled with a gas turbine. The electrical efficiency of SOFCs is 50–60%,$^3$ which increases up to 80% in combined heat and power applications.$^4$ In addition, since SOFCs are all-solid-state devices, they do not require liquid management and offer cell or stack design flexibility.$^5$

Solid ceramic electrolytes are used in SOFCs. The most popular SOFC electrolyte material is 8 mol% yttria-stabilized zirconia (YSZ), which is a good oxygen ion conductor. Nickel-YSZ cermet and mixed ionic and electronic conducting (MIEC) ceramics are used as the SOFC anode and cathode materials, respectively. It has been reported that cathodic polarization is the major phenomenon that deteriorates the power density of SOFCs.$^6$ Thus, the choice of a good MIEC material and strategies for improving the catalytic activity of MIEC cathodes have been widely examined.$^5$ La$_{1-x}$Sr$_x$CoO$_{3-δ}$ (LSC), La$_{1-x}$Sr$_x$Fe$_{1-y}$Co$_y$O$_{3-δ}$ (LSCF), and Ba$_{1-x}$Sr$_x$Fe$_{1-y}$Co$_y$O$_{3-δ}$ (BSCF) have been studied as SOFC cathode materials because of their high catalytic activity for the oxygen reduction reaction and excellent electrical conductivity over a wide temperature range.$^{5-10}$

Over the past few years, because of the decrease in the SOFC operating temperature, ferritic stainless steel has gained immense attention as an interconnecting material.$^{11}$ Ferritic stainless steel is cost-effective and easy to manufacture and exhibits high electrical and thermal conductivities.$^{12,13}$ However, it requires effective oxidation protective coating and cathode materials that are inert and tolerant to chromium deposition and poisoning.$^{14}$ The oxidative scale reaction between oxygen and water vapor forms volatile Cr(VI) species, which poison SOFC cathodes.$^{15}$ The alkaline earth metal (particularly strontium among LSFC) cathodes are not suitable for long-term operation of SOFCs.$^{36}$ Therefore, various efforts have been made to develop novel cathode materials with high chromium resistance.$^{17}$

Recently, a novel A$_2$MO$_{6+δ}$ (A: alkaline earth or rare earth metal, M: transition metal) oxide compound with a K$_2$NiF$_4$-type structure has gained attention as a promising SOFC cathode material.$^{18-20}$ This compound is characterized by the stoichiometry of excess oxygen and a mixed valency of M. These structural characteristics can lead to high oxygen ion mobility and oxygen surface exchange coefficients.$^{21,22}$ Since NdNi$_{0.86}$O$_{3-δ}$-related materials do not contain strontium or manganese, unlike LSCF or lanthanum strontium manganite (LSM), they exhibit high chromium tolerance, and hence are considered as potential SOFC cathode materials.$^{20}$

However, there is some controversy regarding the chromium poisoning tolerance of nickelate-based cathode mate-

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rials. Park et al. investigated the chromium poisoning mechanism of LSM, Pr$_{0.8}$Sr$_{0.2}$MnO$_3$, Nd$_{0.8}$Sr$_{0.2}$MnO$_3$, and BSCF at 700°C and found that polarization increased with an increase in the deposition of chromium. Schuler et al. showed that Nd-nickelate cathodes undergo degradation because of chromium poisoning. In contrast, Yang et al. reported that gaseous chromium species have a minor effect on the surface exchange properties of Nd$_{1.95}$NiO$_{4+\delta}$. This discrepancy may be associated with the composition variations or non-stoichiometry of the materials. In this study, we fabricated electrolyte-supported symmetrical cells consisting of a YSZ electrolyte and Nd$_2$NiO$_4$ electrodes and investigated the chromium poisoning of the Nd$_2$NiO$_4$ cathodes under open-circuit and constant current density conditions at 850°C for 800 h. Gaseous chromium species such as CrO$_3$ or CrO$_2$(OH)$_2$ were produced from porous Cr$_2$O$_3$ powder compacts, and the humidifying air passing through Cr$_2$O$_3$ was delivered to the cell.

