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The Effects of Component Tolerances on the Thermo-mechanical Reliability of SOFC Stacks

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The reliability of solid oxide fuel cell (SOFC) systems is closing the gap to meet the requirements for market implementation. Finite-element (FE) stack models, typically used for stack reliability analyses, commonly consider idealized components. In reality, dimensions and geometry of the produced stack components have statistical variations. The resulting variability in shape is expected to have an impact on the distribution of the contact pressure over the cell active area. In this study, the initial deformation of the metallic interconnect (MIC) is implemented in the stack model. The simulation starts with the simulation of the stack production and qualification. The results of this first calculation are used to simulate either thermal cycling or prolonged continuous operation. The distribution of the simulated contact pressure on the active area is found to evolve differently during thermal cycling and operation, if the initial deformation of the MIC is included in the stack model.

Introduction

Solid oxide fuel cell (SOFC) based systems are co-generators of electricity and heat, which stand out for their high efficiency, low pollutant emissions and fuel flexibility. The reliability of these systems has received growing attention in recent years, in order to satisfy the requirements for mass-market implementation. Considerable efforts have been made to enhance the reliability of SOFC stacks towards both thermal cycling and long-term operation. However, the foreseen transition from small- to large-scale production imposes stricter reliability requirements as well as lowered costs in terms of production and maintenance, whereas the current occurrence and severity of mechanical failures in SOFC stacks remain one of the most salient limitations for SOFC system commercialization, and restricts the practical operation of such systems.

The SOFC stack is an in-series assembly of SRUs (single repeating units). The nominal operation of the stack is guaranteed if all the SRUs are structurally intact. Potential mechanical failures in even a single SRU may lead to reduced efficiency and increased degradation in the best case, to temporary interruption of the operation or in the worst case to the end-of-life of the entire stack (1,8).

Decrease of the contact pressure is reported to increase the contact resistance at the interface (2), which modifies the spatial location of electrochemical reactions. This worsens not only the overall stack performance but also the current density homogeneity, potentially leading to colder zones over the cell active area. Severe thermal gradients and thus high stresses may arise, which may compromise the mechanical integrity of the cell. Then, re-oxidation is likely to occur if cracks propagate to the electrolyte, yielding to parasitic combustion that in turn increases the local thermal gradients. A further decrease of the contact pressure may lead to detachment of the contact interface. In this case, electrical contact cannot be fully recovered.

To the best of our knowledge, the capability to monitor experimentally the structural integrity of the SOFC stack components during operation has not been proven yet. For this reason, numerical thermo-mechanical investigations are of high interest during the development of new designs and validation of existing systems. They help in understanding and predicting the potential failure modes in SOFC stacks.

Finite elements (FE) models are normally used for such investigations, which consider idealized components, i.e. computational domains imported from computer-aided design (3-10). In reality, the dimensions and geometry of the produced stack components have statistical variations, because of imperfect manufacturing processes and of the costs associated with component quality. In this study, production data show that the metallic interconnect (MIC) is a component subject to such manufacturing tolerances. To our knowledge, the effect of the manufacturing tolerances of components on stack thermomechanical reliability has not been outlined yet. Instead, variability in the shape of the SRU parts, e.g. flatness and/or thickness, may contribute significantly to the uniformity of the contact pressure, and therefore should be included in stack models.

In this work, MIC deformation profiles observed experimentally are implemented in the 3-D finite elements (FE) thermomechanical model of the stack. Then, simulations were performed with this model for characterising the stack thermo-mechanical reliability during combined thermal cycling and prolonged continuous operation. The reliability is here evaluated qualitatively in terms of uniformity of the distribution of the contact pressure on the active area.

Modelling Approach

Thermo-mechanical Model of the SOFC Stack

In this study, the reliability of the SOFC stack is investigated by a FE thermo-mechanical model. This stack is based on planar, anode supported SOFC, and is operated within the intermediate-temperature range, i.e. between 600 and 800 °C.

Modelled Geometry. The nominal power of an SOFC stack is proportional to the number of piled single repeating units (SRUs). An SRU is the elementary unit of a stack. All SRUs in a stack are geometrically identical. To reduce the model runtime, the geometry implemented in the FE thermo-mechanical model comprises one SRU instead of the whole stack. The results of the analysis for an SRU are assumed to remain the same for all SRUs in the stack (7,8). Figure 1 depicts the 3-D geometry of the SRU implemented in the thermo-mechanical model of the SOFC stack analysed in this study.

