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Micromechanical analysis on the influence of the Lode parameter on void growth and coalescence

Imad Barsoum [a,*], Jonas Faleskog [b]

[a] Department of Mechanical Engineering, The Petroleum Institute, P.O. Box 2533, Abu Dhabi, United Arab Emirates
[b] Department of Solid Mechanics, Royal Institute of Technology, SE-100 44 Stockholm, Sweden

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ABSTRACT

A micromechanical model consisting of a band with a square array of equally sized cells, with a spherical void located in each cell, is developed. The band is allowed a certain inclination and the periodic arrangement of the cells allow the study of a single unit cell for which fully periodic boundary conditions are applied. The model is based on the theoretical framework of plastic localization and is in essence the micromechanical model by Barsoum and Faleskog (Barsoum, I., Faleskog, J., 2007. Rupture mechanisms in combined tension and shear—micromechanics. International Journal of Solids and Structures 44(17), 5481–5498) with the extension accounting for the band orientation. The effect of band inclination is significant on the strain to localization and cannot be disregarded. The macroscopic stress state is characterized by the stress triaxiality and the Lode parameter. The model is used to investigate the influence of the stress state on void growth and coalescence. It is found that the Lode parameter exerts a strong influence on the void shape evolution and void growth rate as well as the localized deformation behavior. At high stress triaxiality level the influence of the Lode parameter is not as marked and the overall ductility is set by the stress triaxiality. For a dominating shear stress state localization into a band cannot be regarded as a void coalescence criterion predicting material failure. A coalescence criterion operative at dominating shear stress state is needed.

1. Introduction

It is a well known fact that the stress triaxiality has a significant influence on void growth and coalescence and hence on the ductility of materials. This has been demonstrated by several authors in the past, both experimentally, theoretically and numerically. The classical work by Hancock and Mackenzie (1976), where they perform experiments on notched round bar specimens, show that ductility increases with decreasing stress triaxiality. These experimental findings are annotated by the use of the theoretical void growth models by McClintock (1968) and Rice and Tracey (1969). Recently, Weck et al. (2006) perform an experimental study on void coalescence in voided layers and observe that the voids grow until a critical spacing between them is reached, which corresponds to the onset of coalescence. Beyond this point two different ductile failure mechanisms leading to final rupture are observed. One is void shearing due to that the deformation becomes concentrated into a narrow shear band between the larger voids leading to micro-void nucleation at second phase particles (Cox and Low, 1974; Faleskog and Shih, 1997). The other mechanism is referred to as void coalescence by internal necking, where the ligament between the voids necks down to a point. This event is studied extensively numerically e.g. by Koplik and Needleman (1988), Pardoen and Hutchinson (2000) and most recently by Scheyvaerts et al. (2010), who investigate the influence of the stress triaxiality on void growth and coalescence under axisymmetric conditions by the use of a cell model. However, it has been observed in recent experimental studies by Wierzbicki et al. (2005) and Barsoum and Faleskog (2007a) that the stress triaxiality is insufficient to characterize the stress state in ductile failure. A deviatoric stress measure is also needed and the stress state is hence characterized by the stress triaxiality and the Lode parameter.

Zhang et al. (2001) and Gao and Kim (2006) perform systematic numerical analysis on a cell model with straight boundaries subjected to different macroscopic stress states characterized by the Lode parameter and stress triaxiality. They find that the Lode parameter has a strong influence on the stress carrying capacity of the material and the onset of void coalescence, which they define as the shift to an uniaxial straining mode. As a consequence of the constraint on the cell not allowing for shear deformation, the uniaxial straining mode is the only mode of localization that will occur in their model. Other cell studies by Tvergaard (1981), Tvergaard (1982), Pijnenburg and Van der Giessen (2001) and

* Corresponding author. Tel.: +971 2 6075273; fax: +971 2 6075194.
E-mail address: ibarsoum@pi.ac.ae (I. Barsoum).

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Leblond and Mottet (2008) incorporate the possibility of shear deformation by employing fully periodic boundary conditions, but they do not systematically investigate the effect of the Lode parameter.

In a recent study, Barsoum and Faleskog (2007b) employ a micromechanical model to study the ductile rupture mechanisms observed in their experimental investigation on double notched tube specimens subjected to combined tension and torsion (Barsoum and Faleskog, 2007a). The micromechanical model assumes that ductile failure is a consequence of that plastic deformation localizes into a band and is based on the model introduced by Rudnicki and Rice (1975) and Rice (1977). The model consists of a planar band with a square array of equally sized cells, with an initially spherical void in the center of each cell. The periodic arrangement of cells allows for the study of a single unit cell for which fully periodic boundary conditions are applied within the band. The loading condition of the unit cell is chosen such that it resembles the stress state, characterized by the stress triaxiality and the Lode parameter of the experiments. The model captures the experimental trend fairly well and predicts the different rupture mechanisms involved but does not account for the orientation of the band, which has an important role in the localization behavior. Tvergaard (2009b), Tvergaard (2009a) has very recently carried out a series of similar micromechanical studies, where a combination of normal stress and shear stress is applied to unit cells under plane strain conditions. Tvergaard's results demonstrates that voids deforming under zero or low stress triaxiality may lead to material softening. Also Scheyvaerts et al. (in press) have most recently studied material softening and failure due to growth and coalescence of voids under combined tension and shear. However, both Tvergaard (2009b), Tvergaard (2009a) and Scheyvaerts et al. (in press) use a similar model as in Barsoum and Faleskog (2007b), and do not fully account for the influence of the orientation of the voided cells.