2. Experimental Procedure

Nd$_2$NiO$_4$ powder was synthesized using the solid-state reaction process. Nd$_2$O$_3$ (99.9%, Sigma-Aldrich, St. Louis, MO, USA) and NiO (99.9%, Sumitomo, Tokyo, Japan) were used as the starting materials. Stoichiometric amounts of Nd$_2$O$_3$ and NiO were mixed in ethanol (94.5%, Samchun Pure Chemicals, Pyeongtaek, Korea) using a planetary mill. After drying, the powder mixtures were calcined at 1100–1200°C for 12 h in air. Symmetrical cells consisting of a YSZ electrolyte and Nd$_2$NiO$_4$ electrodes were fabricated using a YSZ disk and Nd$_2$NiO$_4$ paste by screen-printing. The YSZ electrolyte disks were produced by sintering a 8YSZ (yttria-stabilized zirconia, Tosoh Corporation, Tokyo, Japan) powder compact at 1450°C for 5 h in air. The diameter and thickness of the YSZ disk were 20 and 0.2 mm, respectively. Before sintering, the 8YSZ powder compact was cold isostatic pressed at 200 MPa. Nd$_2$NiO$_4$ electrode films were coated on both sides of the 8YSZ disk by screen printing using the Nd$_2$NiO$_4$ paste. The Nd$_2$NiO$_4$ electrode films were dried at 150°C and subsequently sintered at 1050, 1100, and 1150°C for 2 h in air.

For the chromium poisoning test, two symmetrical cells were placed in an electric furnace, which was heated to 850°C, and 3% H$_2$O-humidified air was supplied to the furnace. Gaseous chromium species were produced using a chromium oxide (Cr$_2$O$_3$) powder compact. The Cr$_2$O$_3$ powder (99.0%, Junsei Chemical Co., Ltd., Tokyo, Japan) was dry-pressed into a disk and sintered at 1000°C for 1 h. The temperature of the Cr$_2$O$_3$ powder compact was 700°C. Fig. 1 shows the schematic of the set up used for the chromium poisoning test. The test was carried out under open-circuit conditions and at a current load of 500 mA/cm$^2$. An impedance analyzer was connected to the two cells to apply an electric current.

Phase identification of the synthesized Nd$_2$NiO$_4$ powder was carried out using an X-ray powder diffractometer (XRD, DMAX-2500, Rigaku, Tokyo, Japan) with Ni-filtered CuK$_\alpha$ radiation. Microstructural and compositional analysis was carried out using a field emission scanning electron microscope (S-3200, Philips, Amsterdam, Netherlands). The electrochemical performance of the symmetrical cells was evaluated by electrochemical impedance spectroscopy. AC impedance spectra were obtained on an impedance analyzer (IM6e, Zahner, Germany) under open-circuit conditions at an excitation potential of 20 mV over a frequency range of 1 MHz–0.01 Hz.

3. Results and Discussion

In this study, the Nd$_2$NiO$_4$ powder was synthesized by calcining the mixture of Nd$_2$O$_3$ and NiO powders at various temperatures to obtain a single-phase Ruddlesden-Popper (RP) structure. Fig. 2 shows the XRD patterns of the powder samples calcined at 1100, 1150, and 1200°C for 5 h. The

![Fig. 2. XRD patterns of the powder samples calcined at 1100, 1150, and 1200°C.](image-url)

Fig. 1. Schematic of the set up used for the chromium poisoning test.
The powder sample calcined at 1100°C consisted of the Nd$_2$O$_3$ phase. This indicates that the calcination temperature of 1100°C was too low to obtain a single-phase RP structure. In contrast, the powder samples calcined at temperatures above 1150°C had the single-phase RP structure and did not contain Nd$_2$O$_3$, NiO, or unwanted reaction phases. The obtained Nd$_2$NiO$_4$ powders showed an orthorhombic structure. Nd$_2$NiO$_4$ is orthorhombic at room temperature and becomes tetragonal at temperatures ≥ 800°C.

