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A comparative study of three ductile damage approaches for fracture prediction in cold forming processes

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ABSTRACT

Damage growth and ductile fracture prediction is still an open question for complex stress state applications. A lot of models, both phenomenological and micromechanical, have been extensively developed. There is a real need to compare them to choose the best suitable for complex loading applications. This is done here taking examples in cold metal forming, namely wire drawing and wire flat rolling. In the present study, the prediction of damage for the ultimate wire drawing and the wire flat rolling processes of a high carbon steel is investigated, using three different approaches of ductile damage: uncoupled phenomenological models (or fracture criteria), coupled phenomenological models (accounting for the softening effect of damage), and micromechanical models (accounting for damage associated microstructure evolution). These models were first implemented in a finite element code dedicated to forming process simulations, then calibrated via different mechanical tests exhibiting different stress states. Numerical results of the applications of these models to the two above-mentioned forming processes simulations were compared with experimental ones. These applications help comparing different approaches for fracture prediction in multi-stage forming processes and also in the process that involves important shear effect. The present study supplies important data for the characterization of ductile failure in forming processes, as well as an effective assessment of different phenomenological and micromechanical models, characterizing their performance for different stress states. It also suggests the use of “modular” models for complex loading cases, by combining different driving factors of damage accumulation at different stress states.

1. Introduction

Fracture prediction in real size structures subjected to complex loading conditions has been of utmost interest in the scientific and engineering community in the past century. Numerical simulations with nonlinear finite element (FE) codes allow investigating various complicated problems for damage and fracture prediction in real scale models, which is an important topic in many industries, including metal forming industry. For all industrial cold forming processes, the ability of numerical modeling to predict ductile fracture is crucial. However, this ability is still limited because of the complex loading paths (multi-axial and non-proportional loadings) and important shear effects in several forming processes where the stress triaxiality is nearly zero. Moreover, since forming processes involve large strain, the use of a suitable FE code with robust damage and fracture prediction models is essential to obtain realistic results for both geometry precision and mechanical properties. Regarding ductile damage models, three main approaches have been extensively used and developed for fifty years: uncoupled phenomenological damage models (or fracture criteria), coupled phenomenological models and micromechanical models. The role of microvoids in ductile failure was firstly modeled by the study of McClintock et al. (1966), which analyzed the evolution of an isolated cylindrical void in a ductile elastoplastic matrix. Rice and Tracey (1969) studied the evolution of spherical voids in an elastic-perfectly plastic matrix. In these studies, the interaction between microvoids, the coalescence process and the hardening effects were neglected and failure was assumed to occur when the cavity radius would reach a critical value specific for each material. These results showed that the voids growth is governed by the stress triaxiality, which is the ratio between the mean stress and the von Mises equivalent stress. Gurson (1977), in an upper bound analysis of a finite sphere containing an isolated spherical void in a rigid perfectly plastic matrix, employed the void volume fraction f (or porosity) as an internal variable to represent damage

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D_1, D_2, D_3, D_4, D_5, D_6	material constants in the Bai & Wierzbicki model
E, ν	Young's modulus and Poisson's ratio
E_M, σ_M	Young's modulus and flow stress of undamaged material
Y, $w(D)$	energy density release rate and weakening function (Lemaitre model)
$\alpha_1, \alpha_2, \eta_1, \eta_2, \epsilon_{D0}, A$	additional material constants in the LEL model
$\dot{\bar{\epsilon}}_p$	equivalent plastic strain rate
ϵ_{f0}, p_L, q, k, m, β, γ, ϵ_{DX}, D_c	material constants in the Xue model
η	stress triaxiality
$\bar{\epsilon}_f$	equivalent plastic strain at fracture
$\bar{\epsilon}_p$	equivalent plastic strain
$\bar{\sigma}$	von Mises equivalent stress
σ_0	flow stress
$\sigma_1, \sigma_2, \sigma_3$	three principal stresses, $\sigma_1 \geq \sigma_2 \geq \sigma_3$
σ_m	mean or hydrostatic stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
$\theta, \bar{\theta}$	Lode angle and Lode parameter
b, S, D_c, h, ϵ_D	material constants in the Lemaitre model
f, F_D	plastic potential (yield function in associative flow), damage dissipative potential
p	hydrostatic pressure
$q_1, q_2, S_N, f_N, \epsilon_N, f_c, f_f$	material constants in the GTN model
q_3^*, q_4	additional material constants in the modified GTN model

and its softening effect on material strength. This model was then extensively improved to account for different aspects: prediction accuracy (Tvergaard, 1981), void nucleation and void coalescence (Tvergaard and Needleman, 1984), void shape effect (e.g. Gologanu et al., 1993), void size effect (e.g. Wen et al., 2005), void/particle interaction (e.g. Siruguet and Leblond, 2004), isotropic strain hardening (e.g. Leblond et al., 1995), kinematic hardening (e.g. Muhlich and Brocks, 2003), plastic anisotropy (e.g. Benzerga and Besson, 2001), rate dependency (e.g. Tvergaard, 1989), shear effect (e.g. Xue, 2008).

