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Effect of initial void shape on ductile failure in a shear field

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ABSTRACT

For voids in a shear field unit cell model analyses have been used to show that ductile failure is predicted even though the stress triaxiality is low or perhaps negative, so that the void volume fraction does not grow during deformation. Here, the effect of the void shape is studied by analyzing materials where the voids have initially ellipsoidal shapes. The cell models are in plane strain, so that the voids are modeled as cylindrical holes. Periodic boundary conditions are used to represent a material with a periodic distribution of voids having different spacings in the two in-plane coordinate directions, and subjected to different average stress states. Depending on the initial orientation of the ellipsoidal voids, the principal axes of the elongated voids rotate initially in different directions relative to the shear field. After some deformation the behavior is much like that found for voids with circular cross-section, i.e. the voids in shear flatten out to micro-cracks, which rotate and elongate until interaction with neighboring micro-cracks gives coalescence. Even though the mechanism of ductile failure is the same, the load carrying capacity predicted, for the same initial void volume fraction, is rather different for different initial orientations of the ellipsoidal voids.

1. Introduction

Voids deforming in a ductile material subject to shear under low stress triaxiality have been studied in a number of recent investigations. Barsoum and Faleskog (2007a) have carried out full 3D analyses for shear specimens containing spherical voids in order to model their experiments (Barsoum and Faleskog, 2007b) on ductile fracture in a double notched tube specimen loaded in combined tension and torsion. In a number of plane strain cell model analyses for a material containing a periodic array of circular cylindrical voids Tvergaard (2008, 2009, 2012) has shown that in stress states similar to simple shear the voids are flattened out to micro-cracks, which rotate and elongate until interaction with neighboring micro-cracks gives coalescence. Thus, also in shear ductile failure occurs due to the deformation of voids and their interaction with neighboring voids, but the mechanism is very different from the well-known void growth to coalescence mechanism under tensile loading. The mechanism is also found in a 3D analysis for initially spherical voids (Nielsen et al., 2012).

When a ductile material deforms under relatively high hydrostatic tension micro-voids contained in the material will tend to grow large and ductile failure will occur by coalescence of neighboring voids (see reviews by Garrison and Moody (1987), Tvergaard (1990), Benzerga and Leblond (2010)). Thus, both types of ductile failure modes found under different stress states depend on the interaction of voids, leading to void coalescence. But at high stress triaxiality the void volume fraction increases until ductile fracture occurs, while at low stress triaxiality the void volume fraction disappears, as the voids become micro-cracks. In analyses of cases where micro-cracks form it is important to account for the contact between crack surfaces.

The effect of the initial void shape and of void shape evolution has been studied by a number of authors (e.g.

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Gologanu et al. (1997), Pardoen and Hutchinson (2000), Danas and Castaneda (2009a,b)), and 3D analyses for voids in shear fields have been carried out by Leblond and Mottet (2008). The effect of the initial void shape in shear fields has been studied by Scheyvaerts et al. (2006, 2011), who analyzed 3D cell models with ellipsoidal voids subject to overall plane strain conditions, under simple shear or under shear with a tensile load superposed. They found that in shear fields the ellipsoidal voids quickly change their orientations, while they start to deform, and this has an influence on the final failure. In the present paper this is investigated further by considering initially ellipsoidal cylindrical voids in analyses such as those of Tvergaard (2012), which account for the crack surface contact that develops at low stress triaxiality before final failure.

It is noted that a number of experimental investigations have been carried out recently, which consider ductile fracture in shear at a stress triaxiality near zero. Thus, Bao and Wierzbicki (2004), Beese et al. (2010) and Dunand and Mohr (2011) have used special butterfly specimens to study the effect of stress triaxiality and of the Lode angle in stress states dominated by shear. Haltom et al. (2013) have used a tubular specimen in tension–torsion while Ghahremaninezhad and Ravi-Chandar (2013) have used a modified Arcan test to study the same Al alloy.