To investigate the effect of the sintering temperature on the catalytic activity of the Nd$_2$NiO$_4$ cathodes, their impedance spectra were obtained. The polarization resistances of the cells were determined from their impedance arcs. The temperature-dependent polarization resistance of the cells is shown in Fig. 3. The polarization resistance decreased with an increase in the operating temperature. This phenomenon was expected because the activation energies of electrode reactions decrease exponentially with temperature.\(^{25}\) In general, the polarization resistance of SOFC cathodes increases with an increase in the sintering temperature. This can be explained by the reduced triple-phase boundary caused by the grain growth of the electrode when sintering is carried out at high temperatures. This was not observed in this study. In this study, high-temperature sintering enhanced the interfacial adhesion of the porous Nd$_2$NiO$_4$ electrodes to the YSZ electrolyte, thus reducing the polarization resistance of the cell.\(^{28}\)

The effect of chromium poisoning on the long-term stability of the Nd$_2$NiO$_4$ electrodes was investigated. The cell potential and polarization resistance of the Nd$_2$NiO$_4$/YSZ/Nd$_2$NiO$_4$ symmetrical cell as a function of time at 500 mA/cm$^2$ are shown in Fig. 4. The resistance values shown in Fig. 4(b) were obtained from the impedance analysis results shown in Fig. 5. The Nd$_2$NiO$_4$ electrode sintered at 1150°C for 5 h was used. As shown in Fig. 4, stable and slightly improved cell performance was observed over the 500 h of operation. The initial decrease in the potential occurred because of the activation of the cathode. The cell required time to reach a steady-state condition, indicating that the voltage or current readings did not change over time.\(^{29}\) This delay occurred because of the changes in the microstructure of the electrode and in the reaction atmosphere. After the activation, the potential became rather stable and did not change (~ 0.6 V) even after 500 h of operation. In contrast, during 500–540 h of operation, the potential showed an unexpected increase with time. This can be attributed to the chromium poisoning of the Nd$_2$NiO$_4$ cathode or the contact problems between the Nd$_2$NiO$_4$ cathode and the YSZ electrolyte.

Figure 5 shows the impedance spectra of the Nd$_2$NiO$_4$ electrode after 84, 492, and 788 h of operation under gaseous chromium species. The impedance spectra showed two arcs; a large arc in the medium-frequency range (~ 10$^3$ Hz) and a small arc in the low-frequency range (~ 10$^0$ Hz). No significant change was observed in the polarization resistance (difference between the high- and low-frequency arc intercepts with the real axis) even after 788 h of operation. This suggests that the catalytic activity of the Nd$_2$NiO$_4$ electrode did not degrade appreciably in the presence of gaseous chromium species. However, the ohmic resistance showed a two-fold increase with an increase in the operation time from 788 to 492 h (high-frequency arc intercept with the
We believe that this increase in the resistance resulted in the abrupt voltage decrease (increase in potential) during 500–540 h of operation, as described in the previous section (Fig. 4).

With an increase in the operation time, the shape of the impedance arc changed slightly. The low frequency arc increased after 884 h of operation. The medium frequency arc can be attributed to the charge transfer during the oxygen reduction reaction at the cathode, while the low frequency arc can be attributed to the mass transfer or interface between the electrolyte and the electrode.

The subtle change in the structure of the YSZ/Nd$_2$NiO$_4$ interface might have increased the low frequency arc. The deposition of chromium on the Nd$_2$NiO$_4$ electrode during the chromium poisoning test was confirmed by energy-dispersive spectroscopy (EDS) analysis. The analysis was carried out under open-circuit conditions and at a current load of 500 mA/cm$^2$. For comparison, we also carried out the EDS analysis of the cell before chromium poisoning under the same conditions. Fig. 6 shows the concentration profiles of nickel, neodymium, and chromium obtained from the EDS line scan from the cross-section of the Nd$_2$NiO$_4$ cathode/YSZ electrolyte interface. Although some fluctuations were observed in the cathode region, the nickel and neodymium concentrations decreased sharply at the interface and became nearly zero in the YSZ region, suggesting that the diffusion of nickel or neodymium into the YSZ electrolyte was negligible. The chromium concentration remained almost constant throughout the electrode before and after the chromium poisoning test. Chromium deposition was not observed at the cathode or the interface between the electrode and the electrolyte.

