Journal of the Mechanics and Physics of Solids 66 (2014) 133–153

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Effect of Lode parameter on plastic flow localization after proportional loading at low stress triaxialities

Matthieu Dunand [a,b], Dirk Mohr [a,b,*]

[a] Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

[b] Solid Mechanics Laboratory (CNRS-UMR 7649), Department of Mechanics, École Polytechnique, Palaiseau, France

ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form
3 January 2014
Accepted 31 January 2014
Available online 28 February 2014

Keywords:
Ductile fracture
Localization
Lode angle
Stress triaxiality
Unit cell analysis

ABSTRACT

The effect of the stress state on the localization of plastic flow in a Levy–von Mises material is investigated numerically. A unit cell model is built with a spherical central void that acts as a defect triggering the onset of flow localization along a narrow band. Periodic boundary conditions are defined along all boundaries of the unit cell. Shear and normal loading is applied such that the macroscopic stress triaxiality and Lode parameter remain constant throughout the entire loading history. Due to the initially orthogonal symmetry of the unit cell model the deformation-induced anisotropy associated with void shape changes, both co-rotational and radial loading paths are considered. The simulation results demonstrate that the macroscopic equivalent plastic strain at the onset of localization after monotonic proportional loading decreases in stress triaxiality and is a convex, non-symmetric function of the Lode parameter. In addition to predicting the onset of localization through unit cell analysis, an analytical criterion is proposed for monotonic proportional loading which defines an open convex envelope in terms of the shear and normal stresses acting on the plane of localization.

1. Introduction

The localization of plastic deformation within a narrow band is an important precursor to ductile fracture. Following the works of Marciniak and Kuczynski (1967) and Rice (1977), it is common practice to predict the onset of localization based on macroscopic constitutive theories through infinite band localization analysis (e.g. Mear and Hutchinson, 1985, Duszek and Perzyna, 1991). As noted by Rice (1977), the identified onset of localization corresponds to the loss of ellipticity of the governing equilibrium equations. Consequently, onset of localization maps can also be directly computed by assessing the loss of ellipticity of incremental moduli (Michel et al., 2007, Danas and Ponte Castañeda, 2012).

For most metals, the strains at the onset of localization are very large. As a consequence, the effect of voids on the elasto-plastic moduli needs to be taken into account when computing the instant of the onset of localization. This requires advanced constitutive theories such as the Gurson model (Gurson, 1977) and its extensions accounting for void nucleation (e.g. Chu and Needleman, 1980), for the loss of load-carrying capacity associated with void coalescence (e.g. Tvergaard and Needleman, 1984), for void shape effects (e.g., Gologanu et al., 1993, 1994; Garajeu et al., 2000; Pardoen and Hutchinson, 2000) and for plastic anisotropy (e.g., Benzerga et al., 2004). As shown by Nahshon and Hutchinson (2008), additional

* Corresponding author. Phone +33 1 6933 5801.
E-mail address: mohr@mit.edu (D. Mohr).

http://dx.doi.org/10.1016/j.jmps.2014.01.008
0022-5096

modifications representing shear softening are necessary to obtain reasonable predictions of strain localization at low stress triaxialities.

Unit cell models provide a computationally-expensive alternative to macroscopic constitutive theories to describe the large deformation response of metals of low porosity. The early analysis with unit cell models was mostly limited to two-dimensional models, e.g. axisymmetric mechanical systems with spheroidal voids (e.g. Koplik and Needleman, 1988, Brocks et al., 1995, Pardoen and Hutchinson, 2000) or plane strain models with cylindrical voids (e.g. Tvergaard, 1981). Fully three-dimensional models have only been employed rather recently for plane strain conditions (e.g. Scheyvaerts et al., 2011, Nielsen et al., 2012, Rahman et al., 2012) and selected three-dimensional stress states (e.g. Barsoum and Faleskog, 2007, 2011, Tekoglu et al., 2012). Aside from the macroscopic response, unit cell models provide valuable insight in the local deformation fields and allow for the detailed analysis of the void growth and coalescence process (e.g. Scheyvaerts et al., 2011). As discussed by Pardoen and Hutchinson (2000), it is useful to define *void growth* as the phase prior to the localization of deformation inside the intervoid ligament, while *void coalescence* describes the deformation process thereafter. Normal localization may be seen as diffuse necking of the ligament, while shear localization is characterized by the development of a shear band at the microscale. Due to the inherent periodicity of microstructures defined through unit cell models, the *onset of coalescence* corresponds to the *onset of normal and/or shear localization* of plastic flow within a narrow band at the scale of the void.

