Comparative study of phenomenological coupled damage models - Application to industrial forming processes

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Abstract

Xue's damage model [Xue, 2007] accounts for the third invariant of deviatoric stress tensor, allowing a better balance between respective effects of shear and elongation on damage. It has been implemented in Forge® Finite Element (FE) software to investigate ductile damage occurring during industrial forming processes. Material and damage parameters identification has been carried out for both Xue and Lemaître models. Application to wire drawing followed by flat rolling shows that in such shear-inducing processes, both models predict damage at different locations, due to their different emphasis on shear with respect to elongational strain damage.

Damage models

Lemaitre's model

[Lemaitre and Desmorat, 2005] define a scalar variable D from which material weakening is described. The energy density release rate Y is the associated thermodynamic variable, derived from the state potential:

$$Y = \frac{\bar{\sigma}^2}{2E(1-D)^2}.\left[\frac{3}{3}(1+\nu) + 3(1-2\nu).\left(\frac{-p}{\bar{\sigma}}\right)^2\right] \qquad (1)$$

where $\bar{\sigma}$ is von Mises stress, E Young's modulus, ν Poisson's ratio, p hydrostatic pressure. $-p/\bar{\sigma}$ is the stress triaxiality ratio and plays an important role on ductile damage. The evolution of D is given by:

$$\dot{D} = \dot{\bar{\varepsilon}}^{pl}.\left(\frac{Y}{S}\right)^s \quad if\ \bar{\varepsilon}^{pl} > \bar{\varepsilon}_D \quad and \quad \frac{-p}{\bar{\sigma}} > -\frac{1}{3} \qquad (2)$$

$\dot{\bar{\varepsilon}}^{pl}, \bar{\varepsilon}^{pl}$ are the equivalent strain rate and equivalent strain, respectively. S and s are two damage parameters to identify. The conditions mean that damage accumulates only after a threshold strain ε_D (to be measured as well) and only if triaxiality is less compressive than a pure compression test. Moreover, in all compressive stress states, D is attenuated by a factor h = 0.2 to account for the micro-crack closure effect.

Xue's model

In the model above, only stress triaxiality is involved, so that e.g. damage under pure shear (p = 0) remains small. This has been shown not to be the case experimentally. Therefore, Xue's phenomenological damage model [Xue, 2007] defines fracture strain ε_f as a function of both hydrostatic pressure p and Lode angle θ_L $(-\pi/6 \le \theta_L \le \pi/6)$:

$$\varepsilon_f = \varepsilon_{f0}.\mu_p(p).\mu_\theta(\theta_L) \qquad (1)$$

$$\mu_p = 1 - q.Ln\left(1 - \frac{p}{p_L}\right) \quad \mu_\theta = \gamma + (1-\gamma).\left(\frac{6|\theta_L|}{\pi}\right)^k$$

p_L is the limit pressure below which damage does not occur, γ is the ratio between fracture strains under shear and uniaxial tension under the same imposed pressure; k and q > 0 are material parameters. The Lode angle is linked to the 3rd stress invariant and is defined in terms of principal stresses as:

$$\theta_L = \tan^{-1}\left(\frac{1}{\sqrt{3}}.\frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}\right) \qquad \sigma_1 \ge \sigma_2 \ge \sigma_3 \qquad (2)$$

From the expression of μ_p, there exists a cut-off value of pressure p_{cr} where μ_p and ε_f reduce to 0 (the material fails immediately):

$$p_{cr} = p_L(1 - \exp(1/q)) \qquad (3)$$

The scalar damage variable D_X is used as an internal variable to define material degradation. The weakening function is:

$$\bar{\sigma} = (1 - D_X^\beta).\sigma_M \qquad (4)$$

where β is the weakening exponent, σ_M is the yield stress of the undamaged matrix and:

$$\dot{D}_X = m.\left(\frac{\bar{\varepsilon}^{pl}}{\varepsilon_f(p,\theta_L)}\right)^{m-1}.\frac{\dot{\bar{\varepsilon}}^{pl}}{\varepsilon_f(p,\theta_L)} \qquad (5)$$

Similar to [Lemaitre and Desmorat, 2005], the damage accumulation process is activated only after a threshold strain ε_{DX},. At the other end of the damage evolution, when $D_X = D_c$, a meso-crack is initiated. D_c is another material parameter to identify.

Parameter identification

The material is high carbon steel grade. Damage has to be identified from force - displacement curves under diverse states of stress. One of the key points is that weakening by damage competes with strain hardening on the one hand, with structural weakening (e.g. necking in tension) on the other hand. A number of different tests are therefore necessary to identify simultaneously all material and damage parameters while covering a broad range of stress triaxiality and Lode angle. Axis-symmetric tension tests

($-p/\sigma_0$=1/3, θ_L=-π/6), compression tests ($-p/\sigma_0$=-1/3, θ_L=π/6) and notched tension tests ($-p/\sigma_0$>1/3, θ_L=-π/6) have been performed, together with torsion tests ($-p/\sigma_0$=0, θ_L=0). Figure 1 shows the results of the identification in tension as an example, with different work-hardening laws. It must be emphasized that as damage parameters are mostly identified from tension tests beyond necking, the choice of the strain hardening law, which strongly impacts the shape of the curve there, is of primary importance for damage parameter identification. In this specific case, Voce's model (whereby stress saturates at large strain) has been found to be the most relevant one.

