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Material Characterization and Validation Studies for Modeling Ductile Damage during Deep Drawing

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Abstract

Modern high strength steels can exhibit ductile damage evolution till fracture which drops ductility for certain loading conditions. This complex formability characteristic as well as shear induced fracture cannot be described by standard methods like forming limit curves. As a remedy, the continuum damage models (CDM) can be applied. In this study, a variant of Lemaitre CDM was investigated to model ductile fracture of an advanced high strength steel, DP1000 in deep drawing processes. This model variant scales the effect of maximum shear stress on damage evolution to predict especially the shear cracks under low stress triaxialities. A decelerated damage evolution due to compressive stress components is taken into account. The material characterization for the damage model requires several tests such as tensile tests with notch, shear test and biaxial cupping tests to capture some characteristic stress states that can occur during deep drawing and further sheet forming processes. An inverse parameter identification methodology using the finite element modeling of whole samples is applied. From the experimental data, force displacement curves and optical strain measurements were used. Test parts were simulated for the validation of the model integrated in the commercial software LS-Dyna. The identified model parameters were finally validated on a cross die cup of high strength steel. The model predictions show good agreement with experimental observations.

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Keywords: sheet metal forming; damage modeling; Lemaitre model; parameter identification; shear fracture

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1. Introduction

The increasing demand on lightweight materials pushes the development of modern steel grades like high strength dual phase steels. Distinguished characteristics of those materials from the conventional deep drawing steels, such as reduced ductility and sensitivity to shear fracture require new failure prediction methods. Continuum damage models for the prediction of the failure due to fracture are mainly related to the damage phenomenon which is related to the micro-events of the voids (nucleation, growth and coalescence of them). The Lemaitre model family uses the scalar damage variable D, which indicates a measure of homogenized micro-voids and micro-cracks to describe the damage in the material phenomenologically [1]. Several studies have already shown that those models can be applied for sheet metal forming processes [2-3]. Recently, new improvements on this model family including the Lode angle effect for damage evolution have been studied to predict the shear fracture [4-5]. In this paper, a model variant of the Lemaitre model, in which the damage evolution is modified according to the maximum shear stress to include the effect of Lode angle parameter, is investigated. The parameter identification for this model is presented and the validation studies for a deep drawing with a cross die are conducted.

2. Damage Model: Modified Lemaitre model including the effect of the maximum shear stress

In the continuum damage mechanics model of Lemaitre [1], the concept of effective stresses $\tilde{\sigma}$ provides the coupling between damage evolution in the workpiece and the deformation. An increase in damage (void intensity) of the material reduces the effective load carrying capacity until the onset of a macro-crack. To simulate the macro-crack occurrence in the numerical analysis, the critical damage value is defined as a threshold.

The constitutive equations for a general 3D formulation of the coupled damage model are summarized in [2]. The damage model was integrated in an elasto-plastic framework with plastic anisotropy of Hill'48 type. The damage evolution equation reads:

$$\dot{D} = \lambda \left\langle \frac{-Y - Y_0}{S} \right\rangle^{\delta} \frac{1}{(1-D)^{\beta}} \qquad (1)$$

In Eq. 1 λ is the plastic multiplier, Y_0 is the threshold parameter, which defines the onset of the damage evolution. The thermo-dynamically conjugate variable to the damage variable is the elastic energy density Y. S, δ, β are material-dependent damage model parameters.
For the model variant (variant I) which weighs the effect of compressive stress states by introducing an additional scaling parameter h, the modified elastic energy density expression becomes [1]:

$$Y = \frac{1+\nu}{2E}\left[\frac{\langle\sigma_{ij}\rangle\langle\sigma_{ij}\rangle}{(1-D)^2} + h\frac{\langle-\sigma_{ij}\rangle\langle-\sigma_{ij}\rangle}{(1-hD)^2}\right] - \frac{\nu}{2E}\left[\frac{\langle\sigma_{kk}\rangle^2}{(1-D)^2} + h\frac{\langle-\sigma_{kk}\rangle^2}{(1-hD)^2}\right] \qquad (2)$$

where ν is the Poisson's ratio and E is the Young's modulus. For $h = 0$ only tensile stresses are effective in the damage evolution whereas for $h = 1$ the model boils down to the original Lemaitre model. For a value of h between zero and one ($0 < h < 1$) just a fraction of the compression stresses is considered for the damage evolution. Fig. 1 shows the representative fracture strain curves for the extreme values of the h parameter as a function of triaxiality.

The Lode angle θ is an indicator for the middle principal stress and distinguishes the stress state between axisymmetric and shear stress state. It is related to the normalized third deviatoric stress invariant J_3 as follows [6]:

$$\xi = \frac{27}{2}\frac{J_3}{\sigma_{eq}^3} = \cos(3\theta) \qquad (3)$$

In order to modify the cumulative damage for Lemaitre model according to the shear stress states, the shear fracture related parameter of the fracture model in [7] is introduced to the damage evolution rate of the model. Then the damage evolution equation in Eqn. 4 reads: