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A REVIEW OF STRESS ANALYSIS ISSUES FOR SOLID OXIDE FUEL CELLS

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ABSTRACT

Solid oxide fuel cells represent a potentially important application for ceramic materials. There are, however, some significant issues which can affect the reliability and durability of the cell. The generation of stresses and associated strains in fuel cells is an important concern that needs to be addressed in order to avoid mechanical failure of the cell. Few comprehensive studies have been published on the subject of stress analysis of planar and tubular SOFCs to-date, although various numerical methodologies have been used to obtaining the stress distribution in specific SOFC components over the last 10 years. The objective of this paper is to summarize the state-of-the art of solid oxide fuel cell stress analysis efforts so that the salient issues can be identified.

Key words: Solid oxide fuel cells, stress analysis, thermal expansion coefficient, mechanical failure

1. INTRODUCTION

Solid oxide fuel cells (SOFCs) are electrochemical reactors that convert chemical energy into electrical energy and typically operate at temperatures around 800-1000°C

(though so-called low temperature SOFCs are the subject of much research). Both planar and tubular SOFCs structures are commonly found. The planar geometry consists of a trilayer, flat plates of anode-electrolyte-cathode, and interconnects (Fig. 1) [1]. Tubular structure consists of cathode or anode as the internal part of the tube and the anode or cathode as the external part of the tube (Fig. 2).

Fig. 1: Schematic representation of a planar SOFC

Fig. 2: Tubular solid oxide fuel cell

Nowadays SOFCs systems are being developed as alternative energy conversion devices with several potential benefits, including low pollutant emissions, excellent operating efficiency, as well as the potential for use with existing hydrocarbons, in addition to hydrogen and hydrogen-rich fuels. Although the high operating temperature of the SOFC has various benefits over other types of fuel cells, including flexibility of fuel used and relatively inexpensive materials, it can also lead to problems for example large stresses due to the different expansion coefficients of the various cell materials, electrode sintering, and interfacial diffusion between the electrolyte and electrode and between the electrode and interconnects [4].

In SOFCs, stresses play an important role from the structural and the operational point of view. The temperature changes cause variation in thermal expansion coefficients (TECs) that result in thermal stresses. Furthermore, temperature gradients that occur differently during start-up, shut down, and operation can make it worse. During cooling procedure, outside surface temperature is lower than the inside temperature of the component, due to which outside surface of the cell material tends to shrink (Fig.3. (a)). Thus, the outside surface of the cell component remains under tensile stress while the inside is subjected to compressive stress, see Fig.3. (b).

Fig. 3: (a) Shrinkage of cell component after cooling. (b) Stresses in cell component after cooling.

Since the various layers in composites are rigidly bonded, any difference in properties of composite materials can cause residual stresses. If these stresses exceed the strength of the materials, crack or fracture may occur in the sealant or cell and eventually cause failure of the entire stack of cells [5]. Electrolyte cracks may lead to fuel leakage across the cathode and associated reaction with air with no generation of electricity [6]. Moreover, the difference in thermal expansion of electrolyte and electrode material may cause delamination of electrodes which results in interruption of the current path. All these factors can significantly reduce the reliability and lifetime of a SOFC.

Durable and reliable design is essential for the successful fabrication of SOFC systems. Therefore, it is imperative to find and eliminate the reasons behind stress-related failures in SOFCs. Failures of SOFC stacks arise from the degradation of materials and large temperature gradients under steady-state operating conditions. It may not be possible to completely eliminate stress related failure at the present time, but it can be mitigated by addressing the issue to make a more robust cell design. The goal of this paper is to identify the basic causes of failure due to stresses in SOFCs. This will be helpful in identifying the as yet unsolved problems of cell failure during heating and cooling.

2. FUNDAMENTAL CAUSES OF STRESSES IN SOFCs

The following are the main causes of stresses in a fuel cell:

1. The sintering stage, during the manufacturing process, generates residual stresses owing to mismatch of the TEC of the cell materials.
2. A normal mechanical load (compressive force) is applied during the assembly of the stack in order to ensure good electrical and mechanical contact to prevent leakage of the gases. After loading, friction prevents the tangential expansion of components during heat-up and operation.

