APPLICATION OF A GRADIENT DUCTILE DAMAGE MODEL TO METAL FORMING PROCESSES INCLUDING CRACK PROPAGATION AND MESH ADAPTIVITY

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ABSTRACT

The entire process of ductile failure is modelled, from the initiation of damage to crack propagation. The microscopic material degradation mechanisms which trigger cracks are modelled by a softening elastoplastic behaviour. Mesh objectivity and length scale effects are accounted for by a gradient enhancement. The two governing partial differential equations, i.e. equilibrium and a nonlocal averaging equation, are solved in a staggered manner, which renders a very simple implementation in existing finite element codes. Adaptive remeshing is used to optimise the use of finite elements, so that finer elements are used in the regions of high strain localisation. Upon complete material failure cracks are introduced via remeshing. A number of metal forming simulations are shown which illustrate the main model features.

1 INTRODUCTION

In the design of blanking and other metal forming processes, it is not only important to predict when and where cracks will originate, but also their trajectory, since these trajectories determine the shape of the final products. Optimising this shape may allow to eliminate subsequent processing steps and thus result in considerable savings.

The microscopic processes which are responsible for fracture can be modelled in the form of material softening, as in continuum damage mechanics (Lemaitre [1]) or softening plasticity (Gurson [2]). In a finite element context, strongly mesh dependent results can be avoided by using regularising techniques. Among them, gradient models enjoy great popularity. They have been used successfully in elasticity and plasticity to account for length scale effects (Fleck and Hutchinson [3]), brittle damage (Peerlings et al. [4]) and ductile damage (Geers et al. [5]).

When the material fails, new free surface is created and a continuous solution can no longer be used. To model discrete cracks different numerical methods can be used, e.g. remeshing (Bittencourt et al. [6]), Partition of Unity Methods (Belytschko and Black [7]) or element erosion. Remeshing has the advantage that besides tracing crack paths, it can also be used to keep the mesh well shaped, which is important in a large strain framework. Adaptive remeshing techniques have been developed to optimise the use of finite elements in a mesh (Zienkiewicz et al. [8]). Mesh adaptivity is desirable in combination with softening materials, since these tend to form highly localised deformations in relatively small narrow regions, in which a high element density is desired.

In this work a combined continuous softening – discontinuous crack model is presented. A gradient enhancement in the form of Geers et al. [5] is used, which introduces a length scale. A staggered approach is used, which circumvents the solution of the coupled problem (equilibrium plus nonlocal averaging), thus rendering its implementation in existing elastoplastic models straightforward. Remeshing is used for the above mentioned threefold purpose: to trace the crack geometry, keep the mesh well shaped and for adaptivity.

2 GRADIENT ENHANCEMENT OF AN ELASTOPLASTIC MODEL

Ductile damage is introduced as in Geers et al. [5] by degrading the yield stress of an elastoplastic model by a softening factor $(1-\omega_p)$:

$$f(\boldsymbol{\sigma}, \varepsilon_p, \omega_p) = \sigma_{eq} - (1-\omega_p)[\sigma_y(\varepsilon_p)] \leq 1 \; . \tag{1}$$

ω_p is a damage variable ($0 \leq \omega_p \leq 1$), f denotes the yield function, σ_{eq} the equivalent vonMises stress and $\sigma_y(\varepsilon_p)$ the undamaged yield stress as a function of the equivalent plastic strain.

Unlike in Geers et al. [5], where a hyperelastoplastic model was used, here an existing hypoelastoplastic model of a commercial software, MSC.MARC, is used. This allows to take full advantage of features which are needed for forming processes, e.g. contact, a range of constitutive material models, thermal effects, etc.

Strongly mesh dependent results are avoided by introducing a non local variable $\bar{\psi}$, which is related to ω_p via the Kuhn-Tucker loading-unloading conditions

$$\dot{\omega}_p \geq 0, \qquad \bar{\psi} - \omega_p \leq 0, \qquad \dot{\omega}_p\,(\bar{\psi} - \omega_p) = 0\ , \tag{2}$$

as well as an initial value $\omega_p(t = 0) = 0$ and the limit $\omega_p \leq 1$.

$\bar{\psi}$ and its local counterpart ψ are related by the partial differential equation (PDE)

$$\bar{\psi} - \ell^2\, \nabla^2 \bar{\psi} \ = \ \psi\ . \tag{3}$$

In this equation, ∇^2 denotes the Laplacian with respect to the current (Eulerian) configuration; ℓ is an internal length parameter which sets the width of the localisation band, and for which a physical interpretation can be found, e.g. the average void spacing. Homogeneous Neumann boundary conditions are assumed for $\bar{\psi}$.

