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Numerical assessment of an anisotropic porous metal plasticity model

S.M. Keralavarma [a,*], A.A. Benzerga [b,c]

[a] Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843-3141, USA
[c] Department of Materials Science & Engineering, Texas A&M University, College Station, TX 77843-3141, USA

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ABSTRACT

The objective of this paper is to perform numerical assessment of a micromechanical model of porous metal plasticity developed previously by the authors. First, upper bound estimates for the yield loci are computed using homogenization and limit analysis of a spheroidal representative volume element containing a confocal spheroidal void, neglecting elasticity. Unlike in the development of the analytical model, the computational limit analysis is performed without recourse to approximations so that the obtained yield loci are rigorous upper bounds for the true criterion. Next, the model's macroscopic dilatancy at incipient plastic flow is compared against that of the numerical limit analysis approach. Finally, finite-element calculations, with elasticity included, are presented for transversely isotropic porous unit-cells loaded axisymmetrically. The effective stress–strain response as well as evolution of the unit-cell porosity and void aspect ratio are compared with theoretical predictions.

1. Introduction

The primary mechanism of ductile fracture is the growth and coalescence of micro-voids or blunted micro-cracks. In metals, these nucleate from hard inclusions and second phase particles (Argon et al., 1975), or sometimes at slip- or twin-boundaries and intersections (Kondori and Benzerga, 2014). Microvoid growth and coalescence are natural outcomes in porous metal plasticity (Benzerga, 2015); also see Benzerga and Leblond (2010) for an extensive review. Earlier models were isotropic and only accounted for void growth (Gurson, 1977; Rousselier, 1987) with subsequent extensions to coalescence being heuristic (Tvergaard and Needleman, 1984). Later, porous metal plasticity models accounting for anisotropy and coalescence have been developed with increasing degree of accuracy, e.g., (Gologanu et al., 1993; Benzerga and Besson, 2001; Madou and Leblond, 2012a,b; Benzerga and Leblond, 2014).

Of particular interest are models having a micromechanically-derived capability to couple void shape and plastic anisotropy (Keralavarma and Benzerga, 2008; Monchiet et al., 2008; Keralavarma and Benzerga, 2010). Modeling void shape evolution is essential to various fundamental problems in ductile fracture mechanics such as: (i) developing criteria for the onset of void coalescence (Benzerga et al., 1999; Pardoen and Hutchinson, 2000; Benzerga, 2002); (ii) accounting for damage and fracture anisotropy (Benzerga et al., 2004); and (iii) understanding damage accumulation under complex loading conditions, for example void rotation in a shear field (Nielsen et al., 2012; Tvergaard, 2014) (obviously, rotation of a void is meaningful if the void has a non-spherical shape). On the other hand, modeling plastic anisotropy is essential to a host of engineering materials, notably aluminum alloys and hexagonal close packed materials such as magnesium,

* Corresponding author.

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titanium and zirconium alloys. What is of particular importance is that the net rate of void growth in an anisotropic material can be virtually suppressed or enhanced, under any stress state, depending on the degree of anisotropy (Benzerga and Besson, 2001; Keralavarma et al., 2011). This fact begins to be recognized in the mechanics literature but remains to be taken fully advantage of in designing damage-tolerant, fracture-resistant materials.