3. There are changes in the mechanical properties of the anode materials which occur during the reduction and re-oxidation process when fuel is fed for the first few times at cell start-up. It has been reported that fractures can occur due to the rapid oxidation and volume expansion of the Ni particle in Yttria-stabilized zirconia (YSZ) matrix [7]. The volumetric expansion (cubical dilatation) also causes an increase in the anode volume. Malzbender et al. [7] suggest that this expansion in the anode results in tensile strain in the electrolyte, which can cause fracture of the electrolyte. Cell-component curvature (bending) can develop due to shrinkage of the anode material on the support.

4. The temperature profile during operation depends on the cell design and fuel and air flows. Regions of high temperature may cause buckling of the structure and redistribution of the assembly load, which may further lead to partial loss of electrical contact and sealing pressure on the gaskets. Knowledge of temperature profiles in the stack is thus very important to obtain a good reliable design.

3. OVERVIEW

A rather limited body of research has been conducted on stress analysis of SOFCs. Montross et al. [8] published what appears to be the first paper on thermal stress analysis for planar SOFCs. They examined lanthanum chromite ceramic material and found that the change in the crystal structure is the basic reason for thermal stresses as it changes the thermal expansion coefficient and elastic modulus of the cell material. Khaleel et al. [9], who examined SOFCs but did not focus specifically on thermal stress analysis, considered transient temperature profiles for cross-flow, co-flow and counter-flow configurations. Selimovic et al. [10] focused on the stress caused by the differences in thermal expansion coefficient when high temperature gradients occur in SOFC layers during steady-state and transient operation (heat-up, start-up and shut-down). The stresses to which the ceramic components are subjected can arise from: manufacturing (residual stresses), differential thermal expansion coefficients of the cell layers, temperature gradients, oxygen activity potential, and external mechanical loading. The magnitude of these stresses depends on the material properties, the operating conditions and the geometry of the design. Residual stresses will arise due to differences in thermal expansion coefficient and/or Young's modulus of adjacent layers. The mismatch stresses can result in delamination of layers and the formation of micro cracks in the weaker layers [10].

Nakajo et al. [11-13] calculated thermal stress in anode-supported planar SOFC stacks in three different studies. In the first study, they modeled thermal stress in a tubular SOFC in order to assess the probability of cell survival [11]. They found that the stress fields consist of high tensile stresses in a limited area at the ends of the cell in the electrolyte and significant values in the whole anode, which was due to a high coefficient of thermal expansion. In the second study, they related the probability of cell failure to various factors including stress due to the magnitude of thermal gradients [12].

In the third study, Nakajo et al. [13] examined how cell stresses led to failures due to loss of gas tightness, electrical contact and thermal buckling. Lin et al. [14, 15] also published two papers on thermal stress analysis of planar SOFC stacks. In the first paper, a thermal analysis of glass-ceramic sealant (rigid seals) at shutdown, start-up, and steady-state stages of a planar SOFC stack was conducted, and the authors investigated the effects of bottom support frame condition, cell position, temperature gradients, viscous behavior of the glass-ceramic sealant, and the sensitivity to thermal expansion coefficient using a 3D finite element analysis (FEA) code [14]. In the second paper, mica-based compressive seals were considered to describe effects of thermal stress analysis and thermal expansion coefficient in planar SOFC stacks [15]. Mica-based compressive seals are non-bonding and compliant; therefore, thermal expansion mismatch is not as severe as for rigid seals.

