INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 17941–17951

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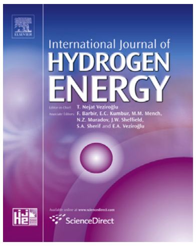

Simulation of creep and damage in the bonded compliant seal of planar solid oxide fuel cell

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ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form
24 August 2014
Accepted 27 August 2014
Available online 22 September 2014

Keywords:
Solid oxide fuel cell
Bonded compliant seal
Brazing
Creep
Damage
Multi-axial stress effect

ABSTRACT

Planar solid oxide fuel cell (SOFC) operates at high temperature and requires a good creep strength to ensure the structure integrity. This paper presents a creep and damage analysis of a bonded compliant seal (BCS) structure of a planar SOFC considering the effect of as-bonded residual stress and thermal stress, as well as the effect of filler metal and foil thickness. A modified continuum creep-damage model is used in the finite element simulation. It demonstrates that the BCS structure meets the requirement of the long-term operation at the high temperature of 600 °C with an appropriate braze bonding process. The results show that the failure location is not in the region of maximum creep deformation due to the effect of high level multi-axial stress which drastically decreases the multi-axial ductility. Reasonably reducing the thickness of filler metal and foil can decrease the damage of the BCS structure. Based on the consideration of creep and damage, it is proposed that the thickness of filler metal and foil should not exceed 0.1 and 0.05 mm, respectively.

Introduction

Solid oxide fuel cells (SOFCs) are considered as one of the promising electrochemical energy conversion devices due to their high efficiency, fuel flexibility, low pollutant emission and stack scalability, etc [1–4]. As the power of a single cell is only tens of watts, it is necessary to assemble a number of parallel cells into a cell stack to provide desired voltage and power outputs. The planar SOFC stack usually employs a peripheral seal between the ceramic cell and adjacent window frame, which must be airtight throughout the lifetime. An important issue is that the stack operates at approximately 800 °C [5,6], which requires a good creep strength for the cell-to-window frame seal. The high operating temperature has limited the development and application of SOFC, and resulted in high failure rates and production costs. Newly developed, high-conductivity electrolytes and nanostructured electrode designs allow a lower operation temperature (≤650 °C) [7–9]. Suzuki et al. [10] confirmed that the SOFC with an electrolyte of single-grain-thick yttria stabilized zirconia (YSZ) layer and an anode of Ni-YSZ could be used for low temperature operation at or under 600 °C. The low temperature reduces the system cost due to wider material choices for

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http://dx.doi.org/10.1016/j.ijhydene.2014.08.130

interconnects and sealants, as well as the increase of maximum theoretical efficiency [7]. At the same time, the long term and safe operation can be better guaranteed.

