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Void growth in power-law creeping solids: Effect of surface diffusion and surface energy

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Abstract

This paper addresses the growth of a void in a nonlinearly creeping material in the presence of the void-surface energy effect and void-surface diffusion driven by surface curvature gradients. Large strain finite element analysis of the coupled problem indicates that microstructural variables (porosity and void aspect ratio), as well as macroscopic deformation rates are strongly affected by the relative strength of the void-surface energy effect and the void-surface diffusion process vis-a-vis the rate of creep deformation in the bulk of the solid. The phenomenon is characterized by two-dimensionless groups, one measuring the strength of the surface diffusion process with respect to the nonlinear creep deformation in the interior of the solid, and the other the magnitude of the surface energy of the void in relation to the applied load and the size of the void. The computations reveal a rich variety of solutions that reflect a wide range of external load, material, and geometric parameters. Classical void growth studies that ignore both surface diffusion and surface energy effects are shown to recover only one case of this family of solutions. The computations also serve to quantitatively evaluate recent constitutive theories for porous nonlinear materials that account for continuously evolving microstructure, but do not include surface diffusion or surface energy effects.

Keywords: Material creep behavior; Porous media; Voids; Surface diffusion; Surface energy

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1. Introduction

It is well-known that the growth of small voids in inelastic materials plays a central role both in ductile fracture of metals at room temperature and creep rupture at elevated temperatures. Previous investigations have dealt with void growth in both nonlinearly viscous solids (e.g., Budiansky et al., 1982; Needleman et al., 1995) and materials deforming by rate-independent plasticity (e.g., see the reviews of Tvergaard, 1989; Needleman et al., 1992). The present investigation focuses on void growth in nonlinearly viscous solids, specifically of the power-law creeping type. For these materials, the work done to date has addressed the evolution of the shape and size of voids with time. Budiansky et al. (1982) have obtained detailed solutions for a void growing in an infinite viscous matrix under a variety of remote axisymmetric loading states. More recently, Needleman et al. (1995) have considered the effect of void interaction and void shape change on the void growth rates through extensive finite-element calculations, also under axisymmetric conditions. The cell model employed by them is that of Needleman and Rice (1980) who studied growth of cavities occurring by the combined action of grain-boundary diffusion and power-law creep in the adjoining grains. Their analysis was employed by Sham and Needleman (1983) to study the effect of triaxial stressing on diffusive cavity growth.

Although it is well understood that mass transfer over the void-surfaces is of great relevance in determining surface profiles, and indeed demonstrated through numerical computations (Subramanian and Sofronis, 2001, 2002), in the studies to date on void growth, very little attention has been paid to the process of surface diffusion over the void-surfaces. In the classical void growth models (e.g., Budiansky et al., 1982; Needleman et al., 1995), the void shapes are affected only by the viscous deformation of the solid; reconfiguration of the void-surface due to mass transport over it due to surface diffusion is completely ignored. On the other hand, in the creep cavitation models (e.g., Needleman and Rice, 1980; Sham and Needleman, 1983), surface diffusion is assumed to be extremely fast leading to a void that always maintains a spherical-caps shape. Chuang et al. (1979) developed models for diffusive cavitation that were not based on a quasi-equilibrium void shape, and allowed the void shape to be determined as part of the solution; however, the grains were assumed to be rigid. Thus, none of these models account for void shapes that result from the concurrent action of void-surface diffusion and nonlinear bulk deformation. A notable exception to this is the work of Suo and Wang (1994) and Wang and Suo (1997) who studied the interaction of void-surface diffusion with the elastic deformation in the surrounding matrix under biaxial tension. These investigators found that when the void-surface energy effect is dominant the void evolves to an equilibrium shape close to an ellipse, whereas when the bulk elastic energy effect dominates the void never reaches equilibrium and crack-like shape instabilities emerge. It should be noted though that the classical Laplace relationship between the void curvature, void-surface energy, and the normal traction in the adjoining bulk material (Herring, 1951; Rice and Chuang, 1981) was not enforced in any of these calculations.

Based on these results and those of Subramanian and Sofronis (2001, 2002), one concludes that the interaction between void-surface diffusion and bulk deformation mechanisms plays a vital role in determining the void shape and size changes. Further, as length scales relevant to modern engineering applications shift from microns to nanometers, surface energy effects and hence the void-surface traction take on increased significance. For instance, in a material with a surface energy γ_p of 1 J/m^2 (a typical value for metals), normal tractions in the bulk material adjoining a void of radius 1nm are of the order of 1 GPa. Certainly, no claim is being made here that the present continuum mechanics study will be applicable at the level of clusters of atoms. However, it is emphasized that that surface energy effects will be more prominent as void size decreases from tens of microns to hundreds of nanometers.

On the other hand, rigorous constitutive theories for the macroscopic response of nonlinearly deforming voided materials in the absence of any void-surface diffusion or surface energy effects have been proposed by Ponte Castañeda and coworkers (Ponte Castañeda and Zaidman, 1994; Kailasam and Ponte Castañeda, 1996; Ponte Castañeda, 1997; Kailasam et al., 2000). Apart from a relationship between the overall