In planar SOFC designs, seals are required between each cell to prevent or minimize leakage of gases from the stack and mixing of fuel with oxidant gas [16]. A seal should be stable at elevated temperatures and in harsh operating environments (oxidizing, reducing, and humid). Essentially there are two types of cell-to-frame seals that designers employ in the planar SOFC stack design: (1) rigid seals and, (2) compressive seals. Each seal has its own set of advantages and limitations. In rigid seals, ceramic cell and metallic interconnect are rigidly bonded to each other [17]. Rigid seals are classified into glass or glass-ceramic sealants and metallic brazes. Glass or glass-ceramic materials are the most common sealant materials and have been demonstrated to operate for more than 1000 hours without any degradation [18]. The glass transition temperature, T_g , and TEC play an important role in selecting glass sealants. T_g is the critical temperature at which glass changes its behavior from hard and brittle to elastic and flexible (i.e. glassy to rubbery state). It is lower than the melting temperature, T_m , of the glass. For glass or glass-ceramic sealant, T_g varies from 667°C to 760°C and TEC from 10.6 ppm/°C to 11.5 ppm/°C. Typically-used glass and glass-ceramic sealants are boroaluminosilicates, borosilicates, aluminosilicates, silicates, and borate. Above the SOFC operating temperature, glass seals become soft and viscous to provide hermetic seal by mechanical or chemical bonding [19]. On the other hand, below the operating temperature, glass crystallizes to form a rigid bonded seal. A metallic braze is the other approach to obtain a rigid seal in which metallic materials (generally based on silver and gold) are used. Metallic materials can undergo plastic deformation and have higher stiffness than ceramics. These allow accommodation of thermal and mechanical stress during operation. This type of seal has been shown to operate at 750°C for 800 hours without any degradation in strength. In compressive seal, gas leakage is prevented by applying sufficient compressive load to deform a metallic gasket. Here residual stresses are not produced (or are considerably reduced) because the compressive seal is not rigidly bonded to the ceramic cell and metallic interconnect as in rigid seals. Compressive seals are also classified into two groups as metallic compressive seals and mica-based

compressive seals. Ductile metals (silver and gold as base materials) are used in the metallic compressive seal while mica-based materials are used in mica-based compressive seals. Muscovite and phlogophite are the most commonly used mica-based sealants. Mica-based seals have a TEC of 12-13 part per million (ppm) /K and can operate up to 800°C without any degradation. Compressive seals offer excellent material compliance and; therefore, the capacity to accommodate large mismatched strains between components that display significantly different thermal expansion coefficients and reduce leak rates by closing small gaps. However, the rigid bonded seal eliminate the need for a load frame, which is required in the compressive seals. However, there are several challenges with the use of rigid seals in SOFCs. They are susceptible to crack formation because of their brittle behavior below T_g , and glass tends to react with other cell component, for example it reacts with the electrodes at SOFC operating temperatures [19]. In addition, glass or glass-ceramic sealant is vulnerable to thermal shock [17]. On the other hand, in compressive seals the individual stack components are free to expand and contract during thermal cycling because these seals are non-bonding. Weil et al. [20, 21] were the first to introduce the bonded compliant seal in planar SOFC on the basis of previous knowledge of seals. They developed compliant seals or bonded compliant seals that attempt to incorporate the advantages of both rigid and compressive sealing. The bonded compliant seal is composed of a thin, deformable metal foil which is bonded to the adjacent metal and ceramic components (Fig.4); it is generally expected to display an excellent hermetic seal with high mechanical integrity under thermal cycling and mechanical vibration.

Fig. 4: Schematic of a bonded compliant seal

One of the main advantages that this type of seal offers is that a wide range of alloy compositions can be considered for use in planar SOFC interconnects. Weil and Koepfel [21] concluded that the initial cell design is likely to work well in terms of thermal stress reduction, but will require further modification to reduce the potential for excessive cell bowing. The amount of bowing was relatively small when the structure was cooled to the operating temperature (800°C), but increased when cooled down to room temperature. According to Weil et al. [20], the

maximum stresses and strains calculated in each component during each thermal cycle are within acceptable limits for the materials under consideration. A computational analysis of the thermal effects occurring in the structure during a second thermal cycle indicated that nearly all of the component stresses are lower than those experienced in the first cycle. Compared to the glass ceramic sealant and brazed seal, the bonded compliant seal sustained more stress in a ceramic cell with thermal expansion mismatch between adjacent metal components [22]. Seals are the most important component to control or reduce stresses by allowing free expansion and contraction of the cell and the interconnect during thermal cycling and operation.