To investigate adequately the effect of variations in the shape of the MIC on the stress state in the stack, several profiles of MIC initial deformation should be considered, i.e. a short stack comprising a number of identical SRUs should be modelled. In this study, a model with two SRUs is considered. This model is hereafter called “Pre-deformed MIC”. A comparative model, constituted by one SRU, is simulated. This model, hereafter referred to as “Flat MIC”, does not account for any initial deformation of the MIC. The simulation of this model aims at predicting the contact pressure distribution over the active area if very strict geometric tolerances on the MIC are imposed.

Figure 1. Exploded geometry of one SRU (8).

3-D second order, reduced integration, continuum elements are used to discretise the anode domain and the MIC. The electrolyte, compatibility layer and cathode are instead meshed by second order, reduced integration shell elements. The glass-ceramic sealants are meshed by 3-D first order, reduced integration, continuum elements.

Implementation of the Components Pre-deformation. The shape variation of the SRU components is simulated by applying a specific deformation to the component, e.g. flatness and/or thickness. In this study, imperfections in the flatness of the MIC (see Figure 1) are considered. The practical implementation of the initial deformations proceeds as follows. A preliminary FE model (called “IniDef”) including only the geometries of the MICs used in the “Pre-deformed MIC” stack model is used. The flatness of the MIC (i.e. the deformation along the MIC thickness) as a function of the in-plane directions is measured experimentally. These displacements are then applied on each mesh node of the “IniDef” model but in the opposite direction.

The resulting stress state for the three MICs simulated by the “IniDef” model is imported to the correspondent MICs of the “Pre-deformed MIC” stack model. In this second model, i) the parts are in their reference state at the start of the simulation, i.e. they are all un-deformed, and ii) the boundary condition of imposed displacement at the mesh nodes is not imported. To fulfil the force equilibrium of the model, each MIC deforms and acquires the shape measured experimentally. From this point on, the simulation of the “Pre-deformed MIC” stack model is continued with the implementation of the simulated scenarios. Figure 2 shows the arbitrarily chosen deformed shapes of the three MICs implemented in the “Pre-deformed MIC” stack model.

Figure 2. Plot of the initial deformation profile of the three MICs used in the stack model of two SRUs. For explanatory purpose, the deformation is shown magnified. GDLs, cells and sealants are not represented.

Mechanical Properties. The thermo-mechanical properties of the materials are reported in Table I. The symbols E_m , ν , σ_y and ε_{red} represent respectively elastic modulus, Poisson's ratio, yield strength and reduction strain. The temperature-dependent thermo-mechanical properties reported in Table I are at RT and 1073 K. However, the values implemented in the FE stack models include temperature dependence over the full range. A linear elastic behaviour is assumed for all ceramic components and sealants, whereas plasticity with isotropic hardening is applied for the metallic parts (MIC and GDLs). In this work, creep is implemented in all SRU materials. The model used as constitutive law for creep the Norton power law expression, which considers only the secondary creep regime (8). In this study, ferroelastic behaviour of the cathode material is not implemented.

Boundary Conditions. Under the assumptions that (i) the analysed SRU is far from the end-plates of the stack and (ii) that the stack is relatively large, modified periodic boundary conditions (MPBCs) are well suited for the thermo-mechanical analysis of the SRU (4,6,8). With this type of boundary conditions, the periodicity on the in-plane directions is respected, whereas the respective nodes on the lower and upper MIC are allowed to rotate around the y axis, as shown in Figure 3. This relative rotation is constrained to be the same for all nodes on which the MPBCs are applied.

Figure 3. Schematic of the MPBC applied on the SRU, and equations implemented in the model.

The superscripts i and j correspond to the indices of the mesh nodes, which are respectively on the upper and lower MIC. The reference nodes for the multi-point constraint are indicated by p1 and p2.

Further reduction of the computation demand is achieved by modelling only half the SRU geometry, because of the Y-axis symmetry of both the design and the temperature profile (8). This assumption is extended to the “IniDef” model (used in conjunction with the “Pre-deformed MIC” model), but it valid only if the real deformation profile of the MIC is sufficiently symmetric along the Y-axis.

