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Effects of anode porosity on thermal stress and failure probability of planar solid oxide fuel cell with bonded compliant seal

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ABSTRACT

The effects of anode porosity on thermal stress and failure probability of a planar solid oxide fuel cell (SOFC) are investigated by finite element method (FEM). The thermal stress and failure probability in planar SOFC with and without considering porosity (CP) were compared. The results show that the compressive stresses are generated in the electrolyte layer, while tensile stresses are generated in Ag–CuO and BNi2 layer because of the compatibility of deformation. In the case of considering anode porosity, the compressive stresses in anode and electrolyte layer and the tensile stresses in cathode layer are all decreased. Comparing to without CP, the thermal stress with CP in electrolyte and cathode layer decreases by 33.2% and 46.9%, respectively. The anode layer has a large risk of failure (5.6489×10^{-4}) than that of cathode and electrolyte layer at as-fabricated state. And the failure probability at cathode layer at start-up reaches 0.998. The failure probability decreases gradually in the period of creep. The failure probability in anode, cathode and electrolyte layer with CP all decrease comparing to without CP. The porosity of anode could lead to the decrease of tensile thermal stress, resulting in the decrease of failure probability in cathode layer. The reduction speed of failure probability at creep stage with CP is bigger than that without CP. As the increase of porosity, the failure probability decreases due to the decrease of the tensile stress.

Introduction

With growing international concern regarding the depletion of the world's natural resources and the need for greater environmental protection, the problem of developing renewable energy sources has attracted significant attention in recent years. Planar solid oxide fuel cell (SOFC) are considered as a promising medium for the conversion of chemical energy into electrical power in terms of its high efficiency, low emissions, and fuel flexibility [1,2]. They are widely regarded as an ideal solution for meeting the future energy needs of both industrial and private consumers.

The practical application of the conventional SOFC is limited mainly because of their high operating temperature. At high temperature, thermal stress is one of the key reasons for SOFC leakage because of the mismatch of material properties, which are the main reasons for the mechanical failure for SOFC [3]. Kim et al. [4] developed a mathematical model to estimate the thermal stresses and predict the lifetime of planar solid oxide fuel cell under thermal cycling conditions and found that the number of cycle for failure decreased with

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the increase of electrolyte thickness. Colpan et al. [5] developed a transient heat transfer model to simulate the heat-up and start-up periods of direct internal reforming SOFC. Zhao et al. [6] have made a review on the recent progress on intermediate temperature SOFCs especially with non-hydrogen fuels. Because of hostile operating conditions, how to construct a suitable seal is a critical issue for the planar SOFC. Weil et al. [7] recently developed a new sealing method called the bonded compliant seal (BCS), which combines the advantages of rigid and compressive seals. The BCS uses a thin foil to bond the cell and the window frame, thereby mitigating a large amount of thermal stress in the cell [8]. Recently, Jiang and Zhang et al. [9–12] studied the as-bonded residual stresses and creep behavior of SOFC with BCS structure. The thermal stress and creep behavior in SOFC have a great influence on failure probability. Fabio Greco et al. [13] assessed the effect of creep on the failure probability of a rigid seal-SOFC by FEM on a single repeating unit. R. Clague et al. [14] used FEM to study the stress development during a duty cycle for a rigid-seal SOFC, and the time independent and time dependent probability of failure has been investigated by stress analysis and the Weibull method [15].

