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Structural analysis of solid oxide fuel cell under externally applied compressive pressure

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Abstract

Solid Oxide Fuel Cells is considered as the power source having potential to satiate electrical as well as thermal energy demands for domestic and commercial applications. Assembly of the SOFC structure is subjected to a wide range of pressures on the surface, resulting in normal force on the plates. The application of pressure causes deformation of composite sealant which exhibits plastic behavior at high operating temperature. The present study shows the effect of externally applied pressures on the contact pressure between cell components. The natures of stresses in the flow channels, gaskets and both electrodes have also been evaluated. This holds importance as a measure of safety for the electrodes. It is noted that significant stress generation occurs near to the edge where the channel makes contact with the electrode. The study highlights a safe pressure range (0.05 – 0.1 MPa) for operation of the SOFC under consideration.

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Keywords:

1. Introduction

Solid Oxide Fuel Cells are regarded as a viable domestic power source due to the capability of generating both electric and high quality heat energy.While the principal focus is to achieve efficient production of electricity, the exhaust of the SOFCs can also be utilized as a source of heat energy and in combination with a Micro-Gas Turbine

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to extract mechanical work[1-2]. Thus, it is important to study and optimize solid oxide fuel cells for good performance. It has been observed from experimental studies that performance of the SOFC substantially deteriorates with increase in the active area. Amongst allother factors, contact resistances between the electrode and interconnect has a major contribution to the overall observed loss [3]. Both the meeting surfaces have some inherent surface roughness as it is not possible to achieve a perfectly smooth surfaceby any mechanical treatment [4-5]. When brought in contact, the surface irregularities are compressed and microscopic contact areas are generated. A larger contact area is favourable in order to reduce contact resistance [1][6-7].This can be achieved by applying an external load on the cell, the magnitude of which is carefully determined.It is also essential that the applied load leads to proper sealing of the cell so as to avoid reactant losses. However, there is a limit to the load, surpassing which would cause mechanical failure of the components [8-9]. Thus, an optimum load can be estimated to fulfill the requirement of having low contact resistance at the interfaces and proper sealing of the cell and at the same time ensure its mechanical durability.

In our previous work, we have developed a micro-scale mathematical model to estimate the contact resistance based on contact theory [3]. The results of the model have been successfully validated with experimental data. In this study, we have carried out simulation of the same scenario using Finite Element Method (FEM) based approach.

2. Methodology

In the present study, only perpendicularly oriented external loads are considered for application on the faces of the cell. The emphasis of solution to be evaluatedconcerns the determination of the contact pressure between the electrode and interconnect. To evaluate the safety of the system, stress generation is also studied. At first, a 3D FEM of the SOFC single cell component has been developed. Geometry creation is carried out in solid modelling software SOLIDWORKS. The chosen geometry is similar to the cell used in experimental investigation so as to avoid any ambiguity.The solid model is then imported to a Finite Element package for discretization.After discretization, load and appropriate boundary conditions are applied to complete the set-up of the finite element model (Fig. 1). The solution is carried out using commercial software package ANSYS 14.0.

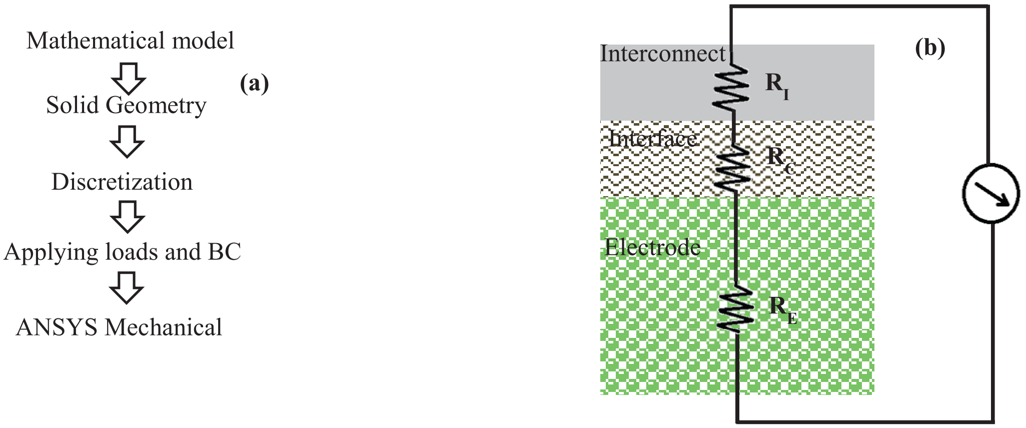

Fig. 1 Schematic diagram of (a) Solution procedure and (b) equivalent electrical resistance of an electrode interconnect.