To further examine the chromium deposition on the Nd$_2$NiO$_4$ cathode, its transmission electron microscopy-EDS (TEM-EDS) analysis was carried out after removing it from the electrolyte. Fig. 7 shows the TEM images and the corre-
sponding EDS analysis results of the Nd$_2$NiO$_4$ cathode. It can be observed that the increase in the chromium concentration after the chromium poisoning test was nearly negligible. Interestingly, Figs. 7(b) and 7(c) show that the chromium concentration was nearly the same for the cells operated under open-circuit conditions and at the current load of 500 mA/cm$^2$. This suggests that the electrochemical deposition of chromium compounds was negligible and that the Nd$_2$NiO$_4$ cathode was highly resistant to gaseous chromium species.

Figure 8 shows the XRD patterns of the YSZ electrolyte surface and Nd$_2$NiO$_4$ cathode before and after the chromium poisoning test. Fig. 8(b) shows that the Nd$_2$NiO$_4$ cathode had an orthorhombic structure before the chromium poisoning test, as was also shown in Fig. 2. In contrast, peaks corresponding to the tetragonal structure were detected at $2\theta = 31$ and $32^\circ$ after the chromium poisoning test. This phenomenon was more remarkable when a current of 500 mA was applied. This indicates that after the chromium poisoning test, the Nd$_2$NiO$_4$ sample showed mixed phases with the orthorhombic and tetragonal structures. Generally, the crystal structure of R-P phases such as Nd$_2$NiO$_4$ depends on factors such as oxygen vacancy and thermal history. Hence, Nd$_2$NiO$_4$ samples exposed to high temperatures and potentials for long durations can experience crystal structural changes.

As shown in Figs. 8(a) and 8(b), chromium-related compounds were not detected in the cells operated under the
open-circuit conditions and at the current load of 500 mA/cm² even after 800 h of operation. Therefore, only small amounts of chromium-related compounds were deposited on the electrode surface. Additionally, the electrochemical deposition of chromium did not occur at the Nd₄NiO₄/YSZ interface.

4. Conclusions

In this study, we investigated the electrochemical performance and chromium poisoning of symmetrical cells consisting of Nd₄NiO₄ electrodes and a YSZ electrolyte. The sintering temperature significantly affected the catalytic activity of the Nd₄NiO₄ cathode. High-temperature sintering resulted in a strong adhesion between the cathode and the YSZ electrolyte, thus decreasing the polarization resistance of the cell. Up to 500 h of operation, the cell showed a constant potential of 500 mA/cm² in the presence of gaseous chromium species. The potential increased over the operation duration of 540–550 h. This can be attributed to the electrode/electrolyte interface and not chromium poisoning. The impedance spectra of the cells showed no significant increase in the polarization resistance after the chromium poisoning test. In addition, the XRD and EDS results suggested that no chromium-related compound was found in either the Nd₄NiO₄ cathode or the cathode/YSZ interface. Therefore, Nd₄NiO₄ is a promising material for SOFC cathodes because of its high catalytic activity and chromium poisoning tolerance.

