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A criterion for void coalescence in anisotropic ductile materials

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ABSTRACT

Plastic anisotropy in the form of texture development and void shape evolution can significantly affect damage growth rates and overall strain to failure in ductile materials. A criterion for the onset of coalescence, which is the transition from void growth by diffuse plastic deformation to localized plasticity in the ligament connecting neighboring voids, is a critical component of any predictive model for ductile fracture. In this paper, a new micromechanics-based criterion for void coalescence, combining both forms of anisotropy above, is developed using homogenization and limit analysis of a hollow cylindrical representative volume element made of an orthotropic material of the Hill type. Two possible modes of coalescence, corresponding to necking instability and shear strain localization in the transverse inter-void ligament, are accounted for in the analysis. The final form of the coalescence criterion has an interesting symmetry with Gurson-type yield criteria for porous materials and is shown to be an improvement over existing models for the special case of isotropic matrix behavior. For validation of the analytical model, quasi-exact numerical coalescence loci are computed using a finite elements based limit analysis method for the special case of transversely isotropic materials. The analytical model is shown to be in good agreement with the numerical data, except for highly oblate void shapes approaching penny shape cracks. A heuristic modification for the model is proposed, which significantly improves the model predictions in that limit.

1. Introduction

The nucleation, growth and coalescence of micro-voids is the primary damage process in metals undergoing ductile fracture. Voids that nucleate by cracking or debonding of second phase particles and inclusions, grow in isolation as a result of plastic deformation of the surrounding material until a critical condition is reached when neighboring voids start to interact through plastic strain localization in the inter-void ligament. The latter process, known as void coalescence, is quickly followed by plastic collapse of the ligament and crack extension so that accurate prediction of the onset of coalescence is critical to predictive modeling of ductile fracture. Different modes of coalescence are possible depending on the state of stress and the arrangement of voids, the most common being ligament collapse by necking transverse to the direction of the maximum principal stress. Other possible modes of coalescence are shear strain localization along an inclined band of voids at roughly 45° to the major loading direction and the relatively rare 'necklace coalescence' mode by link up of voids parallel to the

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loading direction (Benzerga and Leblond, 2010; Pineau et al., 2016). Some fracture experiments have reported reduced ductility under shear dominated loadings compared to triaxial loadings (Bao and Wierzbicki, 2004; Barsoum and Faleskog, 2007), in apparent contradiction to the accepted wisdom that ductility is a monotonically decreasing function of the stress triaxiality (ratio of the hydrostatic stress to the Von Mises effective stress). As a result, ductile fracture under low triaxiality loading conditions has been the subject of much attention in the recent experimental literature (Luo et al., 2012; Haltom et al., 2013; Roth and Mohr, 2016). The reduction in macroscopic ductility at low triaxialities is postulated to be due to a transition in the coalescence mode from internal necking to the so called ‘void sheeting’ mode by shear localization at the microscopic scale of the voids. Extensions of isotropic damage growth models, accounting for the effect of the third invariant of the stress tensor, have been proposed to model damage evolution at low triaxialities (Nahshon and Hutchinson, 2008; Zhou et al., 2014; Cheng et al., 2015) and failure loci for ductile materials have been proposed as functions of the current stress state (Bai and Wierzbicki, 2008; Stoughton and Yoon, 2011; Dunand and Mohr, 2011, 2014). However, the applicability of isotropic damage growth models under low triaxiality conditions and failure criteria that do not account for possible non-proportional loading history effects are questionable, based on evidence from unit cell calculations (Nielsen et al., 2012; Benzerga et al., 2012).