The remained challenge issue is then the development of appropriate techniques for hermetical sealing of the SOFC stack. Usually, rigid seal and compressive seal methods were applied to the planar SOFC stack [11]. For the rigid seal [12], the sealants such as glass or glass-ceramic can be used to bond the components of planar SOFC. But they are brittle and cracks can be easily generated after some thermal cycles. The silver and gold can be used to substitute the glass for the sealing materials, while they are too expensive for large-scale applications. For the compressive seal [13,14], the components do not rigidly bonded together, but applying a compressive load on the SOFC stack to keep the tightness by metal or mica-based composite as sealants. Compared to the rigid seal, compressive seal has more seal materials to choose, but the disadvantage is that the applied load can be relaxed by creep at high operating temperature and thus leads to leakage. Although the new composite sealants can produce a better hermetic joint between the components, the planar SOFC still can hardly meet the requirements of the long-term operation at high temperature due to the large stress existed in SOFC stack. The seal of planar SOFC has thus been a problem entangling researchers and meanwhile arousing their curiosity to develop a new seal method. In recent years, a method named bonded compliant seal (BCS) has been developed by Weil et al. [15], which incorporates the advantages of both rigid and compressive methods by using a thin foil metal to bond the frame and cell. The advantages of the BCS have been verified from the perspective of residual stress by finite element method [16,17]. Compared with the features of rigid seal and compressive seal, they concluded that deformation of foil can mitigate a significant portion of the strain mismatch of the components. Since the braze bonding temperature and operating temperature are very high, large thermal stresses [18,19] are engendered and have a great effect on the strength. Jiang et al. [20–22] studied the as-bonded residual stresses by FEM and how to decrease the residual stress has been fully discussed by optimizing the structure dimension. And we also proposed that the residual stress can be decreased by short-time creep during the braze bonding process [23]. But its reliability at high temperature operation should be proved for its future application. Recently, Jiang et al. made a creep analysis of the BCS structure on the basis of Norton creep law [24]. It concluded that the creep effect can decrease by 16% of the cell deformation due to the stress redistribution in the whole structure. The potential failure areas are located at the middle of the cell edge and filler metal of the BNi-2. However, the effect of the multi-axial stress on the creep damage was not fully taken into account. It is known that the stress multi-axiality has a great influence on the stress redistribution in the creep process [25]. The increase of stress multi-axiality can lead to an enhanced damage at the same level of inelastic strain. In this paper, a modified continuum creep-damage model has been used to calculate the time-dependent changes of stress-strain states. The constitutive equation for creep model can describe the three stages of creep based on the multi-axial effect, and the ductility exhaustion model has been used to conduct the damage analysis. Then, creep and damage analyses considering the effect of residual stress and thermal stress are conducted to verify whether the BCS structure of SOFC can meet the requirement of the long-term operation at 600 °C.

Finite element analysis of creep-damage

Finite element model

Fig. 1 shows the exploded view of 1/4 model of the BCS structure. At the joint interface of each component, dissimilar materials are assumed to be perfectly bonded by brazing. The electrolyte used in present analysis is YSZ, and the thickness is about 1 μm [10]. The thickness and material of each component are listed in Table 1, which are the same as Refs. [16,17], and the other sizes are shown in Fig. 2. The chemical compositions of each material are listed in Tables 2–6 [24].

Considering the computation time and symmetry of the geometry structure, the 1/4 model of BCS structure was adopt. Finite element analysis has been carried out by the commercial code ABAQUS. The element type is C3D8R, and the finite element meshing is shown in Fig. 3. There are 66,798 elements and 90,297 nodes in the 3D model. It has already been demonstrated that the used mesh sizes are appropriate to guarantee the calculation precision [23].

Boundary conditions

Due to the symmetry of BCS structure, two cross sections of the model were applied X symmetric (XSYMM) and Y symmetric (YSYMM) boundary conditions. And all the nodes on the bottom face of the frame were constrained in Z-direction ($U3 = 0$), see Fig. 4.

It should be noted that an absolute internal pressure (0.105–0.12 MPa) exists in the SOFC [26], but it acts only on the gas channels in the cell [19] and has no effect on the BCS structure. Hence it is not taken into account as a pressure boundary.

Thermal stress calculation

The thermal stress is mainly caused by the mismatch of the dissimilar materials. There are two types of thermal stresses exist in the BCS structure. The first is the stress produced in the bonding process. In this stage, the temperature cools from the braze bonding temperature (1050 °C) to the ambient temperature (25 °C). The other is generated in the start-up process

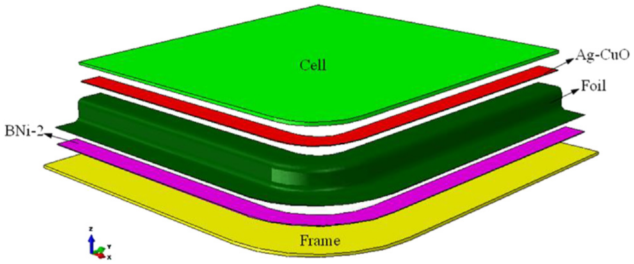

Fig. 1 – The exploded views of BCS structure.