On the other hand, the Continuum Damage Mechanics (CDM) models have been developed within a consistent thermodynamic framework, in which the evolution of the phenomenological damage parameter is obtained through a thermodynamic dissipation potential. This class of models has been continuously developed and widely used, especially the Lemaitre model Lemaitre (1986) – see Besson (2010) for a complete review of continuum models of ductile fracture).

In addition to the phenomenological CDM models and micromechanics-based damage models, uncoupled phenomenological models have been increasingly developed, especially for industrial applications. Uncoupled models employ an indicator variable to predict material failure when its critical value is reached. This variable is often taken as a weighted cumulative plastic strain, in which the weighting function accounts for the effect of stress state on the fracture initiation.

The early ductile damage models used only the stress triaxiality in order to account for the influence of stress state. Several recent studies (e.g. Barsoum and Faleskog, 2007) also demonstrated the important effect of the third stress invariant in damage evolution, especially at low stress triaxiality; the Lode angle parameter is generally used to include it. This parameter combines the second and third invariants of deviatoric stress tensor. Xue (2007) developed a damage-plasticity model, which accounts for the influence of hydrostatic pressure and the Lode angle. Bai and Wierzbicki (2008) constructed an asymmetric fracture locus using a weighting function of the stress triaxiality and the Lode parameter. More recently, the same authors transformed the stress-based Mohr–Coulomb failure criterion into the space of the stress triaxiality, the equivalent plastic strain and the Lode parameter (Bai and Wierzbicki, 2010). The common idea of these works is to account for the whole stress state in damage model formulation, which is defined by the stress triaxiality, the von Mises equivalent stress, and the Lode parameter. Gurson-based models have also been enhanced to better describe ductile damage for low stress triaxiality (e.g. Nahshon and Hutchinson, 2008).

Despite their increasing developments, among numerous ductile damage models proposed in the literature, very few were actually applied and validated on complex industrial applications, such as multi-stage forming processes. The comparison of the three above-mentioned damage approaches on real complex multi-stage manufacturing processes is important to clarify the advantages and drawbacks of each one. In the present study, multi-stage ultimate wire drawing and wire flat rolling processes were chosen to serve for this purpose.

Regarding damage in wire drawing process, defects in drawn wire come from both the initial defects from the preform and the deformation process itself. The common defect observed in drawing is chevron cracking or central burst (also called "cupping" – cup and cone fracture). However, under certain conditions of material and microstructure states (e.g. large defects on the surface of the initial wire), fracture can initiate at the surface due to the presence of important shear effect at this position. Interested readers are invited to the recent work of Cao et al. (2014d) for a study of ductile fracture in multi-stage drawing, and references therein for a literature review on ductile damage in this process.

Concerning the wire flat rolling process, numerous studies were carried out by Kazeminezhad and Karimi Taheri. Kazeminezhad and Taheri (2005a) performed experimental studies on the rolling force and the deformation behavior of rolled wire. They found that the rolling force depends on rolling speed and rolling reduction, but lubricant has a negligible effect on both rolling force and geometry (width of contact area and lateral spread). An analytical relationship was proposed by these authors (Kazeminezhad and Taheri, 2005b) to evaluate the lateral spread for both low and high carbon steels, which is a function of the ratio between initial and final heights of flattened wire. In terms of stresses and strain analyses, Kazeminezhad and Taheri (2006a) used analytical analyses and found that there exists a maximum in the pressure distribution similar to that observed in strip rolling. They also revealed shear bands on the cross section of the flattened wire in form of a cross (the so-called "blacksmith" cross[1]) by using combined finite and slab element methods and metallographic observation (Kazeminezhad and Taheri, 2006b). In addition, the deformation pattern was found inhomogeneous, both on longitudinal and transverse cross sections. Vallellano et al. (2008) showed that this inhomogeneity of deformation has strong impacts on contact and residual stresses.

The above studies principally concentrated on geometry (e.g. spread) or loading (e.g. rolling force) predictions, there are few studies in the literature dealing with damage and fracture prediction in cold rolling of long products. Recently, (Massé et al., 2012) performed Scanning Electron Microscope (SEM) observations of damage state in a wire flat rolling process. These authors reported a higher void density in the wire core and in the "blacksmith cross", which led them to a conclusion that these zones were danger zones in such a process. They then used the Lemaitre damage model to study the localization of damage but it failed to predict

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[1] The concentration of the strain rate on the diagonals of the section, in the shape of a cross, when the section height and width are of the same order.