Chiang et al. [23] constructed a 3D SOFC model to evaluate thermal fluid behavior, with electrochemical reactions and thermal stresses in an anode-supported SOFC. Zhang et al. [24] focused on analytical modeling of planar SOFCs and examined the main stresses resulting from the differential TECs. They found that for a fixed anode thickness, stress decreased with increase in electrolyte thickness. On the other hand, for a fixed electrolyte thickness, stress decreased with decrease in anode thickness. The analysis suggested that the anode is the layer which is most susceptible to fracture, at least for anode supported positive electrode-electrolyte-negative electrodes. Therefore, the stresses in the anode are of primary concern to improve the reliability of the anode supported positive electrode-electrolyte-negative electrode. Further, Fischer and Seume [25] modeled tubular SOFCs to improve the understanding of thermomechanical stress, in particular to clarify the three following aspects: (1) The impact of direct versus indirect internal reforming of methane on thermomechanical stress in the ceramic positive electrode-electrolyte-negative electrode assembly; (2) The separate contribution of absolute temperature, and thermal gradients to the production of stress; and (3) The thermal model accuracy required for thermomechanical stress analysis. Fischer and Seume [25] also found that in tubular SOFCs, thermal gradients are a much less significant cause of thermal stress than is generally believed.

Cui and Cheng [26] constructed a 2-D axisymmetric numerical model of a micro-tubular SOFC to evaluate various failure factors including thermal stresses. The results of this work indicated that a micro-tubular cell can operate without failure, unless there are interfacial defects or high tensile stresses at the electrolyte, when failure will occur. Jiang and Seume and Chen [27] predicted cell temperature by means of a finite-volume model which was subsequently imported into a FEA code to calculate the thermal stresses for a bonded compliant seal design. In SOFCs, ceramic and cermet components may fail due to brittle fracture, and metallic components due to plastic deformation [28]. The brittle fracture is more damaging than plastic deformation.

4. TYPES OF STRESSES IN A SOFC

4.1. Residual stresses

Residual stresses are internal stresses that occur in a component, assembly, or part, in the absence of external loads

or temperature gradients. Large temperature changes upon cooling from, say, 1400°C to room temperature during cell fabrication induce residual stresses [29]. In general, one component in the SOFC structure is mechanically stiffer than the rest, therefore, other components are forced (as long as they are adherent) to be comply with the the displacement of the stiffest component which remains nearly stress-free [28]. For example, residual stresses are smaller in unconstrained or constrained flat electrolyte supported cells. As reported by Atkinson and Sun [28], in electrolyte supported SOFCs, anode and cathode are subjected to a residual tensile stress upon cooling to room temperature because they have higher TECs (13.1ppm/K and 12.4 ppm/K, respectively) than electrolyte (10.5 ppm/K). In planar SOFCs, three layers are rigidly bonded together; therefore, any mismatch in thermal expansion of the materials can cause residual stresses that result in curvature of cells [5, 7]. This curvature is smaller in sealed cells as compared to unconstrained cells, because of thermal expansion differences between the materials in the laminated surfaces. When a cell is sealed into the external structure of the frame and interconnects, the stiffest component of the cell is the interconnect, not the anode. Residual stresses in anode-supported SOFCs depend on the relative values of the TECs of the anode and interconnect materials.

Atkinson and Selcuk [30] produced laminated ceramic positive electrode-electrolyte-negative electrode by using layers of YSZ, 5μm thick and gadolinia-doped ceria, 180μm thick. They estimated the residual stresses from the curvature of the laminates and the elastic constants of the individual layers. Yakabe et al. [31] determined residual stresses experimentally and numerically in the electrolyte of an anode-supported planar SOFC at room temperature. According to the authors, an accurate simulation of thermal stresses is difficult to achieve in practice, because the residual stresses in the cell after cooling are not well-known. Malzbender et al. [32] discussed residual stresses in terms of addressing aspects of curvature during the reduction of the anode in an anode-supported planar SOFC. They concluded that the curvature indicated the presence of residual stresses in the cells. In an anode-supported planar SOFC, the nature of stresses in the anode was observed to be tensile because the curvature is lower than the curvature of the electrolyte due to higher stiffness. In the electrolyte, these stresses have been found to be compressive. Any change in the dimensions of the components due to effects of thermal expansion, sintering or reduction can be harmful to the stack integrity and ultimately the reliability of the cell.

