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Creep rate induced by surface diffusion of porous media

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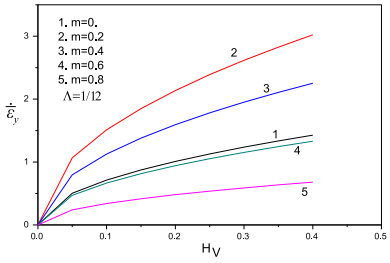
HIGHLIGHTS

- The creep rate is induced by surface diffusion of porous.
- The creep rate is controlled by the morphology of porous.
- The creep rate depends on the strain energy and surface energy.

GRAPHICAL ABSTRACT

An analytical method is presented to describe the creep rate solely induced by the hole surface diffusion of porous materials, and the scale effect is considered by using finite element method.



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ABSTRACT

Holes in materials can cause improved or unique performance of the material when the sizes, shapes, and orientation of holes as well as grains are controlled in materials. In the paper, a computational method for creep rate induced by hole surface diffusion of porous materials is presented. The driven force for diffusional mass transport along the hole surface is the surface diffusion energy of hole and the strain energy acting on the surface, which is obtained from rigorous elastic theory. In order to apply the present solution to the realistic porous materials the scale effect is considered by using finite element method based on two-dimensional unit cell for porous materials under uniaxial tension.

1. Introduction

Porous materials, such as acoustical porous materials, biomechanical metal porous materials, shape memory alloy (SMA), porous tungsten electrode materials, porous stainless steel materials and porous copper materials, have attracted worldwide attention related to their popularity various engineering applications due to their special properties in lower density, larger specific surface area, higher mechanical strength and excellent permeability [1–10]. Li and Chen [11] and Yu and Li [12] had demonstrated that the Coulombic traction on the surface of pores is significant and lead to the non-traction-free boundary condition on the surface of pore in materials.

Many researches [13–17] found that the application efficiencies of porous materials may be influenced by their mechanical properties. Authors [13] described the mechanical properties of open-cell nickel foams for the range of densities used in industrial applications for energy storage. In literature [14], fabrication and mechanical properties of porous silicon nitride materials are described. Authors [15] described the creep characteristics of the composite consists of a porous alumina matrix reinforced with Nextel 610 fibers coated with monazite in a symmetric cross-ply $(0°/90°/0°/90°)_S$ orientation. A microstructure-dependent creep model for a body containing a distribution of spheroidal pores is developed by Authors [16]. The body's constitutive behavior is

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described by microstructure-dependent creep potentials for dislocation (power law) and diffusion-accommodated grain-boundary sliding. Creeping motions of a porous spherical shell in a concentric spherical cavity are described in literature [17]. From the literatures [15–17], it is seen that the creep characteristics of porous materials affect the strength and the deformation of the porous materials. Thus, it is important to determine creep behaviors of porous materials for their engineering applications. Generally, the creep of materials is induced by diffusion-accommodated grain-boundary sliding. But, because porous materials have larger specific surface area, the creep characteristics of porous materials induced by the hole surface diffusion should be considered.

So far, a majority of the studies focus on developing simulation techniques, such as finite element method [18–22], to model the two relaxation processes, which brought much understanding to the interfacial slip and diffusion on the creep strength of the composites. Because numerical simulation analysis is limited to fixed calculation parameters and the intricacy of the numerical results in the individual situation, generally characteristics are hard described. However, an analytical solution for the creep characteristics of porous materials induced by the hole surface diffusion has not been obtained yet.

In this paper, an analytical method is presented to describe the creep rate solely induced by the hole surface diffusion of porous materials, where the creep deformation of the matrix is omitted. Thus, the surface diffusion of hole will be as a separate independent variable of the problem and the contribution of the hole surface diffusion to the creep of the porous materials can be clearly visualized. The driven force for diffusional mass transport along the hole surface is the surface diffusion energy and the strain energy acting on the surface, which is obtained from rigorous elastic theory. In order to apply the present solution to the realistic porous materials the scale effect is considered by using finite element method based on two-dimensional unit cell for porous materials under uniaxial tension. The closed-form solution obtained is an explicit function of the applied stress, the hole volume fraction, as well as the shape and size of hole.