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REFERENCES

1. L. Blum, W. A. Meulenbergh, H. Nabielek, and R. Steinberger-Wilckens, “Worldwide SOFC Technology Overview and Benchmark,” Int. J. Appl. Ceram. Technol., 2 [6] 482–92 (2005).
2. H.-Y. Jeong, K. J. Yoon, J.-H. Lee, Y.-C. Chung, and J. Hong, “Long-Term Stability for Co-Electrolysis of CO₂/Steam Assisted by Catalyst-Infiltrated Solid Oxide Cells,” J. Korean Ceram. Soc., 55 [1] 50–4 (2018).
3. K. Nakamura, T. Ide, S. Taku, T. Nakajima, M. Shirai, T. Dohkoh, T. Kume, Y. Ikeda, T. Somekawa, T. Kushi, K. Ogasawara, and K. Fujita, “Development of a Highly Efficient SOFC Module Using Two-Stage Stacks and a Fuel Regeneration Process,” Fuel Cells, 17 [4] 413-580 (2017).
4. J. H. Yi and T. S. Kim, “Effects of Fuel Utilization on Performance of SOFC/Gas Turbine Combined Power Generation Systems,” J. Mech. Sci. Technol., 31 [6] 3091–100 (2017).
5. H. An, D. Shin, and H.-I. Ji, “Pr₂NiO₄₋₄ for Cathode in Protonic Ceramic Fuel Cells,” J. Korean Ceram. Soc., 55 [4] 358–63 (2018).
6. B. Philippeau, F. Maury, C. Mazataud, S. Fourcade, and J. Grenier, “Comparative Study of Electrochemical Properties of Mixed Conducting Ln₅NiO₄₋₄ (Ln = La, Pr and Nd) and LaₓScₓFe₂O₄₋₄ as SOFC Cathodes Associated to Ce₀.₇Gd₀.₃O₁−ₓ and LaₓScₓSrₓO₄₋₈ Electrolytes,” Solid State Ionics, 249 17–25 (2013).
7. C. Sun, R. Hui, and J. Roller, “Cathode Materials for Solid Oxide Fuel Cells: A Review,” J. Solid State Electrochem., 14 [7] 1125–44 (2010).
8. A. A. Samat, M. R. Somalu, A. Muchtar, O. H. Hassan, and N. Osman, “LSC Cathode Prepared by Polymeric Complexation Method for Proton-Conducting SOFC Application,” J. Sol-Gel Sci. Technol., 78 [2] 382–93 (2016).
9. Çelikbilek, E. Siebert, D. Jauffrès, C. L. Martin, and E. Djerado, “Influence of Sintering Temperature on Morphology and Electrochemical Performance of LSCF/GDC Composite Films as Efficient Cathode for SOFC,” Electrochim. Acta, 246 1248–58 (2017).
10. D. Heidari, S. Javadpour, and S. H. Chan, “Optimization of BSCF-SDC Composite Air Electrode for Intermediate Temperature Solid Oxide Electrolyzer Cell,” Energy Convers. Manage., 136 78–84 (2017).
11. D. Heidari, S. Javadpour, and S. H. Chan, “Optimization of BSCF-SDC Composite Air Electrode for Intermediate Temperature Solid Oxide Electrolyzer Cell,” Energy Convers. Manage., 136 78–84 (2017).
12. J. C. W. Mah, A. Muchtar, M. R. Somalu, and M. J. Ghazali, “Metallic Interconnects for Solid Oxide Fuel Cell,” Int. J. Hydrogen Energy, 42 [14] 9219–29 (2017).
13. J. W. Fergus, “Metallic Interconnects for Solid Oxide Fuel Cells,” Mater. Sci. Eng. A, 397 [1–2] 271–83 (2005).
14. S. Geng, Q. Zhao, Y. Li, J. Mu, G. Chen, F. Wang, and S. Zhu, “Sputtered MnCu Metallic Coating on Ferritic Stainless Steel for Solid Oxide Fuel Cell Interconnects Application,” Int. J. Hydrogen Energy, 42 [15] 10298–307 (2017).
15. J. W. Fergus, “Effect of Cathode and Electrolyte Transport Properties on Chromium Poisoning in Solid Oxide Fuel Cells,” Int. J. Hydrogen Energy, 32 [16] 3664–71 (2007).
16. L. Zhao, S. Amarasinghe, and S. P. Jiang, “Enhanced Chromium Tolerance of LaₓSrₓCuₓFe₂O₇₋₄ Electrode of Solid Oxide Fuel Cells by GdₓCeO₃₋₄ Impregnations,” Electrochem. Commun., 37 84–7 (2013).
17. R. Wang, Z. Sun, U. B. Pal, S. Gopalan, and S. N. Basu, “Mitigation of Chromium Poisoning of Cathodes in Solid Oxide Fuel Cells Employing CuMnₓOₓ Spinel Coating on Metallic Interconnect,” J. Power Sources, 376 100–10 (2018).