4.2. Mechanical assembly stresses

Mechanical stresses are produced due to application of external loads during stack assembly. After loading, friction prevents the tangential expansion of components during heat-up and operation.

4.3. Chemically induced stresses

In SOFCs, interconnects are exposed to oxygen on one side and fuel on the other. A significant oxygen partial pressure

gradient arises on the two side of the interconnect because the different partial pressures of oxygen on cathode side (10^{-4} to $10^{-0.7}$ bar) and on anode side (10^{-18} to 10^{-8} bar) [33]. Furthermore, there are dimensional changes in the interconnect in terms of microstructure, and chemistry at an operating temperature of around 800°C in the presence of oxidizing and reducing atmospheres which cause mechanical stresses which result in cracking or warping of the seal. This reduces the overall performance of the stack. The reliability and service life of the SOFC not only depend on chemical and electrochemical stability of its components but rather its capability to withstand mechanical stresses that are generated during operation [34].

4.4. Thermal stresses

Thermal stresses are among the chief factors in failure of the fuel cell and associated sealants. Thermal stresses arise from temperature gradients and generate cracks in the cell due to mismatch in the TEC of the cell materials at startup and shutdown. These stresses are produced during cell operation. The stress field caused by a uniform temperature distribution and a thermal gradient is just the sum of two individual stress fields (principle of superposition) [25]. From a structural point-of-view, thermal stresses play an important role. Since the SOFC operating temperature is high, there are problems relating to the reliability of ceramics as cell materials [35]. Temperature changes during startup and shut-down induce thermal stresses in the ceramic SOFC components. Rapid localized heating or cooling can result in temperature gradients within the cell, which cause thermal stresses in the structure and potential stack failure due to crack formation and propagation [36]. Therefore the distribution of cell temperature should be as even as possible to avoid failure due to thermal stresses. Thermal stresses develop during operation e.g. with initial warm-up, exothermic fuel oxidation, endothermic fuel reformation (in some cases), and ohmic heating due to the flowing electric current [6]. The mismatch of expansion coefficients of cell components throughout the thermal cycling results in severe thermal stresses which can make the interface layer delaminate [37].

The basic constitutive relationship of thermal stresses and strains for a linear thermoelastic solid is given by the Duhamel Neumann relationship (employing Einstein's summation convention):

$$\varepsilon_{ij} = \frac{1}{2G} \left(\sigma_{ij} - \frac{\nu}{1+\nu} \sigma_{kk} \delta_{ij} \right) + \alpha \Delta T \delta_{ij} \quad (1)$$

where σ_{ij} are the components of the stress tensor, ε_{ij} those of the strain tensor, α is the thermal expansion coefficient, ν is Poisson's ratio, and ΔT is the change in temperature.

$$\Delta T = T - T_0 \quad (2)$$

where T is the final temperature, and T_0 is the initial temperature. The shear modulus, G , is defined as:

$$G = \frac{E}{2(1+\nu)} \quad (3)$$

where E is Young's (elastic) modulus.

5. STRESS ANALYSIS IN POROUS MEDIA

In the porous transport layer(s), the motion of the gases is controlled by various parameters, such as the morphology of the microstructures (e.g., porosity, pore size and shape, permeability, pressure in the channels and porous layers, gas composition, inlet conditions etc. To evaluate thermal stresses a better understanding of thermal engineering applications for porous material is required.

Rice et al. [38] have given an approach to define total stresses, σ_{ij} , and pore pressure, p , as state-variables and relate these to the strains in the solid:

$$\varepsilon_{ij} = \frac{1}{2G} \left[(\sigma_{ij} + p\delta_{ij}) - \frac{\nu}{(1+\nu)} (\sigma_{kk} + 3p)\delta_{ij} \right] + \frac{1}{3} \left(\frac{1}{H} - \frac{1}{K} \right) p\delta_{ij} \quad (4)$$

where the bulk modulus is:

$$K = \frac{2G(1+\nu)}{3(1-2\nu)} \quad (5)$$

and H is the Biot constant. It represents the coupling between the stress and the pore pressure.