The local variable ψ in (3) follows from the evolution law

$$\dot{\psi} \ = \ \frac{1}{C}\left\langle 1 + A\,\frac{\sigma_h}{\sigma_{eq}}\right\rangle \varepsilon_p^B\, \dot{\varepsilon}_p\ . \tag{4}$$

This expression has been inspired by the fracture indicator proposed in Goijaerts et al. [9] and is based on Oyane's work for porous plastic materials (Oyane et al. [10]), which accounts for the fact that damage is driven by the plastic strains and increases for higher triaxiality.

3 NUMERICAL ASPECTS

The equilibrium equation

$$\vec{\nabla} \cdot \boldsymbol{\sigma} = \vec{0} \tag{5}$$

and non local averaging equation (3) form a coupled problem. A monolithic algorithm to solve these equations has been developed by Mediavilla et al. [11]. For many applications, however, a staggered approach similar to that used in Simo and Miehe [12] for thermoplasticity may be more practical. In a staggered approach the coupling of the two PDEs is made only at the end of every increment. First, equilibrium is solved for a constant damage variable ω_p, which will give new stresses $\boldsymbol{\sigma}$ and equivalent plastic strain ε_p. After updating the local variable ψ, the second step is to compute the nonlocal variable $\bar{\psi}$ via the averaging equation. This will allow to update the damage ω_p and the new yield stress σ_y, which are then used in the following load increment. This obviously introduces some degree of error, but for the small time steps which are necessary in real applications, this error has been found to be quite acceptable.

Isodamage step:

For a constant damage, the equilibrium problem is solved in an updated Lagrangian form using the implicit commercial software MSC.MARC. Upon convergence, the local damage variable ψ is updated numerically by employing a one-step integration rule.

$$\Delta\psi \ = \ ((1 - \theta)h_\omega^t + \theta\, h_\omega)\Delta\varepsilon\ , \qquad \text{where} \qquad h_\omega \ = \ \frac{1}{C}\left\langle 1 + A\,\frac{\sigma_h}{\sigma_{eq}}\right\rangle \varepsilon_p^B \tag{6}$$

and h_ω^t follows by evaluation of the latter expression at the end of the previous timestep. The parameter θ allows to select explicit ($\theta = 0$) and implicit integration ($\theta > 0$).

Nonlocal averaging at fixed configuration:

The damage variable follows by enforcing the weak form of Eq. (3), which after making use of the divergence theorem and the boundary conditions reads

$$\int_{\Omega} \left(w\,\bar{\psi} + \ell^2 \vec{\nabla} w \cdot \vec{\nabla} \bar{\psi} \right) \,\mathrm{d}\Omega \;=\; \int_{\Omega} w\,\psi \,\mathrm{d}\Omega \,, \tag{7}$$

where w is a standard test function. This weak form is discretised in a standard manner by inserting interpolated fields for w and $\overline{\psi}$. Solving the resulting linear algebraic system gives the non local variables, which allows to update the damage variable

$$\omega_p \;=\; \max_\tau(\bar{\psi})\,. \tag{8}$$

For each Gauss point, the damage variable is subsequently used to determine the yield stress σ_y according to Eq. (1) and these values are inserted into the plasticity analysis in MSC.MARC.

4 MESH ADAPTIVITY AND CRACK PROPAGATION

Since the plastic strains localise in the regions with highest damage, the mesh density is set depending on the damage spatial distribution.

Cracks are introduced upon total material failure, i.e. at $\omega_p \;=\; 1$, thus rendering a smooth transition from the continuous damage stage to a discrete crack. The crack direction is computed from the damage distribution around the crack tip and full remeshing is performed to accommodate every new crack increment during the crack advancement. Note that each remeshing must be followed by a transfer of state variables from the old discretisation to the new discretisation. The way in which this transfer is done has been found to have an important effect on the accuracy and numerical stability of the computations, see Mediavilla et al. [11] for more details. Each of the above operations is carried out outside MSC.MARC.

5 APPLICATIONS

Simulations of two metal forming processes have been carried out to illustrate the main model features. In these simulations, the standard contact options in MSC.MARC have been used.

