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On the prediction of ductile fracture by void coalescence and strain localization

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ABSTRACT

This paper presents a unit cell model based on the observation that ductile fracture occurs when plastic flow is localized in a band. The unit cell consists of three void containing material units stacked in the direction normal to the localization plane. Localization takes place in the middle material unit while the two outer units undergo elastic recovery after failure occurs. Thus a failure criterion is established as when the macroscopic effective strain of the outer material units reaches the maximum value. Analyses are conducted to demonstrate the effect of the voids existing outside the localization band. Comparisons of the present model with several previous models suggest that the present model is not only easy to implement in finite element analysis but also more suitable to robustly determine the failure strain. A series of unit cell analyses are conducted for various macroscopic stress triaxialities and Lode parameters. The analysis results confirm that for a fixed Lode parameter, the failure strain decreases exponentially with the stress triaxiality and for a given stress triaxiality, it increases as the stress state approaches the generalized tension and generalized compression. The analysis results also reveal the effect of the stress state on the deformed void shape within and near the localization band.

1. Introduction

The ductile fracture process in metals is strongly influenced by the stress state subjected by the material. In these materials, voids nucleated at inclusions and second-phase particles by decohesion of the particle matrix interface or by particle cracking (van Stone et al., 1985; Garrison and Moody, 1987). Under high triaxial stress states, voids grow in size, followed by inter-void flow localization, leading to fracture initiation (Benzerga and Leblond, 2010). On the other hand, under shear-dominated loading, voids change little in size but significantly in shape and orientation, and the onset of material fracture takes place after strain localization in a narrow band (Tvergaard, 2008, 2009; Nielsen et al., 2012).

There is a long history of experimental and modeling efforts to predict ductile fracture. The experimental work by Bridgman (1952) showed that the strain to failure increased significantly when the tensile test was carried out in a pressurized environment. Using notched tensile specimens, Hancock and Mackenzie (1976) and Hancock and Brown (1983) demonstrated that the strain to initiate ductile fracture decreases with the stress triaxiality. In the widely used Johnson–Cook fracture model (Johnson and Cook, 1985), the dependence of the failure strain on the stress triaxiality is described by an exponentially decaying function. More recently, Bao and Wierzbicki (2004), Barsoum and Faleskog (2007), Gao et al. (2010) and

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Zhou et al. (2012) showed that the strain to failure not only depends on the stress triaxiality but also depends on the Lode parameter.

Early micromechanical treatment of ductile fracture considered growth of isolated voids in solids (McClintock, 1968; Rice and Tracey, 1969). Gurson (1977) proposed a homogenized yield surface for void containing materials based on the maximum plastic work principle. The Gurson model, with further development by Tvergaard and Needleman (Tvergaard, 1981, 1982; Tvergaard and Needleman, 1984), has been widely used in modeling of ductile fracture. In the Gurson–Tvergaard–Needleman (GTN) model, damage evolution is completely due to the increase of void volume fraction, which is strongly influenced by the stress triaxiality, and the final void coalescence stage is approximated by artificially accelerating the void growth rate. More recent modifications to the Gurson-type porous material models include the work by Nahshon and Hutchinson (2008), Xue (2008), Zhou et al. (2014), Malcher et al. (2014), Zhai et al. (2016), among others to take into account shear-induced damage.

