International Journal of Solids and Structures 78-79 (2016) 38–46

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Homogenization of steady-state creep of porous metals using three-dimensional microstructural reconstructions

Kawai Kwok*, Dino Boccaccini, Åsa Helen Persson, Henrik Lund Frandsen

Department of Energy Conversion and Storage, Technical University of Denmark, Roskilde, 4000 Denmark

ARTICLE INFO

Article history:
Received 12 March 2015
Revised 11 August 2015
Available online 30 September 2015

Keywords:
Porous metal
Numerical homogenization
Microstructure reconstruction
Creep
Solid oxide fuel cell

ABSTRACT

The effective steady-state creep response of porous metals is studied by numerical homogenization and analytical modeling in this paper. The numerical homogenization is based on finite element models of three-dimensional microstructures directly reconstructed from tomographic images. The effects of model size, representativeness, and boundary conditions on the numerical results are investigated. Two analytical models for creep rate of porous bodies are derived by extending the Hashin–Shtrikman bound and the Ramakrishnan–Arunchalam model in linear elasticity to steady-state creep based on nonlinear homogenization. The numerical homogenization prediction and analytical models obtained in this work are compared against reported measurements and models. The relationship between creep rate and porosity computed by homogenization is found to be bounded by the Hodge–Dunand model and the Hashin–Shtrikman creep model, and closely matched by the Gibson–Ashby compression and the Ramakrishnan–Arunchalam creep models.

1. Introduction

There is rising interest in using porous metals as supports for solid oxide fuel cells (SOFCs) (Blennow et al., 2011; Brandon et al., 2004; Tucker, 2010; Tucker et al., 2007), which represent an emerging technology for efficient and low-emission power generation. A SOFC is a multilayered solid device that converts chemical energy in fuels directly into electricity through electrochemical reactions at elevated temperatures. To achieve high efficiency, the electrochemically active ceramic layers are made as thin as possible. The total thickness of such layers is typically below 100 microns, and therefore need to be supported on a thicker substrate layer. In addition to its mechanical function, the support needs to be porous and electrically conducting in order to allow fuel access to the anode layer and maintain electrical connection with neighboring cells. Conventional SOFCs are supported on porous ceramic/metal composites, which exhibit brittleness and contain expensive materials. In contrast, porous metal supports are ductile and can be made from inexpensive materials. They also possess higher tolerance towards redox and thermal cycling. Such characteristics are expected to improve the reliability and lower the cost of the device (Tucker, 2010). Current metal-supported SOFC development favors stainless steel as the support material due to its good oxidation resistance and low thermal expansion mismatch with the other ceramic layers (Blennow et al., 2011; Tucker et al., 2007).

Solid oxide fuel cells are subjected to stresses due to, for instance, thermal expansion mismatch between the cell layers, temperature and oxygen stoichiometry gradient, and redox expansion and contraction. Such stresses often lead to degradation in performance and even failure when their magnitudes become critical. At the high operating temperatures of SOFC, the stresses are significantly influenced by the creep of the porous support. Since the presence of pores can drastically increase the creep rate, it is important to assess their effect when developing metals supports.

Only limited studies have experimentally investigated the creep of porous metals. Previous work have measured steady-state creep responses of a 54% porous nickel-based alloy (Boonyongmaneerat and Dunand, 2009), and stainless steels with porosities of 40–58% (Scott and Dunand, 2010) and 20–40% (Boccaccini et al., 2014; Glasscock et al., 2013). The dependence of creep on porosity reported in these studies is highly consistent. When the power-law model was used to describe the steady-state creep responses of porous and dense (zero porosity) stainless steels, the stress exponents were found to be invariant with porosity within measurement error. The primary effect of porosity is increasing the rate factor in the power-law creep equation. The invariability of stress exponents has also been found in earlier studies for cellular solids (Andrews et al., 1999; Diologent et al., 2009; Hakamada and Nomura, 2005; Hodge and Dunand, 2003), which are generally differentiated from porous materials by having porosities above 70% (Gibson and Ashby, 1997).

Analytical models have been proposed to capture the porosity effect on steady-state creep from the creep rate of the dense material

* Corresponding author. Tel.: +45 20120785.
E-mail address: kawai.kwok.k@gmail.com, kwok@dtu.dk (K. Kwok).

http://dx.doi.org/10.1016/j.ijsolstr.2015.09.020
0020-7683/

and idealizations of the porous microstructure. Two main approaches are followed in these models.

The first approach is based on the beam theory. Intended for cellular materials, the microstructure is represented as a regular array of cells with simple geometries. The effective creep rate is determined by analyzing a unit cell assuming the deformation is solely controlled by the bending of the cell struts oriented perpendicularly to the applied stress (Andrews et al., 1999; Gibson and Ashby, 1997), or by the strut compression parallel to the applied stress (Hodge and Dunand, 2003). For cellular materials, the cell struts have sufficiently high uniformity and aspect ratio to justify the assumption of bending or compression controlled deformation. This is generally not the case for porous materials in which the struts are less slender and more irregular in their cross-sectional geometry. The issue was addressed in a later study by accounting for shear deformation of the struts and effect of the nodes at which the struts meet. A family of models was developed, which yields explicit closed-form formulas for the creep rate as a function of porosity (Boonyongmaneerat and Dunand, 2009).

