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Anisotropic finite-strain models for porous viscoplastic materials with microstructure evolution

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ABSTRACT

In this work, we propose a constitutive model for the finite-strain, macroscopic response of porous viscoplastic solids, accounting for deformation-induced changes in the size, shape and distribution of the voids. The model makes use of consistent homogenization estimates obtained by the "iterated variational linear comparison" procedure of Agoras and Ponte Castañeda (2013) to characterize both the instantaneous effective response of the porous material and the evolution of the underlying microstructure. The proposed model applies for general, three-dimensional loading conditions and can be implemented numerically for use in standard FEM codes. We also investigate the interplay between the evolution of the microstructure and the macroscopic stress–strain response, in the context of displacement-controlled, plane strain loading (bi-axial straining) of initially isotropic, porous, rigid-plastic materials with power-law hardening. We focus on the effect of strain triaxiality, and consider both extensional and contractile loading conditions leading to porosity growth and collapse, respectively. For both types of loadings, it is found that the macroscopic behavior of the material exhibits an initial hardening regime followed by a softening regime at sufficiently large strains. Consistent with earlier models and experimental results, the softening regime for extensional loadings is a consequence of porosity growth. On the other hand, the softening behavior predicted for contractile loadings is found to be a consequence of void collapse, i.e., of rapid changes in the average shape of the pores leading to crack-like shapes. For both types of loadings, the transition from hardening to softening in the macroscopic response can be identified with the onset of macroscopic strain localization. The associated critical conditions at the onset of localization are determined as a function of the strain triaxiality. The type of localization band ranges from dilatational to compaction bands as the bi-axial straining varies from uniaxial extension to uniaxial contraction.

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1. Introduction

The evolution of residual and/or nucleated voids under finite-strain loading processes plays a crucial role in the macroscopic response of ductile solids. This is the case, for example, during metal-forming processes, such as rolling and forging, where microscopic voids resulting from prior powder-metallurgy processes may undergo substantial changes, not only in size but also in shape and orientation, which may in turn significantly affect the macroscopic properties of the end product. The development of constitutive models properly accounting for the effect of void evolution on the anisotropic macroscopic response of these materials constitutes a prerequisite for carrying out full-scale numerical simulations (e.g., by means of the finite element method) of metal-forming processes. Experimental studies (e.g., Parteder et al., 1999), as well as numerical unit cell simulations (e.g., Segurado et al., 2002), indicate that pore shape changes can have a significant influence on the macroscopic response of metallic materials under compressive loadings, such as those applied during the aforementioned metal-forming processes. Thus, this paper is concerned with the use of homogenization techniques to develop constitutive models for ductile materials accounting for the effect of deformation-induced changes in the volume fraction and average shape of the voids.

Another class of porous materials where the effect of porosity is clearly very important is closed-cell metal foams (Ashby et al., 1998). These materials are lightweight, containing a void volume fraction (or porosity) that may exceed 90%, and have promising applications in the automotive industry and elsewhere, mainly because of their exceptional energy-absorption properties under compressive loadings. Probably the most characteristic aspect of the mechanical behavior of metal foams under compressive loadings is the localization of the macroscopic deformation within nar-

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row compaction or crushing bands (see, e.g., Bastawros et al., 2000). Such compactions bands have also been observed in porous rocks subjected to compressive stresses (Olsson, 1999). The formation of these bands plays a key role in the performance of the material and, therefore, a better understanding of these instabilities is of crucial importance for the development of metal foams with improved properties. At the microscopic level, experimental evidence (Bastawros et al., 2000) indicates that these instabilities result from the plastic buckling of the ligaments between neighboring cells. From a macroscopic point of view, as we will see, the formation of these localization bands may be interpreted as a consequence of progressive macroscopic softening of the material induced by the evolution of the underlying microstructure. While the study of metal foams is beyond the scope of the present work, it will be shown by means of model applications that strain localization instabilities, such as those observed during compression of metallic foams and porous rocks under near uniaxial straining conditions, are within the purview of the homogenization-based constitutive models to be developed here for porous plastic materials.

The constitutive models developed in this work are also expected to be relevant in ductile fracture of metals, which is known to result from complex processes involving the nucleation, growth and coalescence of voids (e.g., Xue et al., 2010). Despite substantial progress over the past fifty years, the determination of the critical conditions for ductile failure remains a controversial subject. Based on a large amount of experimental results (e.g., Hancock and Mackenzie, 1976; Johnson and Cook, 1985), it has been firmly established that the ductility of metals, defined here as the strain required for fracture, decreases monotonically with increasing stress triaxiality X_σ[1] for loading conditions in the range of moderate to large stress triaxialities ($X_\sigma > 1$). In turn, this fact suggests that ductile fracture of metals for moderate to large values of X_σ is controlled by the softening induced by the porosity growth mechanism, since the porosity is known to grow faster with increasing X_σ for sufficiently large values of X_σ. On the other hand, recent experimental work (Bao and Wierzbicki, 2004; Barsoum and Faleskog, 2007; Dunand and Mohr, 2010; Faleskog and Barsoum, 2013) indicates that things may be different for low values of X_σ (corresponding to shear-dominated loadings), including the possible dependence of the material ductility on the Lode angle, which, in turn, suggests that a different fracture mechanism may come into play for low triaxialities. In fact, it has been proposed that this mechanism could be related to the changes in the pore shape, which can become significant under shear-dominated loadings. Note, however, that recent experimental results by Haltom et al. (2013)—albeit for a more restricted range of triaxialities ($0 < X_\sigma < 0.5$)—still show a monotonic reduction of the material ductility with increasing X_σ, which is in contrast with the earlier findings.