While detailed and carefully designed experiments can provide many insights to the ductile fracture process, monitoring the stress state evolution on the microscale and obtaining reliable fracture strain still remain as major obstacles. Micromechanical modeling provides a viable alternative. Finite element micromechanical analysis has proven to be extremely useful in guiding the development of improved ductile fracture models. Typically detailed finite element analyses are conducted for a representative material volume (RMV), often referred to as the unit cell analysis, under various stress states to study the void growth and coalescence process. Koplik and Needleman (1988) conducted axisymmetric unit cell analyses to calibrate the micromechanical parameters in the GTN model and showed that the onset of void coalescence by internal necking can be identified by a shift of the deformation to a macroscopic uniaxial strain state. Faleskog et al. (1998) conducted a series of unit cell analyses and showed that the q-parameters in the GTN model depend on the material flow properties. Kim et al. (2004) and Gao and Kim (2006) showed that the void growth and coalescence process and the resulting macroscopic behavior of the RMV are not only influenced by the stress triaxiality but also influenced by the Lode parameter. It is worth mentioning that in these analyses, only normal stress components were imposed on the unit cell and the deformed boundaries remained parallel to the undeformed boundaries. Barsoum and Faleskog (2007) proposed a unit cell model to simulate a thin-walled, double notched tube subjected to combined tension and torsion loading. Proportional stresses including a shear stress component were applied on the unit cell's periodic boundaries. The failure criterion was based on the theoretical framework of plastic localization into a band by Rice (1977). Following the work by Needleman and Tvergaard (1992), the localization criterion was defined as when the ratio between the norm of the deformation gradient rates inside and outside the band, denoted as η, becomes sufficiently large. In their later work, Barsoum and Faleskog (2011) suggested that the critical η-value should be chosen as 10. However, they also stated that this criterion cannot be used as an indicator for material failure under high stress triaxialities when the Lode parameter is close to zero. Tvergaard (2008, 2009, 2012) conducted a series of plane strain analyses to study the behavior of cylindrical voids in a shear-field. Using the same unit cell model and failure criterion as Barsoum and Faleskog (2007, 2011), Dunand and Mohr (2014) conducted extensive numerical analyses to demonstrate that the macroscopic equivalent plastic strain for material failure after monotonic proportional loading decreases with stress triaxiality and is a convex, non-symmetric function of the Lode parameter. In Dunand and Mohr (2014), the critical η-value was chosen to be 5. The arbitrariness in selection of the critical η-value is largely due to the difficulty in defining η at the unit cell level, which motivated a recent study by Wong and Guo (2015) to propose an energy based method to establish the criterion for onset of void coalescence. The idea supporting this method comes from the observation that as failure by void coalescence takes place in a band, and material outside this band undergoes elastic loading. Elastic unloading is said to have occurred when the overall elastic work rate of the unit cell becomes negative and void coalescence happens when the ratio of the overall elastic and plastic work rates reaches a minimum. However, local unloading may cause the computed overall elastic work rate to become negative. Moreover, void coalescence is due to the competition between the reduction of the ligament between voids and the strain hardening of the ligament material. Since the elastic and plastic work rates of the ligament are included in computing the overall work rates, non-negligible errors in failure prediction may occur for some cases.

From the above literature review, a few points can be made about the unit cell analysis. Firstly, with an assumed periodic void distribution, a material unit can be modeled with detailed finite elements subjected to various stress states. The purpose of the unit cell analysis is to study the deformation and void behavior and to establish a failure criterion in terms of the homogenized, macroscopic quantities at the material unit level. Secondly, failure occurs in a localized band and material outside of this band undergoes elastic recovery. The change of deformation mode outside the localization band gives an indication of fracture initiation. Thirdly, if identical deformation is enforced for all material units, a localized failure band will not appear. In many of the previous studies, all material units were assumed to be the same and subjected to the same deformation, thus the unit cell only included one material unit. Consequently, unrealistic predictions were made under certain conditions.

In this paper, a numerical model is proposed, in which the unit cell consists of a material unit, where fracture initiates, and two adjacent material units outside the localization band. A material failure criterion is established by detecting the occurrence of elastic unloading outside the localization band. Section 2 provides a detailed description of the proposed unit cell model, including how to impose the boundary conditions and how to establish the failure criterion. Section 3 presents and discusses numerical results under various scenarios. The effects of the stress state on void behavior and ductile fracture initiation are discussed. For comparison, analyses are also conducted using the methods proposed by