18. Z. Ding, R. Guo, W. Guo, Z. Liu, G. Cai, and H. Jiang, “Preparation and Electrochemical Properties of Sr-Doped KNiF₃-Type Cathode Material PrₓSrₓCuO₄ for IT-SOFCs,” Fuel Cells, 16 [2] 525–57 (2016).
19. N. Wu, W. Wang, Y. Zhong, G. Yang, J. Qu, and Z. Shao,
“Nickel-Iron Alloy Nanoparticle-Decorated K$_2$NiF$_4$-Type Oxide as an Efficient and Sulfur-Tolerant Anode for Solid Oxide Fuel Cells,” ChemElectroChem, 4 [9] 2378–87 (2017).
20. E. Kravchenko, K. Zakharchuk, A. Viskup, J. Grins, G. Svensson, V. Pankov, and A. Yaremchenko, “Impact of Oxygen Deficiency on the Electrochemical Performance of K$_2$NiF$_4$-Type (La$_{1-x}$Sr$_x$)$_2$NiO$_x$ Oxygen Electrodes,” ChemSusChem, 10 [3] 600–11 (2017).
21. E. Boehm, J. Bassat, P. Dordor, F. Mauvy, J. Grenier, and Ph. Stevens, “Oxygen Diffusion and Transport Properties in Non-Stoichiometric Ln$_{2-x}$NiO$_{4+\delta}$ Oxides,” Solid State Ionics, 176 [37–38] 2717–25 (2005).
22. H. Yokokawa, N. Sakai, T. Horita, K. Yamaji, M. E. Brito, and H. Kishimoto, “Thermodynamic and Kinetic Considerations on Degradations in Solid Oxide Fuel Cell Cathodes,” J. Alloys Compounds, 452 [1] 41–7 (2008).
23. M. Yang, E. Bucher, and W. Sitte, “Effects of Chromium Poisoning on the Long-Term Oxygen Exchange Kinetics of the Solid Oxide Fuel Cell Cathode Materials La$_{1-x}$Sr$_x$CoO$_3$ and Nd$_2$NiO$_{4+\delta}$,” J. Power Sources, 196 [17] 7313–17 (2011).
24. E. Park, S. Taniguchi, T. Daio, J. Chou, and K. Sasaki, “Comparison of Chromium Poisoning among Solid Oxide Fuel Cell Cathode Materials,” Solid State Ionics, 262 421–27 (2014).
25. J. A. Schuler, H. Lbbe, and A. H.-Wyser, “Nd-Nickelate Solid Oxide Fuel Cell Cathode Sensitivity to Cr and Si Contamination,” J. Power Sources, 213 223–28 (2012).
26. Y. Toyosumi, H. Ishikawa, and K. Ishikawa, “Structural Phase Transition of Nd$_2$NiO$_{4+\delta}$ (0.106 \leq \delta \leq 0.224),” J. Alloys Compounds, 408–412 1200–4 (2006).
27. J. Nielsen and J. Hjelm, “Impedance of SOFC Electrodes: A Review and a Comprehensive Case Study on the Impedance of LSM:YSZ Cathodes,” Electrochim. Acta, 115 31–45 (2014).
28. N. Hildenbrand, B. A. Boukamp, P. Nammensma, and D. H. A. Blank, “Improved Cathode/Electrolyte Interface of SOFC,” Solid State Ionics, 192 [1] 12–5 (2011).
29. P. Aguiar, C. S. Adjiman, and N. P. Brandon, “Anode-Supported Intermediate Temperature Direct Internal Reforming Solid Oxide Fuel Cell. I: Model-Based Steady-State Performance,” J. Power Sources, 138 [1–2] 120–36 (2004).
30. F. Mauvy, C. Lalanne, J. Bassat, J. Grenier, H. Zhao, L. Huo, and P. Stevens, “Electrode Properties of Ln$_2$NiO$_{4+\delta}$ (Ln=La,Nd,Pr) AC Impedance and DC Polarization Studies,” J. Electrochem. Soc., 153 A1547–53 (2006).
31. I. B. Sharma and D. Singh, “Solid State Chemistry of Ruddlesden-Popper Type Complex Oxides,” Bull. Mater. Sci., 21 [5] 363–74 (1998).
32. J. Rodríguez-Carvajal, M. T. Fernández-Díaz, J. L. Martínez, F. Fernández, and R. Saez-Puche, “Structural Phase Transitions and Three-Dimensional Magnetic Ordering in the Nd$_2$NiO$_x$ Oxide,” Europhys. Lett., 11 [3] 261–8 (1990).
33. K. Ishikawa, K. Metoki, and H. Miyamoto, “Orthorhombic–Orthorhombic Phase Transitions in Nd$_2$NiO$_{4+\delta}$ (0.067 \leq \delta \leq 0.224),” J. Solid State Chem., 182 [8] 2096–103 (2009).