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An interactive micro-void shear localization mechanism in high strength steels

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Abstract

Ductility of high strength steels is often restricted by the onset of a void-sheet mechanism in which failure occurs by a micro-void shear localization process. For the first time, the micro-void shear instability mechanism is identified here by examining the interactions occurring within a system of multiple embedded secondary particles (carbides ~10–100 nm), through a finite element based computational cell modeling technique (in two and three dimensions). Shear deformation leads to the nucleation of micro-voids as the secondary particles debond from the surrounding alloy matrix. The nucleated micro-voids grow into elongated void tails along the principal shear plane and coalesce with the micro-voids nucleated at neighboring particles. At higher strains, the neighboring particles are driven towards each other, further escalating the severity of the shear coalescence effect. This shear driven nucleation, growth and coalescence mechanism leads to a decrease in the load-bearing surface in the shear plane and a terminal shear instability occurs. The mechanism is incorporated mathematically into a hierarchical steel model. The simulated response corresponds to experimentally observed behavior only when the micro-void shear localization mechanism is considered.

Keywords: Ductility; Microstructures; Voids and inclusions; Constitutive behaviour; Finite elements

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1. Introduction

Damage nucleation in an alloy usually involves some degree of decohesion of an embedded particle from the surrounding matrix or particle fracture (Sarkar et al., 2001; Dierickx et al., 1996). The nucleated damage subsequently grows in a manner consistent with the stress state and the material degrades rapidly as individual damage sites begin to interact.

In the air melted high strength steel examined here, the embedded particles are generally primary particles (titanium nitrides on the order of a micron) and secondary particles (titanium carbides and manganese sulfides on the order of 10–100 nm). It is common to refer to the voids which nucleate at the secondary particle sites as *micro-voids*, to distinguish them from the larger voids which nucleate from the primary particles. Hence there are two potential populations of voids, which exist at two distinct scales.

Two ductile failure mechanisms have been identified in high strength steels:

(a) A void coalescence process in which relatively equiaxed voids grow to impingement (associated with high triaxiality loading).
(b) A void-sheet mechanism in which failure occurs by a micro-void shear localization process (associated with low triaxiality loading).

Mechanism (b) is much more prevalent under shear loading. However, even under high triaxiality loading conditions (*mode*-1 *type loading*), the micro-void-sheet mechanism can initiate and propagate along the plane of maximum shear and severely limit ductility in high strength steels (Goto et al., 1999).

Most of the research previously performed in the area of ductile failure has concentrated on the behavior of primary- and secondary-particle nucleated voids under high triaxiality loading as described by mechanism (a) above. Micromechanical nucleation studies have been performed (Horstemeyer et al., 2003; Horstemeyer and Gokhale, 1999; Gall et al., 1999) and several useful nucleation criteria have been posed for steel alloys (Beremin, 1981). Experimental studies of void growth and ductility have tended to focus on tensile tests, in which the voids are free to grow in the direction of the applied load (Manoharan and Lewandowski, 1989; Humphreys, 1989; Poza and Llorca, 1996; Verhaege et al., 1997). Factors effecting the growth of voids have also been investigated; Rice and Tracey (1969) were the first to predict the changing size of spherical voids in a deforming body. Lee and Mear (1992) extended the model to account for the growth of axisymmetric ellipsoidal voids. Hom and McMeeking (1989) investigated the growth of voids directly ahead of a crack tip and developed several void coalescence criteria which were used to predict fracture initiation. The effect of void configuration on growth and coalescence has been modeled by Horstemeyer et al. (2000) who discovered that coalescence effects can occur between voids as far apart as six void diameters.

The experimental investigations and computational studies outlined above have focused on mechanism (a). The resulting constitutive models therefore fail to predict the onset of the micro-void-sheet mechanism (b) which may occur over a range of loading conditions and which is solely responsible for failure under shear loading. It is this mechanism, and in particular its occurrence under pure shear-loading conditions, which the current paper is focused on.