2. Problem formulation and numerical procedure

As in Tvergaard (2012) the material to be considered here has a periodic array of voids, with the initial spacing $2A_0$ in the x^1-direction and the initial spacing $2B_0$ in the x^2-direction. In the plane strain analysis the voids are cylindrical, either circular cylindrical with radius R_0, or ellipsoidal with axes a and b (see Fig. 1b), such that $ab = R_0^2$ gives the same initial void volume fraction. The material is analyzed by considering a unit cell such as that in Fig. 1, containing only one void.

Finite strains are accounted for, based on a convected coordinate Lagrangian formulation of the field equations, with a Cartesian x^i coordinate system used as reference and with the displacement components on reference base vectors denoted by u^i. The metric tensors in the reference configuration and the current configuration, respectively, are g_{ij} and G_{ij} with determinants g and G, and $\eta_{ij} = 1/2(G_{ij} - g_{ij})$ is the Lagrangian strain tensor. In terms of the displacement components u^i on the reference base vectors the Lagrangian strain tensor is

$$\eta_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i} + u^k_{,i}u_{k,j}\right) \tag{1}$$

where $(\,)_{,j}$ denotes covariant differentiation in the reference frame. The contravariant components τ^{ij} of the Kirchhoff stress tensor on the current base vectors are related to the components of the Cauchy stress tensor σ^{ij} by $\tau^{ij} = \sqrt{G/g}\,\sigma^{ij}$. A finite strain formulation for a J_2 flow theory material with the Mises yield surface is applied, where the incremental stress–strain relationship takes the form $\dot{\tau}^{ij} = L^{ijk\ell}\dot{\eta}_{k\ell}$, with the instantaneous moduli specified in Hutchinson (1973), Tvergaard (1976). The true stress-logarithmic strain curve in uniaxial tension is taken to follow the power law

$$\varepsilon = \begin{cases} \sigma/E, & \sigma \leqslant \sigma_Y \\ (\sigma_Y/E)(\sigma/\sigma_Y)^{1/N}, & \sigma \geqslant \sigma_Y \end{cases} \tag{2}$$

with Young's modulus E, the initial yield stress σ_Y and the power hardening exponent N. Poisson's ratio is ν.

In the analyses, periodic boundary conditions are used on the unit cell model to be able to analyze the material with a doubly periodic array of voids, subject to shear. Thus, the displacements and the nominal tractions on the

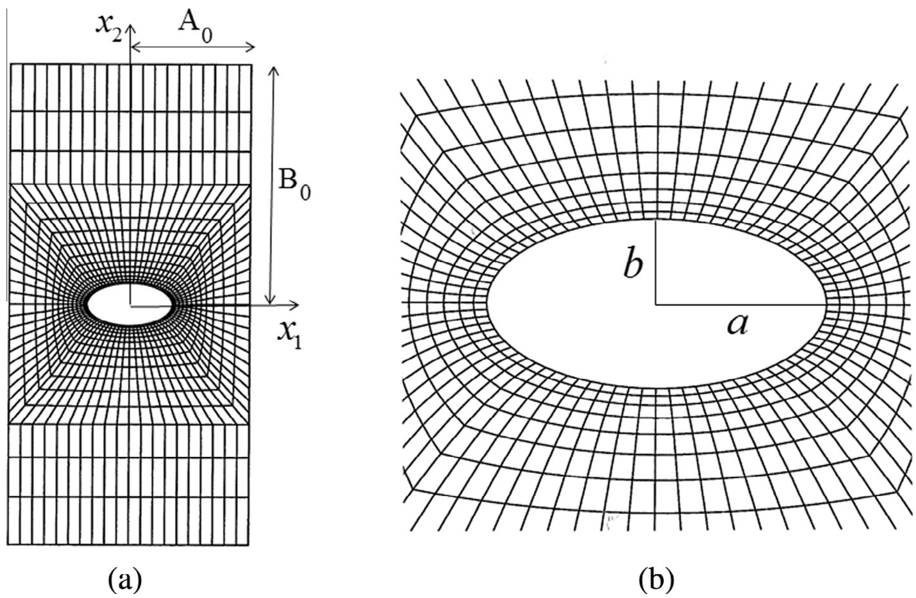

Fig. 1. Example of an initial mesh used for a case with $B_0/A_0 = 2$ and $a/b = 2$.