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Coupled porous plasticity - continuum damage mechanics approaches for modelling temperature driven ductile-to-brittle transition fracture in ferritic steels

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Abstract

Following; (a) the observation that micro-void and micro-crack driven failure mechanisms co-exist in metallic alloys and (b) the two damage state variable definition given in Chaboche et.al.[1], two coupled porous plasticity and continuum damage mechanics approaches to assess temperature driven ductile-to-brittle transition fracture in ferritic steels have been developed. Based on hypo-elastic formulation of Gurson-Tvergaard-Needleman (GTN) thermoplasticity to account for ductile failure following void growth, continuum damage mechanics formalism have been coupled in order to account for micro-crack driven brittle fracture. Keeping GTN thermoplasticity as a basis for ductile fracture, Leckie-Hayhurst creep rupture criterion has been modified and proposed to account for brittle damage,thus cleavage, in the first model. The second approach, which is proposed following the motivation that plasticity exists in and below the lower transition region, replaces Leckie-Hayhurst model with plasticity driven damage evolution law of Lemaitre et.al[2]. Unlike commonly used cleavage models such as Ritchie-Knott-Rice [3] and Beremin [4], both of the proposed models have been aimed to take into account blended effects of micro-voids and micro-cracks in order to capture energy dissipation and softening accompanying and prior to brittle fracture. Numerical implementation has been done for ABAQUS/Explicit and uses staggered solution based on plastic flow-damage correction structure, while its validation has been performed modeling Small Punch Fracture Experiments for P91 ferritic steel, published by Turba et.al[5].

Keywords: Gurson plasticity, damage mechanics, ductile to brittle transition, small punch test

1. Introduction

Two common failure mechanisms in metallic materials are ductile and brittle fracture. Ductile failure is characterized by the nucleation, growth and coalescence of micro-voids leading to rupture, while brittle failure is linked with the inter- or intra-granular cleavage with nucleation, growth and coalescence of micro-cracks, see [6],[7]. Among plasticity models available in literature, Gurson's model is widely used to model void-growth based failure [8]. This model devises a hydrostatic stress dependent yield potential derived using homogenization over void-rigid plastic matrix and limit analysis. This potential is later modified by Tvergaard and Needleman, by the introduction of void shape effects as well as acceleration in the void growth during void coalescence, to be named as Gurson-Tvergaard-Needleman porous plasticity model [9], along with other contributors, e.g., [10],[11],[12],[13],[14],[15],[16] and [17], also with extensions to nonlocal formulation at hyper-elastic setting as in [18].

On the other hand, cleavage in metallic materials has been described in the literature primarily by two models. The deterministic model by Ritchie-Knott-Rice [3], relies on a critical stress over the critical distance principle. In other words, brittle fracture occurs once the principal stresses averaged over a region within a characteristic length exceeds a temperature and rate independent threshold, while it may or may not be accompanied by plastic flow. The model by Beremin Research Group see, e.g.,[4],[19], on the other hand, incorporates plastic flow in their analyses following a

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