Score forming:

To ease the opening of food cans, a groove is made in the can lid. During the forming process which is used for this purpose, known as score forming, cracks may develop which have an important effect on the residual strength of the lid. Experiments and simulations show that shear bands originate at the bottom of the indenter, which accelerate the void growth and eventually give rise to cracks. Adaptive remeshing is used to capture the form of these localisation bands (Fig. 1). The cracks which finally appear initiate at the edges of these shear bands and then follow them. Two cracks grow, from the punch and die, creating a dead zone or wedge. Depending on the material parameters, the model also predicts failure inside the specimen (as in the figure) or at the bottom surface.

Blanking:

During blanking one wishes to accurately predict the shape of the cut surface. Experiments have shown that the clearance between the punch and the die has an important effect on the final shape. In Fig. 2 the mesh and damage field are shown just before the product and sheet are completely separated. Mesh adaptivity was used to capture the gradients in the sheared zone.

6 CONCLUSIONS

To model ductile failure in forming processes, from the nucleation of voids to fully developed crack propagation, ductile damage is used in combination with discrete crack modelling. Mesh independent results are obtained by means of a gradient nonlocal damage variable. The staggered approach followed allows to add a gradient enhanced damage influence to the plasticity formulation of a commercial finite element software. This is of special interest for engineers who wish to have reliable results when using softening materials, since fully coupled implicit models are more difficult to implement.

In this framework, where large deformations, highly localised regions and discrete cracks are present, the use or remeshing has proven to be extremely useful. Adaptive remeshing is highly recommended when

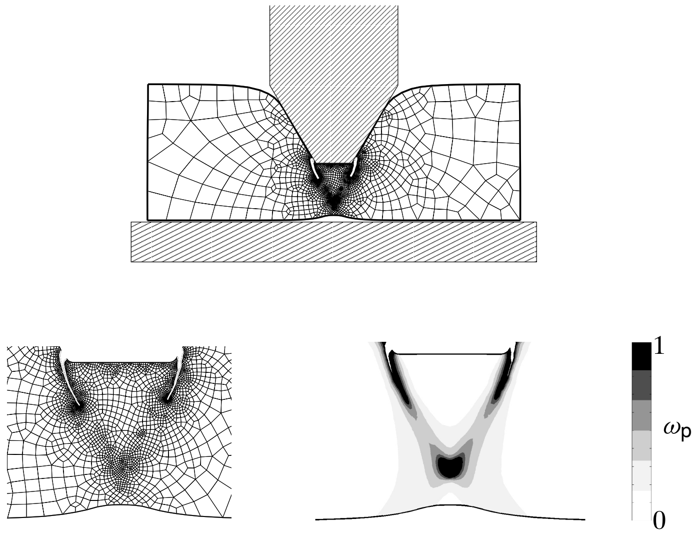

Figure 1: Failure during score forming. Mesh and boundary conditions (top), zoomed mesh (left) and damage (right).

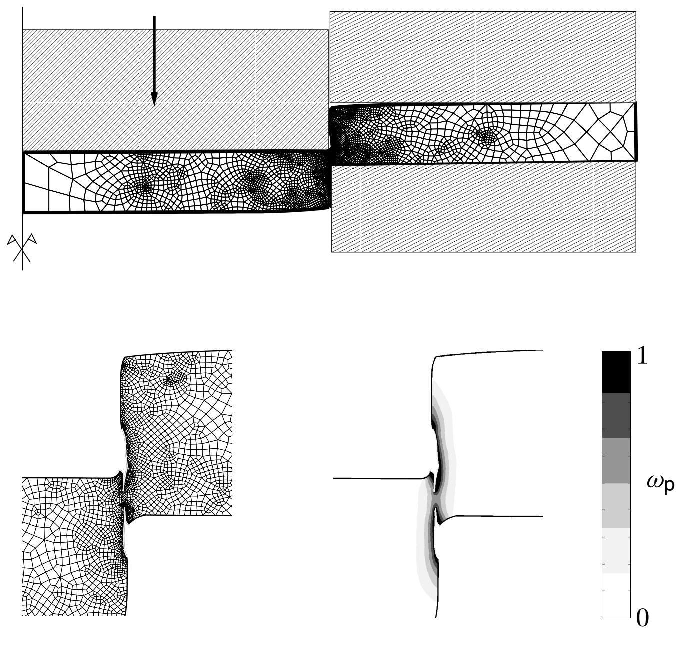

Figure 2: Failure in blanking. Mesh and boundary conditions (top), zoomed mesh (left) and damage (right).

one does not know a priori where cracks originate, since it allows to have an optimum mesh density distribution.

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