The influence of the band orientation on the localization behavior has been the subject of studies in the past. Yamamoto (1978) adopts elastic–plastic constitutive relations for a void-containing material to develop a criterion for localization under plane strain conditions. The same procedure is employed by Saje et al. (1982) where they investigate the influence of void nucleation and band orientation on localization under plane strain and axisymmetric conditions. Tvergaard (1989) uses a two dimensional computational cell model and employs fully periodic boundary conditions to incorporate the possibility of shear deformation to study the influence of band orientation. They all find that the orientation of the band has a significant influence on localization. Nahshon and Hutchinson (2008) propose a modified Gurson model to account for shear failure. They perform a localization analysis, following earlier localization studies employed by Mear and Hutchinson (1985), where they explore the relationship of the localization strain to the Lode parameter, stress triaxiality and band orientation.

In the current study the micromechanical model in Barsoum and Faleskog (2007b) is extended to incorporate the effect of band orientation in a somewhat simplified manner. The objective is to explore the influence of the Lode parameter and the band orientation on the localization behavior, void growth and coalescence. The model is presented in Section 2, the mechanical properties of the materials considered are summarized in Section 3 and the results of the micromechanical analysis are presented in Sections 4 and 5. The paper is concluded in Section 6.

2. Micromechanical model

Building on the work by Marciniak and Kuczynski (1967), Rudnicki and Rice (1975) and Rice (1977) investigate the conditions corresponding to localization of deformation into a planar band and present a general framework for imperfection based localization analysis, as is also discussed by Needleman and Tvergaard (1992). The present micromechanical analysis fits well into the theoretical framework given by Rudnicki and Rice (1975). The micromechanical model employed here assumes that ductile material failure occurs when the deformation becomes highly non-uniform and localizes into a thin planar band as a result of nucleation, growth and coalescence of voids. The material is assumed to contain an initial planar band with a regular square array of pre-existing voids that can be viewed as initial imperfections, which may induce localization of deformation. Thus the stage of void nucleation is not considered in the present study.

A systematic study of the influence of the full range of the Lode parameter, L $(-1 \leqslant L \leqslant 1)$, on void growth and coalescence can be done in several ways. As in Barsoum and Faleskog (2007b) we consider a material subjected to a combination of an axisymmetric and a pure shear stress state, as shown in Fig. 1(a) with reference to the Cartesian coordinate system $X_1^0X_2^0X_3^0$. Localization into a planar band, as shown in Fig. 1(b), may then occur in a symmetric mode, a shear mode or a combination of both modes. In general, the band will localize in the most favorable direction and thus the orientation of the band should be considered. The orientation of the band is here defined by θ, the angle between the band and the macroscopic Cauchy stress component Σ_{33}^0 along the X_3^0-axis, according to Fig. 1(a). As shown by Rudnicki and Rice (1975) and further discussed by Perrin and Leblond (1993), the normal to the plane of localization will always be perpendicular to the direction of the middle principal stress $\Sigma_{\rm II} = \Sigma_{22}^0$ and located in the $X_1^0 - X_3^0$ plane. Hence, the unit normal vector of the band is taken to be in the $X_1^0 - X_3^0$ plane and perpendicular to the X_2^0-axis. At this point we introduce a second Cartesian coordinate system $X_1X_2X_3$, rotated an angle θ such that X_1 is normal to the band in Fig. 1(c) and (d) with $X_2 = X_2^0$, as shown in Fig. 1. The macroscopic stress components Σ_{ij} with reference to $X_1X_2X_3$ acting on the inclined band in Fig. 1(c) can readily be obtained by tensorial transformation of the macroscopic stress components Σ_{ij}^0 in Fig. 1(b). As discussed above, the maximum and minimum principal stresses, $\Sigma_{\rm I}$ and $\Sigma_{\rm III}$, respectively, are located in the $X_1^0 - X_3^0$. Their directions are here defined by the angle α between $\Sigma_{\rm III}$ and the X_3^0-axis. For later purposes we introduce the angle $\varphi = \theta + \alpha$ and note that $\Sigma_{\rm I} \geqslant \Sigma_{\rm II} = \Sigma_{22}^0 \geqslant \Sigma_{\rm III}$, see Fig. 1(d).

The influence of the band orientation is accounted for in a simplified manner in this study. Upon deformation the orientation of the inclined band in Fig. 1(a) will change such that the angle between X_3^0-axis and the band evolves as $\tan\theta_{def} = (F_{13} + F_{11}\tan\theta)/(F_{33} + F_{31}\tan\theta)$, where θ_{def} is the angle in the deformed configuration and F_{ij} are components of the deformation gradient with reference to the Cartesian frame $(X_1^0X_2^0X_3^0)$. Here, we do not account for the evolution of the angle with deformation. Instead, given a fixed set of the stress triaxiality and the Lode parameter, we apply proportional stressing on the aggregate of cells in the inclined plane in Fig. 1(c) and seek the angle θ that minimizes the strain to failure. Hence, the angle θ shown in Fig. 1(a) may be viewed as the angle at the instance of localization. Put in an another way, the stress state in Fig. 1(c) is co-rotating with the inclined band during deformation and thus the coordinate system $X_1X_2X_3$ is used as the reference system. In this way, we can fully employ the micromechanical model developed in Barsoum and Faleskog (2007b) in which the periodic boundary conditions are formulated based on the assumption of proportional stressing. Note that for the special case of no initial band inclination, the band will not rotate during deformation. This special case is also considered below.

Due to the regular array of voids, attention can be restricted to a three dimensional unit cell as indicated in Fig. 1(e), with dimensions $2D_1$, D_2 and D_3. The height of the unit cell $(2D_1)$ is taken large