The theoretical study of void growth in ductile solids includes the pioneering work of Rice and Tracey (1969), which considered the model problem of an isolated void embedded in an infinite medium. Building on the earlier works, Budiansky et al. (1982) investigated both the growth and the collapse of an initially spherical void in a viscoplastic matrix subjected to axisymmetric loading conditions, establishing a strong, coupled dependence of the void growth and shape evolution on the stress triaxiality and material nonlinearity. The first micromechanics-based constitutive model for porous ideally plastic materials accounting for arbitrary values of the porosity was proposed by Gurson (1977). This model, which is exact for the special case of isotropic microstructures subjected to purely hydrostatic loading, was proposed as an approximation for more general loading conditions and microstructures. Nevertheless, numerous studies (see, e.g., the review article by Tvergaard, 1990) have demonstrated the success of the Gurson model in predicting key aspects of the macroscopic response and ductile fracture of metals at moderate and large stress triaxialities ($1 < X_\sigma < \infty$), including the monotonic reduction of the material ductility with increasing X_σ. On the other hand, the predictions produced by the Gurson model at small stress triaxialities ($0 < X_\sigma < 1$) have been found to be inaccurate. This shortcoming can be linked to the fact that the Gurson model neglects the effect of pore shape changes, which are expected to be significant at small stress triaxialities and to induce macroscopic anisotropy.

Over the past three decades, there have been several attempts to improve and generalize the Gurson model. Efforts aiming specifically to incorporate void shape effects were initiated by Gologanu et al. (1993, 1994) and progressively generalized and improved by Gologanu et al. (1997), Gărăjeu et al. (2000) and Madou and Leblond (2012a). Heuristic modifications include recent work to account for ductile failure of metals at small stress triaxialities (Nahshon and Hutchinson, 2008). In particular, Xue et al. (2013) have used the model of Nahshon and Hutchinson (2008) to successfully model the experimental results of Faleskog and Barsoum (2013). A more complete account of the Gurson-type constitutive models can be found in the review articles by Tvergaard (1990) and Benzerga and Leblond (2010).

Alternative models for porous viscoplastic materials (with fixed microstructures) were proposed by Ponte Castañeda (1991), Willis (1991) and Michel and Suquet (1992), making use of various nonlinear homogenization methods (see Ponte Castañeda and Suquet, 1998 for more details). Shortly thereafter, Ponte Castañeda and Zaidman (1994) made use of the "variational" homogenization method (Ponte Castañeda, 1991) based on the notion of an optimally selected linear comparison composite (LCC), together with the bounds of Willis (1977) for linear-elastic composites, to advance constitutive models for porous viscoplastic solids accounting for the evolution of the microstructure (i.e., porosity and average void shape) under finite-strain loading conditions. This model has been generalized to account for void-distribution effects (Kailasam et al., 1997), void rotations under general nonaligned loadings (Kailasam and Ponte Castañeda, 1997), as well as strain-hardening and elasticity for the matrix phase (Kailasam et al., 2000; Aravas and Ponte Castañeda, 2004). The numerical implementation of these models in general purpose finite-element codes (e.g., ABAQUS) was considered by Aravas and Ponte Castañeda (2004), building on an earlier implementation of the Gurson model by Aravas (1987). The predictions generated by these variational models have been found to be quite good for deviatoric loadings, where void shape changes become important, but they become progressively less accurate with increasing triaxiality, especially for low porosities and high material nonlinearities.

In an effort to resolve the limitations associated with the variational linear comparison model, Danas and Ponte Castañeda (2009a,b) proposed an improved constitutive model for porous materials with evolving microstructures. The model was derived by making use of the more sophisticated "second-order" LCC procedure of Ponte Castañeda (2002), together with an *ad hoc* interpolation/extrapolation scheme, enforcing the exact agreement of the second-order model with the Gurson model for the special case of spherical/cylindrical voids subjected to purely hydrostatic loadings. The second-order model was found to deliver fairly accurate results for the macroscopic response in several comparison with FEM and other exact results. In addition, the model was found to predict the development of shear localization instabilities due to void collapse at small stress triaxialities (Danas and Ponte Castañeda, 2012). In this context, it should be remarked that Danas and Aravas (2012) have also proposed a heuristic modification of

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[1] The stress triaxiality X_σ is defined in the standard way as the ratio of the hydrostatic stress over the von Misses equivalent stress.

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