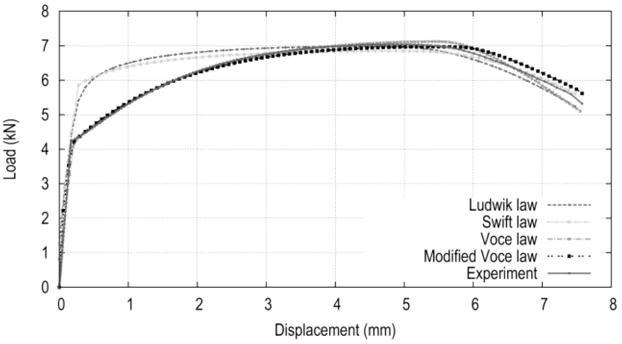

Figure 1. Load-displacement curve in the tension test.

Mapping of damage in forming

The studied wire-drawing pass gives an area reduction of 18.14%. The drawing speed is 333mm/s. The contour plots of Lemaitre's and Xue's damage variables in Figure 2 show significantly higher damage in the wire core than on the surface, as found e.g. by [McAllen and Phelan, 2007]); this also corresponds to the most frequent "cup and cone" wire break in practice. However, the Lemaitre damage variable is restricted to the wire centre, where stress is in a strongly tensile state. In contrast, Xue damage variable spreads through the whole radius. This reflects the deformation pattern in wire drawing, which proceeds with two intense shear surfaces at entry and exit of the plastic zone. Since Xue's model, contrary to Lemaitre's, emphasizes the impact of this shear deformation on damage, the damage variable is found significant everywhere through the section, although maximum in the centre. In both cases, the damage value remains small.

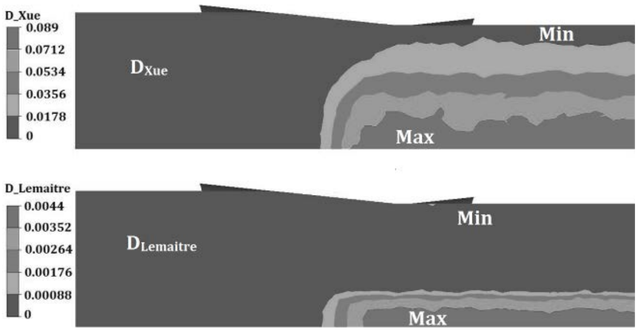

Figure 2. Damage prediction in wire-drawing using Xue's (top) and Lemaitre's(bottom) models.

Next studied is cold-rolling of drawn wire. Damage variables are presented on the vertical cross section in Figure 3 at the end of rolling. Lemaitre's model predicts higher damage in the barrelling, edge zone, where the triaxiality is highest because the more reduced centre forces elongation in tension of the less reduced edges. On the other hand, Xue's model gives a higher value of damage variable in the wire core and on the so-called "blacksmith cross" where intense shear occurs. [Massé, 2010] observed experimentally that pore and micro-cracks were present not only on the edges, but with a high density in the centre and also along the arms of the cross. This confirms that in a single forming operation, damage occurs at different places under different states of stress, so that all three stress invariants are important for damage as well as for constitutive models.

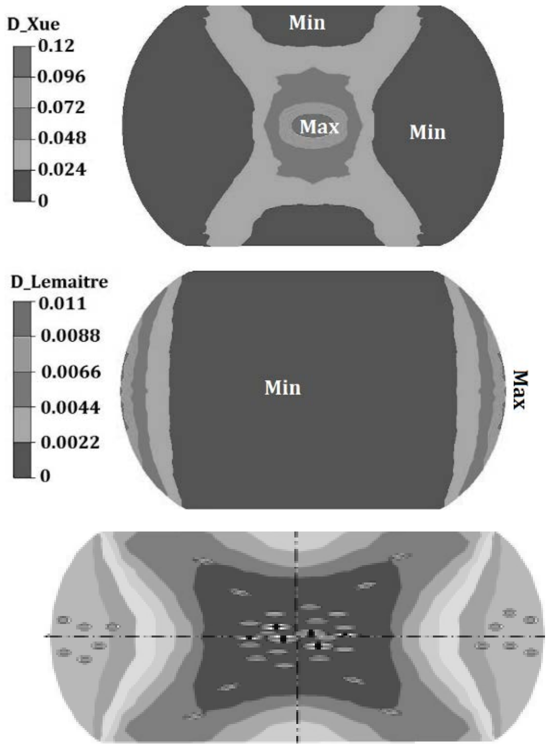

Figure 3. The damage variable on the vertical cross section at the end of rolling process. From top to bottom: predictions by Xue's model, prediction by Lemaitre's model, and schematic description of experimental damage location, superimposed on a strain map showing the "blacksmith's cross" [Massé, 2010]

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