6. EFFECTS OF VARIOUS PARAMETERS ON STRESS GENERATION

6.1. Effects of thermal expansion coefficient (TEC)

The TEC mismatch is the primary reason for thermal stresses in the various layers of a SOFC. Fundamental processes take place across the cell components including heat and mass transfer, electrochemical reactions, and ionic transport across the electrolyte [8]. These generate temperature and other gradients in the cell components. The difference in TEC of the components causes residual stresses that may damage the structure of the SOFC [21]. When the TECs of all the cell components are the same or similar, and there are no temperature gradients, no stress can develop in the system. Jiang and Chen [27] claim that in anode-supported cells, the probability of failure can be reduced by reducing the TEC of the anode. The minimum thermal stress is obtained in a co-flow arrangement (as compared to cross-flow and counter-flow) [27]. Two causes are responsible for temperature gradients: (1) chemical reactions generate more heat near the fuel inlet, and (2) air is effective for cooling, as compared to fuel [14]. Note the TEC cannot be measured directly for every material within a SOFC [39].

6.2. Effects of the cell geometry of the cell

In the case of anode-supported tubular SOFCs, expansion is greater in the outer parts of the cell tube owing to positive (higher) thermal gradient for the inside to the outside of the tube. This leads to a tensile stress at the inner part of the cathode in tubular SOFC. Fischer and Seume [25] concluded that in tubular SOFCs the temperature gradients are less important cause of thermal stress than is commonly believed. In micro-tubular anode-supported SOFCs, the principal stress is

greatest in the electrolyte. The probability of failure in all components of the cell (except the cathode) decreases with a decrease in the cell voltage [27]. The temperature at the entrance of the tubular SOFC is lower than that at the exit [40].

6.3. Effects of type of support used

In an anode supported planar SOFC, the anode is subjected to tensile stresses, while electrode and electrolytes are subjected to compressive stresses [24]. Tensile stresses are a more frequent cause of ceramic material fracture than compressive stresses [27]. The magnitude of the compressive stress in the cathode is lower than that in the electrolyte in an anode-supported SOFC. Therefore, the difference between the TEC of the electrolyte and the anode is the decisive factor of cell failure in anode-supported SOFC. The TEC and tensile strength are the two fundamental issues in electrolytes [41].

6.4. Effects of type of seal used

Two standard seals are used in SOFCs: (a) rigid seals and (b) compressive seals. Glasses or glass ceramics are used in rigid seals and compressive seals require an externally applied load. Both have advantages and limitations. The rigid seal is the simplest and most economical seal, but it cannot be used at the maximum operating temperature of the cell because it becomes soft at higher temperatures [6]. In compressive seals, a compliant high temperature material is compressed by using a load frame external to the stack between two sealing surfaces. The mismatch of TEC in rigid seals is more severe than compressive seals [26]. Furthermore, a compressive sealant is suggested as it is replaceable and more convenient to use. Recently, the bonded compliant seal was introduced by Weil and Koepfel [21]. They found that bonded compliant seals worked well initially, in terms of thermal stress reduction, but some modifications are required to avoid excessive cell bowing.

6.5. Effects of temperature distribution

In SOFCs, the temperature distribution depends on the current density, fuel and oxidant utilization. A uniform temperature distribution can be acquired at 0.3 m s^{-1} fuel flow rate for 2000 A m^{-2} average current density [40]. Kanamura et al. [40] concluded that thermal stresses in the electrolyte region are an extremely important factor for decomposition of tubular SOFCs, because highest temperatures are observed in the electrolyte. Heat energy is produced due to the entropy change associated with the electrode reaction. This change in entropy depends on the partial pressures of hydrogen and steam, and oxygen, [39]. Therefore, changes in entropies of electrodes greatly influence the temperature distribution in SOFCs. The entropy change for an electrode reaction cannot be reduced, because it is a thermodynamic phenomenon. The improvement of anode materials and reduction in electrolyte thickness help to reduce heat generation caused by anode polarization losses and the ohmic resistance of the electrolyte (Joule heating). It has been shown that in electrolyte supported SOFCs, the maximum principal stresses occur in the electrolyte at the maximum

temperature location for the co-flow configuration with internal steam reforming [28]. These maximum stresses are one order of magnitude smaller in internal steam reforming than for external steam reforming, because there is no sudden temperature drop from the endothermic steam reforming reaction.

