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The evolution of pore shape and orientation in plastically deforming metals: Implications for macroscopic response and shear localization

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A B S T R A C T

A constitutive model is proposed for the macroscopic response of porous plastic metals at finite strains. Besides taking into account the porosity evolution, which leads to pressure sensitivity and dilatant response, the model can also account for changes in the average shape and orientation of the pores by means of suitable microstructural variables which play the role of internal variables and serve to characterize the evolving anisotropy of the material. In particular, the model is used to determine the evolution of the average shape and orientation of the voids under simple shear loading, as well as to explore the concomitant implications for the macroscopic response and shear localization. The intrinsic effect of the void rotations is deduced from comparisons with corresponding results for pure shear loading (where the voids change shape, but undergo no rotation on average), and found to be significant. In addition, more general loading conditions, involving combined tension and shear, are considered, and the effect of the stress triaxiality is investigated. For such more general plane strain conditions, it is found that there is an abrupt transition in the localization strain at a certain value of the triaxiality of about 0.3–0.4, with the localization strain dropping sharply both as the triaxiality increases, or decreases from this value. Furthermore, the results suggest that void rotations can dramatically enhance the susceptibility of the material to shear localization for a certain range of triaxiality values (between, approximately, 0.3 and 0.8).

1. Introduction

Ductile metals are known to contain random distributions of micro-voids, which are produced either as a consequence of the forming process itself (e.g., powder metallurgy, HIPPing), or which nucleate in the material from second-phase particles and eventually grow and coalesce leading to material failure (Tvergaard, 1990; Benzerga and Leblond, 2010). When such porous materials are subjected to finite strains, the size, shape and orientation of the voids, as well as the positions of the voids relative to each other, evolve with the deformation. This paper is concerned with the use of certain recently developed homogenization approaches (Agoras and Ponte Castañeda, 2013, Agoras and Ponte Castañeda, 2014) to describe the instantaneous macroscopic response of porous rigid plastic materials given the current state of the microstructure, as well as the evolution of the microstructure with the deformation, and its implications for failure through shear localization. In the present work, however, we focus on loading conditions involving macroscopic loads leading to significant void rotations (as well as changes in porosity and void shape).

It should be emphasized that over the years there have been several other approaches that have been proposed to

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model the behavior of porous ductile materials. Gurson (1977) made use of limit analysis for a spherical shell to propose an isotropic, pressure-sensitive plasticity model accounting for dilatant behavior. This model has been shown to be accurate for nearly hydrostatic loading conditions (i.e., for high stress triaxialities), but less so for deviatoric loadings and, in particular, cannot account for void shape and orientation changes leading to anisotropy development for such loadings. Yamamoto (1978) considered the effects of compressibility and porosity evolution on theoretical predictions for shear localization in porous media, and found that localization is facilitated by increasing triaxiality. In particular, these Gurson model predictions indicate that the material should become more resistant to failure by shear localization at low to intermediate stress triaxialities. However, this is in contradiction with some experimental observations (Bao and Wierzbicki, 2004; Barsoum and Faleskog, 2007), which suggest that lower triaxialities tend to facilitate failure by shear localization at least for a certain range of low to intermediate triaxialities (but see also Haltom et al., 2013). Motivated by these experimental results, Nahshon and Hutchinson (2008) have recently proposed a phenomenological modification of the constitutive model of Gurson (1977), consisting in a reinterpretation of the porosity evolution law as an isotropic damage evolution law to empirically account for the effects of the third invariant of the loading (Lode angle) on the material response at low triaxialities. By introducing suitable parameters and fitting them to appropriate experimental data, this approach has been successful in modeling certain features of material failure at low triaxialities (Xue et al., 2013). On the other hand, the homogenization models of interest in this work aim to be entirely predictive, by introducing suitable microstructural variables directly accounting for the changes in shape and orientation of the voids, and the associated changes in the overall anisotropy and instantaneous hardening of the material. While capturing this level of detail is certainly more challenging, the potential gains in terms of predictive capabilities could justify the added computational cost, which would still be much smaller than that required for full-field numerical simulations.

Additional approaches include micro-mechanical approaches attempting to generalize the work of Gurson (1977) by considering more general spheroidal and ellipsoidal void shapes (Gologanu et al., 1993; Madou and Leblond, 2012). The advantage of these approaches is that they give accurate predictions for high-triaxiality loading conditions, but they are less general than the homogenization approaches, in particular, because it has not been possible to derive corresponding evolution equations for the void rotation by means of these analyses. In this sense, the homogenization approaches to be developed in this work are more general since they provide consistent estimates for the average strain rate and vorticity in the voids, which can in turn be used to generate self-consistent evolution equations for the average void shape and rotation (Ponte Castañeda and Zaidman, 1994; Kailasam and Ponte Castañeda, 1998). Recently, Madou and Leblond (2013) and Madou et al. (2013) have proposed a combined approach making use of the Gurson limit analysis approach to obtain accurate estimates for the yield surface at high triaxialities, and of the homogenization approach of Ponte Castañeda and Zaidman (1994) and Kailasam and Ponte Castañeda (1998), improved through numerical fitting to finite-element simulations of confocal shells, to model the evolution of the void shape and orientation in the porous materials at low triaxialities.

A third approach is to make use of full-field numerical simulations, such as the ones recently carried out by Srivastava and Needleman (2013), Tvergaard (2012, 2014), building on earlier work (e.g., Needleman, 1972; Tvergaard, 1981). These simulations typically assume periodicity of the microstructure so that the numerical calculation can be restricted to a unit cell of the microstructure. While this approach is expected to be more accurate than the approximate homogenization models of interest in this work, the assumption of periodicity of the microstructure is a limiting factor, the microstructures of actual porous metals normally being random. Furthermore, the numerical results for periodic distributions of voids show great sensitivity to the microstructural parameters, suggesting that accounting for the randomness of the porosity distribution may be crucial. In this sense, the homogenization estimates to be discussed here offer the capability of accounting for the random distribution of the voids by means of the two-point correlation functions for their centers, as well as changes in the average shape and orientation of the voids.

The first homogenization estimates accounting for the overall compressibility in the instantaneous response of porous viscoplastic solids were given by Ponte Castañeda and Willis (1988), making use of the nonlinear Hashin–Shtrikman-type variational approach of Talbot and Willis (1985). Improved estimates were obtained by Ponte Castañeda (1991) making use of a new variational approach for a linear comparison composite (LCC) (see also Willis, 1991; Michel and Suquet, 1992 for derivations of these estimates by other methods). Ponte Castañeda and Zaidman (1994) made use of the LCC variational homogenization method of Ponte Castañeda (1991) to advance constitutive models for porous viscoplastic solids accounting for the evolution of the microstructure (i.e., porosity and average void shape) under general triaxial loading conditions. In that work, the changes in pore shape were found to have a significant effect on the macroscopic response of the material at low stress triaxialities. In particular, it was shown that shear localization could take place at low triaxialities by a void collapse mechanism—something that could not be accounted for by the Gurson-type models. By making use of the linear estimates of Ponte Castañeda and Willis (1995), this model was generalized to account for void-distribution effects (Kailasam et al., 1997), void rotations under general non-vanishing spin 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).