TABLE I. Thermo-mechanical properties of the materials of the SRU (8,12).

	T (K)	p (%)	ϵ_{red} (%)	E _m (GPa)	ν (-)	σ_y (MPa)	CTE ^a ($\times 10^{-6} \text{ } ^\circ\text{C}^{-1}$)	B (h^{-1}MPa)	Q (kJ mol^{-1})	n (-)
<i>Anode (oxidised)</i> (NiO-YSZ)	RT 1073	19	-	124.9 119.9	0.39 -	-	12.37	-	-	-
<i>Anode (reduced)</i> (Ni-YSZ)	RT 1073	39	-0.01	72.5 58.1	0.39 -	-	12.41	1.040e+20	640	2.5
<i>Electrolyte</i> (8YSZ)	RT 1073	0	-	196.3 148.6	0.32 -	-	10.21	1.836e+07	640	0.5
<i>Compatibility layer</i> (GDC)	RT 1073	0	-	196.3 ^d 148.6 ^d	0.32 ^d -	-	12.63	6.768e+04	264	1.0
<i>Cathode</i> (LSCF)	RT 1073	29	-	10 ^b 10 ^b	0.32 -	-	15.34	5.551e+10 ^e	392 ^e	1.7 ^e
<i>MIC</i> (Crofer 22APU)	RT 1073	0	-	216.0 65.9	0.3 35	248 35	12.80	1.222e+06	344	4.73
<i>GDL fuel</i> (Ni foam)	RT 1073	93	-	0.37 0.25	0.9 0.3	0.9 0.26	16.20	7.170e+10	284	4.6
<i>GDL air</i> (Crofer 22APU foam)	RT 1073	93	-	0.39 0.12	1.7 0.25	1.7 0.25	12.80	3.380e+13	344	4.73
<i>Sealants</i> (G18 ^f)	RT 1073	0	-	67.4 ^e 14.4 ^c	0.28 -	-	11.10	1.627e+10	283	1.59

^a Temperature-dependent values implemented in the model

^b Assumed value

^c Arbitrary value of 0.2 GPa before sealing procedure

^d Values for YSZ

^e Values for dense LSCF

^f BCAS, glass-ceramic material

Modelling of the Mechanical Contact. The contact mechanical interaction is modelled by implementing both a normal and a tangential behaviour. In this study, the normal behaviour uses a “softened” non-linear pressure-overclosure relationship. This relationship is approximated by the penalty method, which considers that the contact force is proportional to the penetration distance, hence allowing a certain penetration of the contacting surfaces. The non-linear form of the pressure-overclosure relationship allows a better convergence and an acceptable level of overclosure as the contact pressure builds up (11). Furthermore, the pressure-overclosure relationship used in the model of this study does not include separation of the contacting surfaces once they are in contact. This means that independently of the potential tensile stresses built up at the contact interfaces, no detachment is simulated. The discretisation of the contact is made by surface-to-surface approach, because the normal directions of the contacting surfaces of the SRU are well approximately opposite (8,11).

In the SRU here analysed, the relative sliding between the contacting components is mostly caused by i) their thermal expansion mismatches and ii) the accommodation of the parts during the assembly of the stack with pre-deformed components (i.e. the MIC in this study). This relative sliding is expected to be of the same order of the characteristic mesh element length. Under this assumption, the small instead of the large sliding formulation is preferred because computationally less expensive (11).

For the tangential contact behaviour, the model uses a frictionless sliding approach until the end of the first heat up. In other works, friction coefficients of $0.1 \div 0.2$ have been used (3-10). In this study, it is therefore assumed that the contact pastes and the unsintered contacting layers do not constrain the relative sliding of the parts in contact. As soon as the simulated temperature has reached the curing temperature, i.e. at the end of the first heat-up, no-sliding condition is enforced for all contact interfaces, which aims at simulating the bonding caused by the sintering of the contact pastes, contacting layer and glass-ceramic sealants.

Simulated Scenarios

The thermo-mechanical analysis carried out in this study is composed of a first part defined as “initialisation sequence”, and a second part where the operating conditions are simulated, i.e. either thermal cycling or prolonged continuous operation, as represented in Figure 4. For the simulation of the operating conditions, the output of the initialisation sequence is required. For any operating condition, the stack design, material properties and manufacturing specifications remain the same. Therefore, a single initialisation sequence is simulated, and used for the analysis of all operation scenarios.