2.1 Contact Resistance Measurement

At contact current, the potential differences are measured using high precession multimeter. The internal resistances of the materials of electrode and interconnect are accountable to the resistivities of the respective materials (Fig. 1). These resistances can only be minimized by changes either the temperature or the material entirely. However due to limited number of choices available as the materials for SOFC at such high temperature, the resistance cannot be further lower beyond a certain value.

$$R_T = R_I + R_C + R_E \tag{1}$$

where, R_I and R_E are the bulk resistance of the interconnect and electrode. The contact resistance between the electrode and interconnect is R_C. In order to determine the voltage drop arising from the bulk resistance of the electrode and interconnect, individual components are connected to the current source and corresponding voltage drops are noted. Finally, the voltage drop due to material components is subtracted from the total to obtain the contact resistance at different pressures and temperatures.

2.2 Thermal Stress Theory

The classical theory of thermal elasticity relates the components of the strain tensor with the components of stress tensor and temperature induced components of the strain tensor; as

$$\epsilon_{ij} = \epsilon_{ij}^{e} + \epsilon_{ij}^{T} \tag{2}$$

where ϵ_{ij}^{e} and ϵ_{ij}^{T} represent the elastic strain and thermal strain respectively.

The elastic strain tensor is a function of the stress tensor by Hooke's law as

$$\epsilon_{ij}^{e} = \frac{1}{2G}\left(\sigma_{ij} - \frac{\upsilon}{1+\upsilon}\sigma_{kk}\delta_{ij}\right) \tag{3}$$

where G is the stress modulus and υ is the Poission's ratio.

The thermal strain of an element can be related with the co-efficient of linear expansion α and temperature change ΔT by:

$$\epsilon_{ij}^{T} = \alpha\,\Delta T\,\delta_{ij} \tag{4}$$

Finally, the combined equation can be represented by and its solution is obtained as in Eq. 2

$$\epsilon_{ij} = \frac{1}{2G}\left(\sigma_{ij} - \frac{\upsilon}{1+\upsilon}\sigma_{kk}\delta_{ij}\right) + \alpha\,\Delta T\,\delta_{ij} \tag{5}$$

$$\sigma_{ij} = 2G[\epsilon_{ij} + \frac{\upsilon}{1-2\upsilon}\,(\epsilon_{kk} - \frac{1+\upsilon}{\upsilon}\,\alpha\Delta T\,\delta_{ij}] \tag{6}$$

The general convention of using Young's modulus and Poission's ratio for stress-strain relation is followed as in reference [10].

$$\epsilon_{xx} = \frac{1}{E}[\sigma_{xx} - \upsilon(\sigma_{yy} + \sigma_{zz}] + \alpha\,\Delta T \tag{7}$$

$$\epsilon_{yy} = \frac{1}{E}[\sigma_{yy} - \upsilon(\sigma_{xx} + \sigma_{zz}] + \alpha\,\Delta T \tag{8}$$

$$\epsilon_{zz} = \frac{1}{E}[\sigma_{zz} - \upsilon(\sigma_{yy} + \sigma_{xx}] + \alpha\,\Delta T \tag{9}$$

$$\epsilon_{xy} = \frac{\sigma_{xy}}{2G}, \quad \epsilon_{yz} = \frac{\sigma_{yz}}{2G}, \quad \epsilon_{zx} = \frac{\sigma_{zx}}{2G}$$

Since, the components of an SOFC have different material properties, the thermal expansion is different under a given temperature change. This leads to stress generation at certain areas depending upon the geometrical constraints even in no loading conditions.

2.3 Geometry

The SOFC assembly is created in SOLIDWORKS as shown in Fig. 2. The cathode and anode channels are retained so as to evaluate the stress generation at the joints. The geometries are exported to ANSYS Workbench 14.0 Academic Release for meshing and static structural analysis. The mesh controls are adjusted after performing mesh convergence criteria to get the most accurate results.

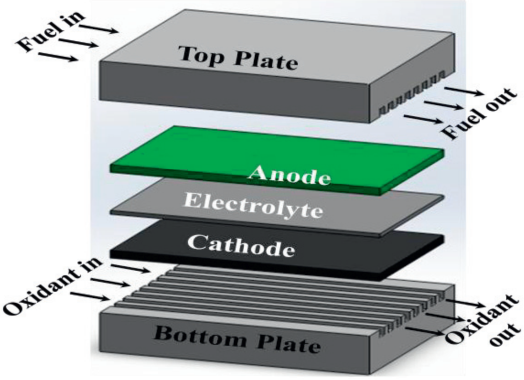

Fig.2: Schematic diagram of SOFC components.

To simulate realistic boundary conditions, the bottom surface of the anode is assigned the ‘Fixed’ boundary condition. A pressure normal to the surface is applied on the top surface of the cathode which varies in magnitude for a number of trials. The cell is joined by means of bonded contact pair. Similar contact pair is used for interconnect and the sealants.