The second approach is based on the nonlinear homogenization theory (Castañeda, 1991). A porous material is treated as a composite consisting of an empty phase and a solid phase with power-law creep behavior. By employing either the incremental or secant approach, the nonlinear homogenization problem is broken down into successive linear homogenization tasks for which the well-established mean-field techniques can be readily applied. For uniaxial steady-state creep deformation, a closed-form expression for the creep rate can be derived using the modified secant formulation (Qiu and Weng, 1992; Suquet, 1995) if the elastic modulus of the porous material is related to that of the dense material by a multiplicative function of the porosity (Mueller et al., 2007).

Both approaches predict the stress exponent of the porous body to be identical to that of the dense one, which is in conformity with experimental observation. The predicted rate factors however diverge significantly, as the models adopt different simplifications on the microstructure and stress state.

The discrepancy between analytical models can be overcome by numerical homogenization, where finite element analyses are performed on models that simulate samples of the microstructure. Various strategies have been proposed to generate models that approximate the microstructure as closely as possible.

The most straightforward strategy is to randomly distribute spherical or ellipsoidal voids in a solid cube. A variety of models were generated this way by choosing between overlapping (Roberts and Garboczi, 2000; 2002) or non-overlapping (Fritzen et al., 2012; Segurado and Llorca, 2002) pores, and between uniform (Fritzen et al., 2012; Roberts and Garboczi, 2000; 2002; Segurado and Llorca, 2002) or non-uniform (Ghezal, 2013) pore size distribution. More realistic models can be created by requiring their characteristics to match that of real microstructures in a statistical sense. This was achieved by quantifying the geometric features captured in two-dimensional images with statistical functions, and forcing the generated models to display the same characteristics via optimization procedures (Shen and Brinson, 2006; Tabei et al., 2013).

The closest representation thus far is provided by direct reconstructions, where a stack of images obtained from microscopy are combined to form a volume image that is discretized directly for numerical analysis (Delette et al., 2013; Shan and Gokhale, 2001; Takano et al., 2003; Vaidya and Kim, 2013). This approach involves the least assumptions in generating microstructural models, and is becoming increasingly attractive due to recent advances in high-resolution imaging techniques. However, except for the work of Shan and Gokhale (2001) where damage evolution due to void growth was modeled, previous studies have only focused on linear elastic properties.

This work presents a study of the steady-state creep response of porous metals based on numerical homogenization and analytical modeling. The material chosen for study is a porous stainless steel currently being considered for metal-supported SOFC applications. The porous microstructure is reconstructed from X-ray tomographic data. Based on the homogenization technique, the steady-state creep response of the porous metal is evaluated from finite element models directly converted from the reconstruction. The effects of model size, boundary conditions, and statistical representation on the numerical results are investigated. Two analytical models are derived by extending the Hashin–Shtrikman bound and the Ramakrishnan–Arunchalam model in linear elasticity to steady-state creep based on nonlinear homogenization. Numerical predictions are discussed with respect to reported experimental measurements conducted at SOFC application conditions. The accuracy of different analytical model predictions is assessed.

2. Experimental methods

2.1. Material

The porous metal used in this study was fabricated by tape casting of a slurry made of metallic powder, binder, plasticizer, and other organic additives required for processing. The metallic powder is composed of 22% of chromium and other elements balanced by iron. The casted tape was cut to shape, heat-treated in air for debindering, and finally sintered under proprietary conditions above 1000 °C in a reducing atmosphere (H_2/Ar). The sintered porous metal sheet has a thickness of 0.25 mm. A detailed description of the fabrication process can be found in (Blennow et al., 2011).

The porosity of the porous metal was determined to be 19% using a Autopore IV 9500 V1.05 mercury porosimeter from Micromeritics Instrument Corporation. The characteristic pore size is 9.2 μm.

2.2. X-ray tomography

The microstructure of the porous metal was imaged with X-ray microtomography. A SkyScan 1172 X-ray micro-CT scanner system equipped with a 100 keV X-ray source and an 11 megapixel X-ray detector was employed. A volume of 2.6 mm x 0.5 mm x 0.25 mm was scanned with a frame averaging of 2 and a rotation step of 0.37. The entire thickness of the fabricated porous metal was covered.

The stack of two-dimensional images obtained from X-ray scanning and shown in Fig. 1 was aligned to produce a three-dimensional image. The pore and the solid phases were distinguished by threshold segmentation. The pore phase is percolating, as required for gas permeation in solid oxide fuel cell application. The microstructure is characterized by connected open pores.

2.3. Creep test

Since the porous metal was not available in dense form, a material with highly similar composition was used for creep testing to provide the dense metal creep parameters required for modeling. The metal

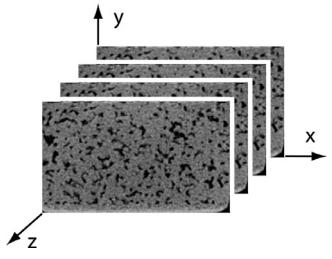

Fig. 1. Stack of two-dimensional images for three-dimensional reconstruction.