In this study, thermal transients (in Figure 4, the intervals 1-2, 3-4, 4-5 and 6-7) are assumed to occur within a time-scale much smaller than the processes at steady-state temperature (i.e. in Figure 4, the intervals 2-3 and 5-6). This entails that the creep deformation is disabled during thermal transients.

Figure 4. Representation of the simulated scenarios. Points from 0 to 4 comprise the phases of the stack production and qualification, including the first thermal cycling (shut-down 3-4). Points 4 to 7 illustrate the prolonged operation followed by shutdown.

Initialisation Sequence. The initialisation sequence aims at calculating the stresses in the stack during its manufacturing and conditioning. The production steps of interest for the thermo-mechanical analysis are (8):

- Cell sintering: the residual stresses caused by the sintering of the cell layers, i.e. anode, electrolyte, compatibility layer and cathode, are reproduced in the stack model by simulating artificial thermal strains. These thermal strains are generated by assigning an artificial CTE for each material of the cell layers and by increasing the temperature of the cell by 1 °C. The artificial CTEs are calculated using an Euler-Bernoulli 1-D model (13) including elasticity and creep, which simulates the residual stresses during the cool-down from the sintering temperature of each layer to RT.
- Assembly of the stack: a force equal to 1200 N is applied on the stack, and maintained constant over the full stack lifetime. In the model, this force is applied on the stack by using multipoint constraint.
- First heat-up: the stack is heated up to a uniform temperature of 800 °C. At the end of this simulation step, the tangential contact behaviour is switched from frictionless to no-sliding condition.
- Sealing curing: the glass-ceramic material (sealants) crystallises, and consequently a change of mechanical properties occurs. In the model, the elastic modulus is changed from 0.2 GPa to the effective value of the crystallised sealants (see Table I). The low elastic modulus before the sealing curing guarantees that negligible stresses in the sealants built up.
- Anode reduction: In the thermo-mechanical model, the mechanical properties of the anode are here switched from those of oxidised to reduced conditions.
- Stack qualification: the I-V characterisation is carried out. A uniform temperature field of 800 °C is maintained for 10 h, during which creep relaxation of the stresses in all the SRU parts takes place.

Thermal Cycling and Prolonged Continuous Operation. The resulting stresses computed from the initialisation sequence are imported as initial stress state into the thermo-mechanical simulation of the operation cases, which for this study are:

- a first thermal cycle consisting of a shutdown of the stack right after the I-V characterisation (from point 3 to 4 in Figure 4). The stack is cooled down from the uniform temperature of 1073 K to RT.
- a prolonged continuous operation in co-flow operation for 150 h. This scenario includes a first cool down from the uniform temperature of 1073 K to RT (point 3 to 4 in Figure 4), followed by heat up to the operating temperature profile (point 4 to 5). This temperature profile is maintained constant for 150 h (point 5 to 6). After this operation, the stack is cooled down to RT (point 6 to 7).

The 3-D temperature profile imported in ABAQUS for the simulation of the stack operation is calculated by an electrochemical-, fluid dynamics model, uncoupled from the thermo-mechanical one. In this model, a co-flow configuration is used. The simulated operation is internal steam-methane reforming with a partial pre-reforming of 0.5. The fuel utilisation is 0.85, whereas the temperature at the inlet of the fuel and air are both equal to 973 K. The maximum temperature on the cell is fixed to be 1100 K by manipulations of the air ratio.

Results and Discussion

The contact pressure simulated by the “Flat MIC” and “Pre-deformed MIC” models is in this work plotted as probability density function (PDF). The analysed contact interface is that between the cathode and GDL-air, since this is reported to be more critical than the one between anode and GDL-fuel (4). Positive and negative contact pressure indicates that the interface is respectively under compressive and tensile stresses. Since the “Pre-deformed MIC” model includes two SRUs (and thus two cathode/GDL-air interfaces subjected to a different contact pressure field) with an identical mesh, the equivalent contact pressure is calculated for each mesh element on the interface cathode/GDL-air as:

- the average of the values of contact pressure between one element of the GDL-air on the first SRU and the corresponding element on the GDL-air of the second SRU, if the values on the two elements are both positive.
- the minimum value of contact pressure between one element of the GDL-air on the first SRU and the corresponding element on the GDL-air of the second SRU, if at least one of the two values of contact pressure is negative. With this criterion taken into account, emphasis is placed on the probability of interface separation at either one or both SRUs, which may cause alteration of the electrical field.