Table 1: Materials properties of SOFC components

Materials	E (GPa)	υ	ρ (gm cm^{-3})	Ref.
Anode (Ni-YSZ)	41	0.3	6.15	[4]
Electrolyte (YSZ)	200	0.3	6.1	[9]
Cathode (LSM)	22	0.36	2.0	[4]
Interconnect (Coffer 22 APU)	44	0.3	7720	[11]
Glass sealant	25	0.23	2.22	[12]

3. Experimental

The experimental results obtained by researchers in [3] show optimized values of contact resistances of 48 mΩ cm^2 at 800 ^{O}C and 0.074 MPa. The variation of the contact resistance on cathode side and the anode side found using numerical simulation closely agrees with the experimental results as in Fig. 7. An initial steep decline of drop in contact resistance value occurs with the application of load, the drop then becomes gradual and finally, the contact resistance shows negligible change.

4. Results and Discussion:

Fig.3 shows the state of the electrode. The contacting areas are darker and can be identified by its orange tone. Under pressure application the magnitude of these contact surfaces increase. The regions in blue hardly make any contact with interconnect and are potentially sites with very high local contact resistance. The regions with intermediate local contact resistance are marked in yellow. The status of the membrane can be visualized by a contact pressure profile using the inverse relationship between contact area and contact resistance. To achieve the minimum value of the contact resistance, the area under the name ‘Sticking’ has to be as large as possible.

The contact pressure profiles between anode and interconnectat temperature 500 and 800 ^{O}C can be seen in the Fig. 4. The contact pressure profile between the anode and interconnect is almost similar with subtle differences. The difference in contact pressure profiles between cathode and interconnect at the two different temperatures are noticeable and can be seen in Fig. 5.

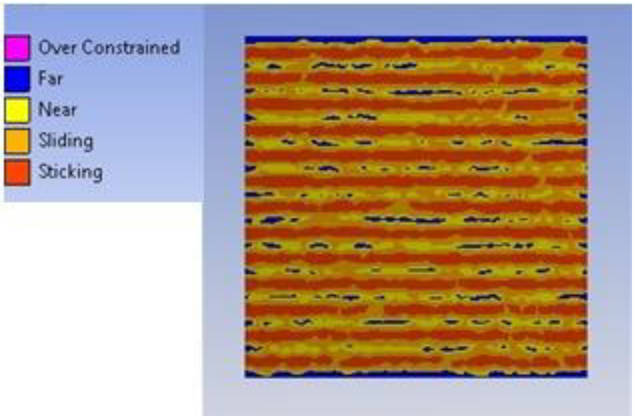

Fig. 3: Nature of the contact on the active cell area.

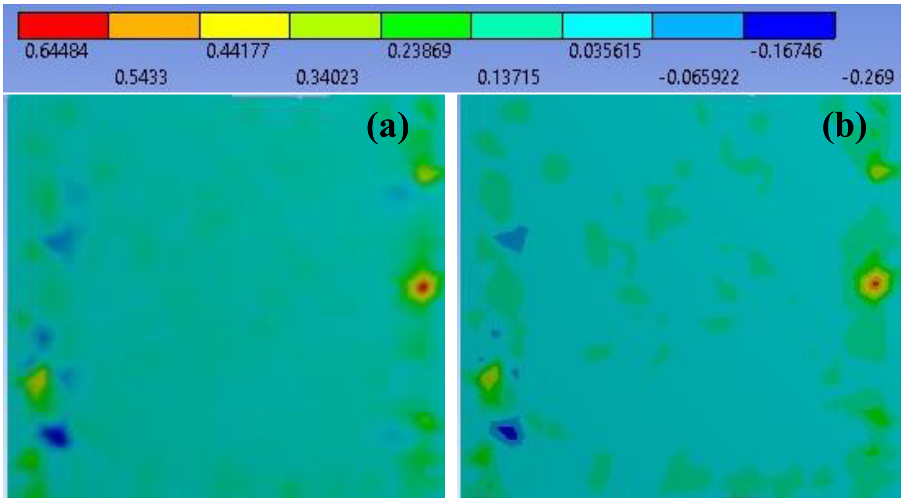

Fig.4: Interfacial contact pressure between anode and interconnect (a) 500^{O}C and (b) 800^{O}C.