The constitutive models of anisotropic porous metal plasticity were developed based on nonlinear homogenization combined with the theory of limit analysis. Their derivation typically involves consideration of a hollow spheroidal representative volume element (RVE) made of a Hill orthotropic material and various kinematically admissible trial velocity fields at the microscale (Benzerga and Leblond, 2010). For instance, Monchiet et al. (2008) developed a model based on consideration of the velocity fields used by Gologanu et al. (1993), Gologanu et al. (1994) in their earlier versions of the GLD model, and Keralavarma and Benzerga (2008) developed an improved solution using a broader space of velocity fields (Lee and Mear, 1992) also used by Gologanu et al. (1997) in their improved GLD model. The model is, however, restricted to axisymmetric loadings and microstructures for which the void axis is aligned with one direction of material orthotropy. Later, Keralavarma and Benzerga (2010) developed a generalized model applicable to arbitrary loadings and void orientations. This model thus constitutes a generalization of the GLD model to plastically anisotropic matrices and also a generalization of Benzerga and Besson's (2001) model to spheroidal voids. Evolution equations were supplied for the void volume fraction, void aspect ratio and void rotation. It is worth noting that plastic potentials for ellipsoidal voids in an isotropic matrix have been previously derived using an alternate non-linear homogenization procedure by Ponte Castañeda and Zaidman (1994) and later improved by Danas and Ponte Castañeda (2009). However, neither of these works considered the case of anisotropic matrices. Within a similar variational framework Han et al. (2013) and Paux et al. (2015) have recently proposed yield criteria for porous single crystals. These models inherently account for plastic anisotropy effects at the crystal level but only for spherical voids. Other works have addressed the problem computationally. For example, Yerra et al. (2010) investigated the effects of plastic flow anisotropy using a crystal plasticity description of the matrix to study the growth of spherical voids in single crystals. Interestingly, they noted that when a Hill criterion is fit to the crystal plasticity model their results can be rationalized for the most part on the basis of the Benzerga–Besson model (2001). More recently, Lebensohn et al. (2013) studied the growth of initially spherical voids in a polycrystalline matrix by means of a fast Fourier transform formulation. When fully developed, such results will provide a basis for assessing anisotropic porous metal plasticity models. Also, crack-void interactions were investigated in textured polycrystals (Sreeramulu et al., 2013). However, for these more refined descriptions of matrix plasticity, closed form yield criteria have not been developed, presumably due to the analytical complexity of the homogenization problem.

The objective of the present paper is to perform a detailed numerical assessment of the approximate analytical model of Keralavarma and Benzerga (2010). The model considers aligned spheroidal voids in a Hill orthotropic matrix. The assumption of a spheroidal void shape entails some restrictions, although the problem is sufficiently general for the purpose of illustrating coupled effects of void shape and matrix anisotropy on ductile damage evolution. A brief summary of the analytical model is presented in Section 2 for ease of reference. The performance of the model is assessed using two different approaches. In Section 3, a numerical method is developed to compute upper-bound yield loci for anisotropic materials subjected to axisymmetric stress states following a limit analysis procedure using a large number of trial velocity fields derived from the incompressible axisymmetric velocity fields proposed by Lee and Mear (1992). Due to limitations of the trial velocity fields employed, tight upper bound loci are only guaranteed in the case of fully axisymmetric problems, even though rigorous bounds are obtained in all cases. Recently, a finite-element based limit analysis method has been proposed that obviates the need to choose trial velocity fields *a priori* (Morin et al., 2014), albeit at a higher computational cost. In Section 4, the analytical yield criterion is validated by comparison with these numerically derived upper bound yield loci. Additional results for the macroscopic dilatancy due to void growth at incipient yielding, obtained from the normality property of plastic flow, are also compared. In Section 5, the analytical model is integrated for specified loading paths and the evolution equations for the microstructural variables are validated by comparing the model predictions with finite-element predictions for the same using micromechanical unit-cells.

2. Model synopsis

In Keralavarma and Benzerga (2010), the framework of Hill–Mandel homogenization (Hill, 1967; Mandel, 1964) and limit-analysis was used to derive an approximate analytical yield criterion for anisotropic porous materials, containing spheroidal voids embedded in a Hill-type orthotropic matrix (Hill, 1948). The kinematic approach of homogenization was used, following previous works on void shape effects (Gologanu et al., 1997) and material anisotropy effects (Benzerga and Besson, 2001), wherein the representative volume element is subjected to homogeneous deformation rate boundary conditions. The RVE was chosen to consist of a thick spheroidal shell containing a confocal spheroidal void, as illustrated in Fig. 1. Evolution laws were also derived for the microstructural variables, porosity, void aspect ratio and orientation. The main results are summarized here for completeness.

2.1. Yield criterion

Following the Hill–Mandel homogenization approach, the macroscopic or 'average' stress, $\mathbf{\Sigma}$, and deformation rate, $\mathbf{D}$, for the RVE are given by

$$\mathbf{\Sigma} = \langle \boldsymbol{\sigma} \rangle_{\Omega}, \quad \mathbf{D} = \langle \mathbf{d} \rangle_{\Omega} \tag{1}$$