2. Model and solving method

Porous materials with elliptic holes are considered as a periodical microstructure shown as Fig. 1. Thus, the behavior of the porous material can be modeled by the response of a unit cell [22],

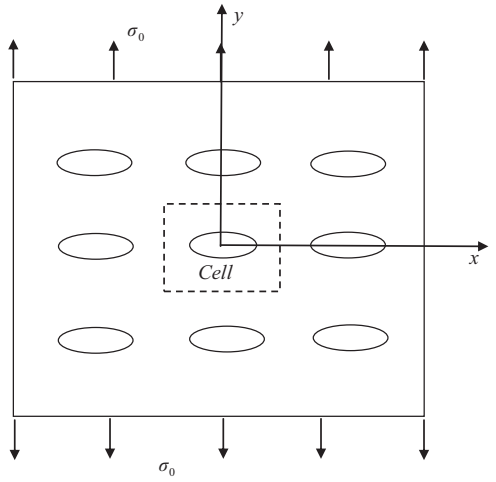

Fig. 1. A periodical porous material with elliptic holes under uniaxial tensional loading.

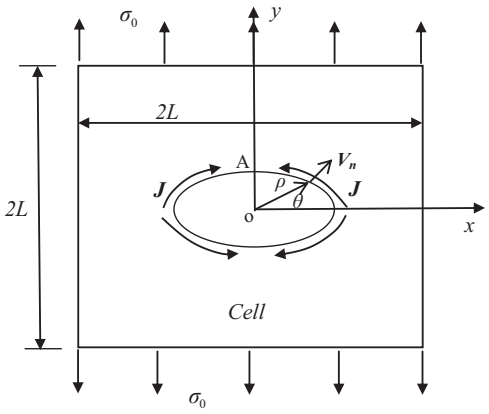

Fig. 2. The analytical model based on a cross-sectional view of a unit cell for a periodical porous material with elliptic holes, in which the diffusion long the free surface of elliptic hole results in creep along loading direction.

shown as a square with an elliptic hole from a cross-sectional view of a unit cell for the porous material in Fig. 2. The elliptic hole were located at the centre of each cell, and its volume fraction in each cell was obtained as the quotient of the elliptic hole and the cell volume. The creep characteristics of the porous materials is described by assuming the cell with an elliptic hole under lognitudinal tension σ_0, in which during loading the gradient of strain energy along the surface of elliptic hole and the surface diffusion energy drive diffusion mass transport from the sides to the poles of the elliptic, leading to creep strain in the loading direction

The shape for an elliptic hole in porous materials shown as Fig. 2 is considered as having the same area as a circle of radius ρ as follows

$$x = \rho\sqrt{\frac{1+m}{1-m}}\cos\theta, \quad y = \rho\sqrt{\frac{1+m}{1-m}}\sin\theta, \tag{1}$$

where θ is the angle between the vector radius ρ of ellipse and x–axes, and $m$is the shape parameter of the hold. The shape parameter $m = 0$ corresponds to a circle, $m \to +1$ to x–direction slit and $m \to -1$ to y–direction slit, respectively.

General, the surface diffusion is faster than the bulk one, so that only the surface diffusion is considered as the major mechanism for the diffusion creep. Because the surface of elliptic hole in matrix material is free, the normal stress acting on the surface of the elliptic hole, σ_n, is zero. So that the chemical potential of the atoms on the free surface of hole in porous materials is written as

$$\mu = \mu_0 - \Omega\gamma_s\kappa + W_\rho\Omega \tag{2}$$

where μ_0 is the reference value of the potential, γ_s is the surface energy of elliptic hole, κ is the surface curvature of the hole, positive for convex, W_ρ is the strain energy density on the hole surface, Ω is the atomic volume.

Because the atomic flux, J, on the free surface of hole is defined by the number of atoms per time crossing unit arc length on the free surface of hole, the mass conservation requires

$$\frac{dJ}{ds} + \frac{V_n}{\Omega} = 0 \tag{3}$$

where V_n represents the rate of accumulation or depletion of matter on the free surface of hole, positive for accumulation and negative for depletion.

The atomic flux along the free surface of hole is expressed as

$$J = -\frac{D_s}{\Omega kT}\frac{d\mu}{ds} = \frac{D_s}{kT}\left(\gamma_s\frac{d\kappa}{ds} - \frac{dW_\rho}{ds}\right) \tag{4}$$

where k represents the Boltz-mann's constant, T the absolute