Contact Pressure upon Stack Production and Qualification

The probability density function of the contact pressure between cathode and GDL-air at the end of the simulation of the stack assembly is plotted in Figure 5.

Figure 5. Probability density function (PDF) of the simulated contact pressure between cathode and GDL-air interface after the stack assembly (at RT conditions) for the case with flat MIC (blue curve) and with pre-deformed MICs (red curve). The grey part of the plot depicts the zone with negative contact pressure.

In this situation, the “Flat MIC” model predicts a homogenous contact pressure equal to 0.135 MPa. Conversely, the contact pressure simulated by the “Pre-deformed MIC” model is less uniform, and varies between 0.10 and 0.13 MPa.

Figure 6. Probability density function (PDF) of the simulated contact pressure between cathode and GDL-air interface before and after the stack qualification (at 800 °C) for the case with flat MIC (blue and cyan curves) and with pre-deformed MICs (red and orange curves). The grey part of the plot depicts the zone with negative contact pressure.

Part of the cathode/GDL-air interface is not under contact pressure, when the initial deformation of the MIC is simulated. After the first heat up and at the end of the stack qualification, the contact pressure maintains a similar distribution as at the end of the stack assembly, but offset to higher values, as shown in Figure 6.

In this case, the contact pressure of the “Pre-deformed MIC” model becomes more homogeneous after the stack qualification, compared to the contact pressure distribution at the end of the stack heat-up (by comparing the red and orange curve, corresponding respectively to point 2 and 3 of the initialisation sequence). Also at high temperature, both after the first stack heat-up and at the end of its qualification, part of the cathode/GDL-air interface is not under contact pressure for the case with pre-deformed MICs.

Contact Pressure upon Thermal Cycling and Prolonged Operation

The distribution of the contact pressure between cathode and GDL-air for the two simulated operation scenarios is plotted in Figure 7 and Figure 8, respectively at RT and HT.

Figure 7. Probability density function (PDF) of the simulated contact pressure between cathode and GDL-air interface after stack shutdowns (i.e. at RT) for the case with flat MIC (blue and cyan curves) and with pre-deformed MICs (red and orange curves). The grey part of the plot depicts the zone with negative contact pressure.

At the end of the first thermal cycle (i.e. the shutdown right after the stack qualification, from point 3 to 4), the contact pressure for both simulations “Flat MIC” and “Pre-deformed MIC” with the stack cooled down to RT (point 4, as shown in Figure 4) is in general significantly lost over large regions of the cathode/GDL-air interface. The case “Flat MIC” shows that the contact pressure is severely lost, with a small part of the interface subjected to relatively high tensile stresses (see the peaks of PDF between -0.3 and -0.6 MPa in Figure 7). At the same condition, the simulation “Pre-deformed MIC”

shows that the averaged contact pressure is partially lost on the active area, whereas approximately 60% of the interface is maintained under positive contact pressure.

Prolonged stack polarization changes conspicuously the distribution of contact pressure, see cyan and orange curves in Figure 7, corresponding respectively to the simulation of “Flat MIC” and “Pre-deformed MIC”, with the stack cooled down to RT after 150 h of operation (i.e. point 7). In this state, the contact pressure calculations by both the “Flat MIC” and “Pre-deformed MIC” models indicate a partial recovery of the contact pressure: for the first simulation, a large part of the interface remains under tensile stresses, whereas for the second one, the contact pressure is mostly positive and more uniform (from 0.02÷0.13 MPa at point 4, to 0.03÷0.08 MPa at point 7).

Figure 8. Probability density function (PDF) of the simulated contact pressure between cathode and GDL-air interface at the start and at the end of the stack operation (at HT) for the case with flat MIC (blue and cyan curves) and with pre-deformed MICs (red and orange curves). The grey part of the plot depicts the zone with negative contact pressure.

