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Void-sheet analysis on macroscopic strain localization and void coalescence

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ABSTRACT

An operational definition for the onset of macroscopic strain localization is established through the localization analysis on the overall response of a unit cell in a void-sheet. The constitutive relations are obtained from the homogenization of a representative volume element, which is taken to be a void-containing unit cell characterizing a void-sheet in a ductile solid. The unit cell is subjected to three macroscopic normal stresses and one macroscopic shear stress and is proportionally stressed under a maximum reduced shear stress condition. Together with the definition for the onset of void coalescence established previously, it is shown that the two onsets are distinct and separate, with the strain localization being a precursor to void coalescence. It is also shown that for Lode parameter $-1 \leq L \leq 1$, the difference between the effective strains for the onsets of strain localization and void coalescence decreases as stress triaxiality T increases, suggesting that both onsets may occur simultaneously for sufficiently large T. This difference in the effective strains are found to be large for moderate to lower T and in the range between generalized compression ($L = -1$) and generalized shear ($L = 0$). For the range of T and L considered, there exists three scenarios involving strain localization and void coalescence: (1) both strain localization and void coalescence are possible, (2) strain localization is possible but void coalescence is not possible, and (3) both strain localization and void coalescence are not possible. The effects of orientation of the void-sheet on the onset of macroscopic strain localization are also investigated.

1. Introduction

Ductile fracture in metals has been a subject of interest for decades and considerable research effort has been devoted to further our understanding of it. It continues to be a relevant and important topic, for example in the area of metal forming where great importance is placed on the accurate predictions of the formability and ductility of sheet metals (Haddag et al., 2009; Li et al., 2010; Silva et al., 2015). This is particularly so, as scientists are constantly developing tougher and even lighter alloys to meet applicational demands of many industries such as aviation and automotive. Gaining insights to the indicators of ductile fracture thus provide engineers and designers the knowledge of the safe operating envelope of the metals.

Metal alloys typically undergo plastic deformation during the ductile process. A commonly encountered and observed occurrence during such deformation is that of strain localization, an abrupt formation of a band of highly discontinuous deformation field from an overall smoothly-varying one. This band of intense straining, manifesting at different length scales,

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drives the two broadly-categorized failure mechanisms in ductile metals: failure dominated by macroscopic strain localization and failure dominated by void coalescence (Pineau et al., 2016; Tekoğlu et al., 2015). In the first, strain localization is driven by damage softening due to increased porosity and decrease in macroscopic strain hardening. Manifesting as a normal or shear band, its width is typically of length scale comparable to (Pardoen and Hutchinson, 2000; Tvergaard, 1981) or greater than the mean spacing of the voids (Pineau et al., 2016). The accumulated damage may result, in a macroscopic sense, the failure of the specimen or component through material separation. The presence of voids may or may not be essential, though they tend to promote localization. In the second, the band of strain localization is narrower and is confined to the ligaments of neighboring voids, where eventual coalescence takes place due to the necking down of this ligament through the commonly observed process of internal necking or void-sheet coalescence (internal shearing of ligaments), both of which have been extensively studied and have been documented in a number of reviews (Benzerga and Leblond, 2010; Benzerga et al., 2016; Pineau et al., 2016; Tvergaard, 1990). Mohr and Marcadet (2015) have also succinctly described and illustrated the formation of strain localizations during the ductile fracture process where void coalescence is preceded by macroscopic strain localization. While it is clear from literature that the two strain localizations encountered in the ductile fracture process are distinct from each other, there has been no distinction made to differentiate between macroscopic strain localization and strain localization during void coalescence, until recently by Tekoğlu et al. (2015). They have *quantitatively* distinguished the two strain localizations occurring during coalescence by internal necking and macroscopic strain localization due to damage nucleation. This present work is inspired by Tekoğlu et al. (2015), and the motivation of this paper is to explicitly formulate and establish the operational definition for the onset of macroscopic strain localization through the localization analysis of a homogenized continuum. This allows for a formal distinction to be made between the two strain localizations due to macroscopic strain localization and void coalescence.