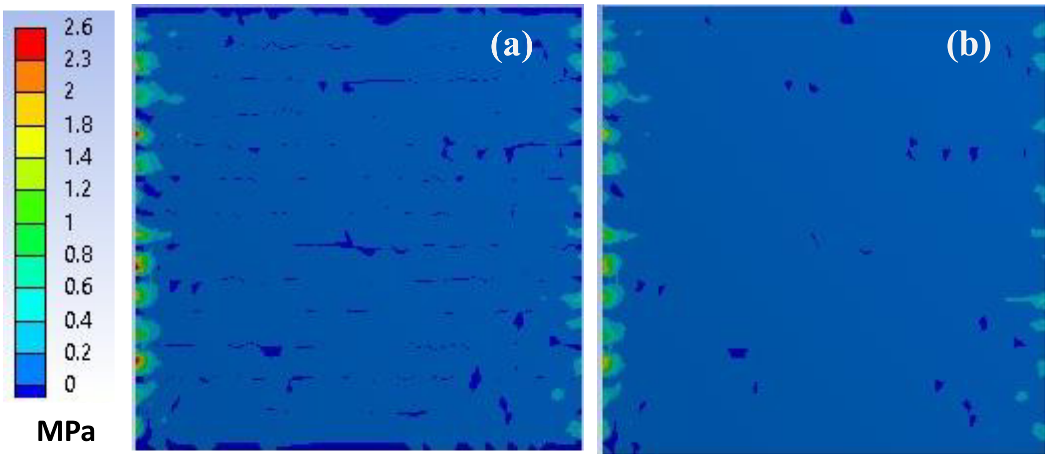

Fig.5: Interfacial contact pressure between cathode and interconnect (a) 500 ^{O}C and (b) 800 ^{O}C.

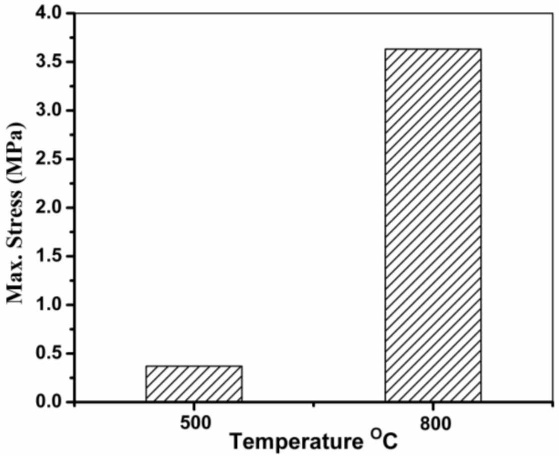

Fig. 6 : Maximum Stress in the interconnect at 500 ^{O}C and 800 ^{O}C.

A trade-off has to be sought between the improvement in the contact pressure profile and deformation in the cell components. Fig. 6 shows the maximum stress evolution in the electrode. The maximum stresses are more near the channel ends which are likely to show failure on application of larger loads. Furthermore, the stresses are larger in magnitude for 800 ^{O}C since greater load transfer takes places at higher temperature due to softening of the sealant. Loads are transferred mainly through the sealant, thus the stress pattern almost identical to the shape of the sealant is observed.

The results obtained from the simulation are plotted in Fig.7 for comparison with experimental results. The characteristics obtained from the simulation are in close agreement with the experimental and analytical values. From the simulation, the optimum pressure for the SOFC under consideration is found to be 0.075 MPa.

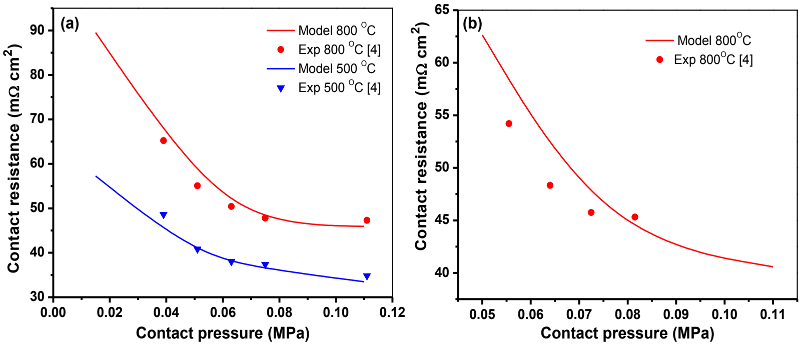

Fig. 7: Validation of contact resistance between (a) anode-interconnect (b) cathode-interconnect interface.

5. Conclusion

SOFC offers a reliable solution to cater the increasing energy demands. Moreover, flexibility of the fuel makes it even more appealing. Thus improvement in the SOFC design procedure will make it easier to design and adapt SOFC technology for the market. The simulation using FEA software presented in this work offers a convenient way of SOFC optimization. It allows for simulating the effects of applied load on all of the components. The optimized loading for the SOFC under consideration is 0.075 MPa which agrees with the value predicted by the mathematical model and experimental validation. The contact resistance at this pressure was found to be 48 mΩ cm^2. Thus, for minimization of the contact resistance, the applied pressure should be at least 0.065 MPa. From the stress plots, it is seen that the stress evolution is maximum at the ends of the flow channels and sealant edges. These are possible sites of cell failure. The applied load is optimized such that it yields stress values lower than the breaking stresses. The study can be integrated into a design procedure of SOFC which makes the FEA tools fit for the optimization techniques.

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