Substantial efforts have been devoted to the development of micromechanics-based coalescence criteria (see review of Benzerga and Leblond, 2010). The first generation of coalescence criteria (Brown and Embury, 1973, Thomason, 1985, Benzerga, 2002) is primarily concerned with the prediction of internal necking as a function of the void shape, relative spacing and the applied normal stress. The effect of shear in addition to normal loads on the coalescence has been addressed recently by Tekoglu et al. (2012). They demonstrate that the introduction of non-linear parameter functions into the Benzerga model leads to an excellent agreement with their unit cell simulations for combined shear and tension. Furthermore, Tekoglu et al. (2012) present a micromechanical analysis to come up with an analytical coalescence model for general loading conditions.

Reliable experimental results on ductile fracture at low stress triaxialities are still difficult to obtain because of significant experimental challenges associated with the proper introduction of loading, the localization of deformation at the specimen level (necking), and the detection of the onset of fracture (e.g. Bao and Wierzbicki, 2004, Mohr and Henn, 2007, Brünig et al., 2008, Fagerholt et al., 2010, Gao et al., 2011, Dunand and Mohr, 2011a, Haltom et al., 2014). Numerical results on localization are therefore of particular value for the development of ductile fracture modes at low stress triaxialities. Tvergaard (2008, 2009) analyzed the behavior of a row of circular cylindrical holes under shear loading. He reports the formation of rotating micro-cracks as the result of void closure at low stress triaxialities. Furthermore, he points out that a maximum in the macroscopic shear stress accompanies the onset of localization of plastic flow. Nielsen et al. (2012) confirmed these observations using a three-dimensional unit cell model. In his most recent work, Tvergaard (2012) considered a square unit cell with a cylindrical void and fully periodic boundary conditions. By varying the normal stress during shearing, he found that increasing the stress triaxiality facilitates failure through shear localization.

Barsoum and Faleskog (2007) performed a micromechanical analysis on three-dimensional unit cells with spherical voids for combined tension and shear loading. Their model represents a layer of preexisting voids in a Levy–von Mises material; it features a height-to-width ratio of 2:1 along with periodic boundary conditions on all three pairs of parallel boundaries. Using a kinematic condition comparing the deformation gradient rate inside and outside a band of localization (as proposed by Needleman and Tvergaard, 1992), they define the onset of shear localization and report the corresponding macroscopic von Mises equivalent strain as strain to failure (due to localization). Their simulation results for a constant stress triaxiality of 1.0 elucidate the effect of the Lode parameter on shear localization for stress states between generalized shear and axisymmetric tension. Their computational results also agree well with the observations from experiments where coalescence occurred by internal necking (triaxiality above 0.7). However, for low stress triaxialities and stress states closer to generalized shear, the macroscopic strains to failure predicted by the unit cell model are significantly higher than those found experimentally.

Gao et al. (2010) applied macroscopic normal stresses along the symmetry axes of a cubic unit cell with a spherical void and boundaries that remain flat and perpendicular throughout deformation. Assuming that void coalescence occurs when the macroscopic strain state shifts to a uniaxial strain state, they computed the corresponding macroscopic effective strain as a function of the stress triaxiality (ranging from 0.33 to 2) and of the Lode angle. Their results indicate that the macroscopic strain to coalescence increases monotonically as a function of the Lode angle from axisymmetric tension to axisymmetric compression. Furthermore, their simulations indicate that this Lode angle effect on coalescence becomes more pronounced at low stress triaxialities. They also show that the effective strain to coalescence decreases when assuming a Gurson instead of a Levy–von Mises matrix.

More recently, Barsoum and Faleskog (2011) made use of their unit cell model to investigate the localization of deformation into a narrow planar band for a wider range of stress states. Irrespective of the stress state, they observe the lowest macroscopic effective strain to localization for bands oriented at an angle of about 45° with respect to the direction of the minimum principal macroscopic stress. The computed localization loci for stress triaxialities ranging from 0.75 to 2 show the lowest strains to localization for generalized shear. The loci are approximately symmetric with respect to the Lode parameter, showing slightly higher localization strains for axisymmetric compression than axisymmetric tension. Tekoglu et al. (2012) considered an elastic perfectly plastic matrix material in their unit cell simulations and performed a limit load