Experimental developments in recent years have provided the multiscale physical and phenomenological observations of strain localization and ductile fracture (e.g. Brünig et al., 2015; Ghahremaninezhad and Ravi-Chandar, 2013; Haltom et al., 2013; Morgeneyer et al., 2016; 2014; Papasidero et al., 2015; Weck and Wilkinson, 2008). Tang et al. (2013) and O'Keeffe et al. (2015) have experimentally reconstructed the microstructure (primary and secondary inclusions) in the fracture process zone and fracture surface, and modeled the zig-zag fracture profile resulting from nucleation of microvoid sheets at the secondary population of inclusions by a hybrid multiresolution approach. Nevertheless, there are significant experimental challenges such as the detection of macroscopic strain localization and void coalescence due to their sensitivity to microstructural effects, loading and boundary conditions (e.g. strain-rate, loading paths) and plastic flow properties. Thus numerical analyses can provide alternative and valuable insights to strain localization and complement the extensive experimental studies on the topic.

Studies on strain localization are primarily built on the general theoretical framework of Rudnicki and Rice (1975) and Rice (1976). Strain localization can be summarily stated as the loss of ellipticity of the governing equations. Following this framework, the onset and formation of localization are commonly analysed by considering material inhomogeneities in an otherwise homogeneous medium. Void coalescence and the associated strain localization has been extensively studied using macroscopic constitutive theories such as the Gurson model (Gurson, 1977) and its variants (e.g. Benzerga et al., 2004; Gologanu et al., 1993; Nahshon and Hutchinson, 2008; Pardoen and Hutchinson, 2000) that account for the effects of void nucleation, void shapes, plastic anisotropy and shear loads at low stress triaxiality. Abeyaratne and Triantafyllidis (1981) and Hutchinson and Tvergaard (1981) have examined the sensitivity of material imperfection on the growth of shear bands in plane strain through perturbation analyses of a finite body. The concept of material inhomogeneity with "weak zones" has also been adopted by Singh et al. (2013), Murali et al. (2013), Singh et al. (2014) to examine shear bands and cavitation, as well as by Sha et al. (2017) and Wang et al. (2017) in their studies on the fatigue behavior due to shear bands in metallic glasses.

Micromechanical cell analyses is another viable alternative to the study of strain localization, albeit confined to the subject of void coalescence. Early two-dimensional analyses on void coalescence by internal necking (e.g. Faleskog and Shih, 1997; Koplik and Needleman, 1988) and void-sheet coalescence (e.g. Tvergaard, 1981; 1989) have laid the foundations for the more realistic three-dimensional models and studies that permit a variety of cell configurations and complex loading conditions (e.g. Barsoum and Faleskog, 2011; Dunand and Mohr, 2014; Liu et al., 2016; Nielsen et al., 2012; Wong and Guo, 2015). While these cell studies typically assume periodic microstructures and that only a single void is considered, they provide valuable insights to the micromechanism of ductile fracture. However, the onset of macroscopic strain localization has not been addressed within the micromechanical framework. To this end and to the authors' knowledge, Tekoğlu et al. (2015) is the only work that examines both macroscopic strain localization and void coalescence with the micromechanical cell model. Their numerical framework consists of a voided cell, representing a double periodic array of voids within a band, sandwiched between two semi-infinite blocks of uniform, void-free material. In their analyses, the onset of macroscopic localization is identified as the point in the loading history in which elastic unloading takes place within the two outer blocks and plastic straining continues in the band, an approach that is consistent with Rice (1976). The onset of void coalescence is taken to be the point in the loading history when the ratio of maximum to minimum effective plastic strain rate on the void's surface exceeds a preset value. It is informative to note that there are other criteria used for indicating the onset of void coalescence/localization. Barsoum and Faleskog (2011), Dunand and Mohr (2014) and Dæhli et al. (2017b) have adopted the approach by Needleman and Tvergaard (1992) to determine the onset of localization by comparing the deformation gradient rates inside and outside of the band of localization. In Bomarito and Warner (2015), the onset is signaled by the attainment