An alternative approach involves taking detailed account of the microstructure information in the form of material texture and the void shape, orientation and distribution effects and using an appropriate homogenization procedure to derive effective constitutive laws at the macro scale. The so called ‘local approach’ (Pineau et al., 2016) in the context of ductile fracture involves developing micromechanical models for the individual damage mechanisms, namely void growth and coalescence, and calibrating these models *post facto* by comparison with experimental data. Accounting for material anisotropy is particularly important for fracture at low triaxialities due to the fact that voids can quickly evolve into highly non-equiaxed shapes such as penny shaped cracks (Nielsen et al., 2012) with the result that the strain to failure can depend strongly on the evolution of void shape (Danas and Ponte Castañeda, 2012). The overall ductility is determined by a combination of the rate of void nucleation, the rate of void growth under multiaxial loading and the critical conditions for the onset of coalescence. Experiments (Benzerga et al., 2004; Benzerga and Leblond, 2010) and previous micromechanical analysis using the unit cell model (Benzerga and Besson, 2001; Keralavarma et al., 2011) have evidenced a strong influence of material texture on ductility. The overall anisotropy of the material is a result of a combination of material texture and the evolving void shape. Unlike void shape effects, which manifest mainly at intermediate to low values of the stress triaxiality, the effect of anisotropy due to material texture persists at all values of the triaxiality and can significantly affect the void growth rates in the pre-coalescence phase as well as the strain at the onset of coalescence (Keralavarma et al., 2011). Motivated by this observation, Keralavarma and Benzerga (2008, 2010) have developed a plasticity model for porous anisotropic materials, accounting for both forms of anisotropy, using homogenization and limit analysis of a representative volume element (RVE) undergoing diffuse plastic deformation in the pre-coalescence regime. Their model considered the growth of spheroidal voids in a Hill-type orthotropic material as is typical of cold-rolled sheet metals. The objective of the present paper is to complement the above model by deriving a micromechanics-based model for void coalescence in an orthotropic Hill material, motivated by recently published analytical results for isotropic materials containing non-spherical voids (Tekoglu et al., 2012; Benzerga and Leblond, 2014; Torki et al., 2015).

Well known micromechanics-based models of void growth such as the isotropic Gurson (1977) model and several anisotropic extensions of the same (Gologanu et al., 1997; Benzerga and Besson, 2001; Monchiet et al., 2008; Keralavarma and Benzerga, 2010) are derived using the upper bound approach of limit analysis (Suquet, 1982) in combination with the Hill-Mandel homogenization theory (Hill, 1967; Mandel, 1964). Homogeneous deformation rate boundary conditions are typically assumed, which precludes the possibility of strain localization within the representative volume element necessary for modeling void coalescence. Early models of coalescence have thus been phenomenological, with the critical condition for the onset of coalescence dependent on attainment of a critical porosity (McClintock, 1968; Tvergaard and Needleman, 1984) or a critical geometry for the inter-void ligament (Brown and Embury, 1973) and independent of the stress state, contrary to experimental evidence. Thomason (1990) first proposed a micromechanics-based criterion for void coalescence using numerical limit analysis of a square prismatic unit cell containing square prismatic voids undergoing coalescence by necking in the inter-void ligament. Thomason's criterion was widely adopted and extended by several authors to account for strain hardening and anisotropy effects (Pardoen and Hutchinson, 2000; Benzerga, 2002; Yerra et al., 2010) and more recently to account for shear localization effects (Tekoglu et al., 2012), although the original criterion was obtained as an empirical fit to numerical data and many of the later extensions have been of a heuristic nature. Recently Benzerga and Leblond (2014) have improved Thomason's analysis by considering a hollow cylindrical RVE and deriving a fully analytical upper-bound solution for the coalescence stress under axisymmetric loading. The RVE geometry and velocity fields considered by these authors were consistent with a transversely isotropic porous material undergoing coalescence by internal necking between the voids. This result was further extended by Torki et al. (2015) by accounting for shear localization in the ligament using an approach similar to that of Tekoglu et al. (2012). Their result thus represented a rigorous limit analysis solution for the problem of coalescence under combined normal and shear stresses, for which an approximate solution was first proposed by Leblond and Mottet (2008) using the Gurson model for an RVE consisting of a porous coalescence layer sandwiched between rigid regions. However, the velocity fields considered by Benzerga and Leblond (2014), Torki et al. (2015) had internal discontinuities which resulted in a non-differentiable surface term in the expression for the plastic dissipation, although the yield surface derived from it was C^1 continuous. Nevertheless, recognizing the fact that the surface dissipation term was an artifact due to the velocity fields considered, Morin et al. (2015) proposed an alternate coalescence criterion using more realistic continuous trial velocity fields, although the resulting criterion could not be expressed in closed form.