Compared to the situation at point 4 shown in Figure 7 (i.e. at RT, after the stack qualification), the distribution of the contact pressure when the stack is heated up to the operation temperature field (from point 4 to 5) evolves differently whether a flat or a pre-deformed MIC is simulated in the stack model, see Figure 8. From the simulation of “Flat MIC” model, the contact pressure is largely recovered in comparison with point 4. However, the distribution is largely heterogeneous, with zones subjected to both relatively high compressive stresses (~ 0.45 MPa) and tensile stresses. Instead, from the calculation on the “Pre-deformed MIC” model, a similar pattern of the contact pressure distribution is found between point 4 and 5, although the values of contact pressure are considerably higher for the point 5 (i.e. with the operation temperature field).

During prolonged stack polarization, the distribution of the contact pressure is found to vary more widely for the “Flat MIC” than for the “Pre-deformed MIC” model, as plotted in Figure 8. For the first model, the simulation results (cyan curve) show that a relatively small zone of the active area is subjected to tensile stresses, in comparison with point 5.

For the second model, the distribution of the contact pressure does not evolve significantly, but the active area is subjected to lower values of contact pressure (orange curve, point 6, compared to the red curve, point 5).

Conclusions

From the “Pre-deformed MIC” model simulation, the contact pressure distribution during the stack production on the cathode/GDL-air interface is found heterogeneous. However, during the I-V characterisation at high temperatures, creep in the stack materials relaxes the stresses. As a result, the contact pressure distribution becomes much more homogenous at the end of the stack qualification.

For the stack design, material, operating conditions and initial MIC deformations considered in this study:

- The highest probability of interface detachment is predicted when the stack is shut down after its qualification with the simulation of a flat MIC in the stack model, because high tensile stresses on a large part of the cathode GDL-air interface are found.
- The evolution of the contact pressure distribution during polarization is less than in the case of a flat MIC. In this last model, not only tensile but also high compressive stresses are found on a small zone of the interface: they may cause relevant inelastic deformations of the GDLs and in turn modify the flow field in the stack.
- Particular worsening of the contact pressure and therefore of the stack reliability is not found if initially deformed MICs are used in the assembly.

However, the modification of the contact pressure distribution upon thermal cycling and prolonged polarization for both “Flat MIC” and “Pre-deformed MIC” suggests that variation of the nominal performances may occur.

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References

1. D. Curran et al., Adv. Solid Oxide Fuel Cells VIII - 36th Int. Conf. Adv. Ceram. Compos. ICACC 2012, 61–69 (2013).

2. T. Dey, D. Singdeo, M. Bose, R. N. Basu, and P. C. Ghosh, *J. Power Sources*, **233**, 290–298 (2013).
3. A. Nakajo, Z. Wullemin, J. Van herle, and D. Favrat, *J. Power Sources*, **193**, 203–215 (2009).
4. A. Nakajo, F. Mueller, J. Brouwer, J. Van herle, and D. Favrat, *Int. J. Hydrog. Energy*, **37**, 9249–9268 (2012).
5. A. Nakajo, Z. Wullemin, J. Van herle, and D. Favrat, *J. Power Sources*, **193**, 216–226 (2009).
6. A. Nakajo, F. Mueller, J. Brouwer, J. Van herle, and D. Favrat, *Int. J. Hydrog. Energy*, **37**, 9269–9286 (2012).
7. F. Greco, H. L. Frandsen, A. Nakajo, M. F. Madsen, and J. Van herle, *J. Eur. Ceram. Soc.*, **34**, 2695–2704 (2014).
8. F. Greco, A. Nakajo, Z. Wullemin, and J. Van herle, *ECS Trans.*, **68**, 1921–1931 (2015).
9. C.-K. Lin, T.-T. Chen, A.-S. Chen, Y.-P. Chyou, and L.-K. Chiang, in, vol. 7, p. 1977–1986, ECS (2007) <http://ecst.ecsdl.org/cgi/doi/10.1149/1.2729310>.
10. C.-K. Lin, T.-T. Chen, Y.-P. Chyou, and L.-K. Chiang, *J. Power Sources*, **164**, 238–251 (2007).
11. ABAQUS 6.14 Documentation, Dassault Systèmes Simulia Corp., Providence, RI, USA, (2014).
12. A. Nakajo et al., *Ceram. Int.*, **38**, 3907–3927 (2012).
13. A. Nakajo, J. Van herle, and D. Favrat, *Fuel Cells*, **11**, 537–552 (2011).