6.6. Effects of porosity

Porosity is an important factor which can affect mechanical properties of cell materials. The dependence of effective modulus of elasticity on porosity is proposed as follows by Kanamura et al. [39]:

$$E = E_0 (1 - 1.9 \times \phi + 0.9 \times \phi^2) \quad (6)$$

Where ϕ is the porosity of the cell material, E_0 is the modulus of elasticity for $\phi = 0$. It has been observed by Radovic and Lara-Curzio [34] that the elastic and shear moduli of NiO-YSZ decrease with increasing porosity. The anode NiO-YSZ is transformed into a Ni-cermet when the first time hydrogen fuel is supplied. There is a change in volume, porosity, and physical and mechanical properties of the anode layer owing to the reduction of NiO into Ni-metal [34]. There is thus also a need to evaluate a relationship between porosity and TEC in future.

6.7. Effects of voltage

Selimovic et al. have found that lower cell voltage (0.6 V) results in higher stresses (48 MPa) owing to higher local currents and accordingly higher temperature gradients [10]. During the changes in electrical load (during start-up and shut down), the temperature distribution may change rapidly [28]. In these cases, the temperature distribution will depend on stack size, heat transfer between the stack and the surroundings, and heat transfer within the stack components.

7. IMPROVEMENTS IN STRESS ANALYSIS

Further improvements in modeling are required to determine accurate values of stresses in stacks and single SOFCs and also at micro-scale levels. There is, to-date, no body of literature specifically related to stress analysis in the consolidated porous transport layers of SOFCs. Porosity clearly plays an important role during the expansion and contraction of ceramic materials in SOFCs, and affects the effective mechanical properties of the cell. Special attention should be given to study the effects of porosity on TEC of ceramic components in SOFCs. Data on the effective physical and mechanical properties of the various SOFC layers for the prediction of the initiation of material delamination and formation of micro-cracks or weak layers needs to be compiled.

8. CONCLUSION

In this paper, a review of the various stresses, reasons for their generation, and impact of different parameters have been presented and discussed. Further improvements in mathematical and computational analysis to evaluate the residual stresses caused by the manufacturing process as well as understanding the impact of TEC, oxygen activity potential, temperature gradient etc. are all required. There is much

variation of TECs within adjacent layers. For example, in a typical anode-supported cell, the TEC of the anode is higher than that of the cathode and the electrolyte, thus, the anode shrinks more than the cathode and electrolyte. This results in differential stresses within adjacent layers. A knowledge of the temperature field is pre-requisite to analysis of thermal stresses in SOFC components. Several methods are available for performing calculations for thermally-induced stresses in SOFC stacks. Existing work presents a variety of different results based on different model parameters, properties of cell materials and methods. Change in properties of the fuel cell materials as a function of temperature and time, is a key factor for introducing stress. At present, it is generally required to use material properties derived from the literature for modeling. Therefore it is necessary to obtain reliable data for mechanical and thermal properties of SOFC materials. There is also a need to conduct studies comparing numerical and experimental results for cells and stacks. The design goal is to match stresses in adjacent layers, as far as possible, in order to improve the reliability and lifetime of the cell. These factors need to be considered in order to predict the behavior of the material during manufacturing, start-up, operation and shut-down stages. In future, to get accurate results from modeling, the studies and models of stresses and strains in porous media are required. Accurate calculation of temperature distribution and knowledge of practical operating conditions are important issues for heat management in SOFCs.

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NOMENCLATURE

E_0 = elastic modulus in pure solid (GPa)
 E = elastic modulus (GPa)
 G = shear modulus (GPa)
 H = Biot constant
 K = bulk modulus (GPa)
 p = pore pressure (Pa)
 T_0 = initial temperature (K)
 T = final temperature
 ΔT = temperature gradient (K)

“Greek Letters”

α = thermal expansion coefficient (ppm/K)
 ϵ_{ij} = strain component
 σ_{ij} = stress component (MPa)
 ϕ = porosity
 ν = Poisson's ratio

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