The porosity is an important factor to determine SOFC material properties. When hydrogen fuel gas is supplied to the cell for the first time, NiO-YSZ is converted into a Ni-YSZ cermet. As a result of the reduction of NiO into Ni, the porosity of the anode layer will change, as well as its physical and mechanical properties [16,17]. It will introduce mismatch stresses, which could affect its structural integrity and reliability. Volume fraction of the voids of the anode structure increases significantly on reduction from NiO/YSZ to Ni/YSZ, with a corresponding change in material properties. Radovic and Lara-Curzio [18] concluded that the changes in bulk material properties on reduction were due predominantly to the change in bulk volume porosity. Mikko Pihlatie et al. [19] use the impulse excitation technique to determine the elastic modulus and specific damping of different Ni/NiO-YSZ composites, and found that the mechanical properties of NiO/Ni-YSZ composites depend on temperature, porosity and redox cycling. M. Asmani [20] presents a study on the influence of porosity on Young's modulus and Poisson's ratio of sintered alumina and found that there is a linear decrease of Young's modulus versus the porosity. Overall, many literature have reported the relation between mechanical properties and porosity. However, little attention has been paid on the effect of anode porosity (shortened by porosity in the following) on thermal stress and failure probability. Therefore, in this paper, we perform a thermo-elastic-plastic analysis on a single planar SOFC unit by finite element model (FEM). The as-fabricated residual stresses were implemented into the model, and the thermal stresses and failure probability with considering porosity (CP) and without CP have been compared.

Finite element model

Model description

Fig. 1 shows a cross section of a planar SOFC with BCS design. The cell is a composite structure composed of anode, electrolyte and cathode layer. An S-shaped sealing foil is bonded to the cell and window frame by silver-based filler metal (Ag–4%CuO) and BNi2 filler metal, respectively. The thickness and material of each component is listed in Table 1. Due to the structure symmetry, only a quarter of the model is built. The model was meshed by 80 541 nodes and 72 501 elements, and the finite element meshing is shown in Fig. 2. Two cross sections of the 3D model are applied symmetric boundary conditions. And all the nodes on the bottom face of the window frame are constrained in Z-direction.

The anode porosity increases significantly from NiO/YSZ to Ni/YSZ. The Young's modulus and Poisson's ratio were linear decreased versus the porosity [20]. Radovic M et al. [18] found that the fraction of reduced NiO is a function of time, and the relative porosity increases with the fraction of reduced NiO. Based on the results in Ref. [18], we can derive the porosity of anode materials versus time at 800 °C as shown in Fig. 3a. A reduction rate kinetic model proposed by Utigard et al. [21] was adopted in this paper. The chemical reduction is modeled by defining porosity using the Abaqus *FIELD keyword. Table 2 show the anode material properties at 800 °C as function of porosity [14]. Therefore, we can deduce that the Young's Modulus and Poisson's Ratio change curve of anode materials with time according to Table 2 and Fig. 3a. The Young's Modulus and Poisson's Ratio curve of anode materials were shown in Fig. 3b and c, respectively. The porosity is defined a user defined field by using USDFLD subroutine which has been embedded into the ABAQUS software, and the thermal stress is updated at the end of the each increment.

Fig. 4 shows the analysis procedure in this study. After the model built, three calculation steps were performed with and without CP. The first step was to calculate the initial as-fabricated stress, and then the thermal stress was calculated to get the total stresses. The third step performed a creep analysis of 25 h induced by the total stresses. Last, the effects of porosity were investigated by comparing the thermal stress and failure probability with and without CP.

Residual stress analysis

Fig. 5 shows the heating history of the fabrication of planar SOFC. The planar SOFC stacking is brazed in the vacuum furnace. At first the stacking is heated to 600 °C at 10 °C min^{-1} and the temperature is held for about 40 min to volatilize the binder. Then it is heated to the brazing temperature of 1050 °C and held about 25 min. At last, the assembly is cooled to the ambient temperature in the furnace. During the fabrication, the cell is assumed to be stress-free at high temperature of

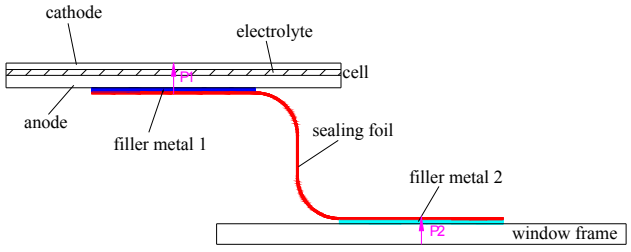

Fig. 1 – The cross section of planar SOFC.