Modelling of damage initiation and propagation in metal forming

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ABSTRACT: Continuum damage mechanics is used to model crack initiation as well as crack propagation in metal forming simulations. For this purpose, a gradient damage formulation is coupled to an existing large-strain elastoplasticity framework. The resulting equations are solved by the finite element method. Crack initiation and crack growth are traced using remeshing. The numerical framework has been successfully used to model metal forming operations in two dimensions. Aspects of the – far from trivial – extension to three dimensions are discussed.

Key words: Ductile damage, Fracture, Computational mechanics, Finite element method, Remeshing

1 INTRODUCTION

Metal forming processes generally introduce a certain amount of damage in the material being formed. Predictions of the damage formation and growth in a series of forming steps may assist in optimising the individual operations and their order. This is particularly true for operations such as cutting and blanking, which rely on the nucleation of damage and cracks in order to separate material. Simulations of such processes require an integral approach towards damage and fracture.

2 DAMAGE-DRIVEN CRACK MODELLING

Damage and fracture of metallic materials are usually governed by a process of initiation, growth and coalescence of microvoids, see e.g. [1]. Continuum damage mechanics provides a consistent framework for modelling the effect of this processes on the mechanical response of the material [2,3]. It models the void density by a continuum field, which interacts with other fields such as (plastic) strain and stress. The evolution of the continuum damage field generally results in a softening stress–strain response and culminates in complete loss strength at a certain critical value of damage. It is the latter state which indicates the initiation of a crack.

It has since long been suggested that apart from predicting crack initiation, continuum damage mechanics can also be used for predicting crack growth, see e.g. [3]. In this approach, which is sometimes termed local approach to fracture, the growth of cracks is governed by the evolution and localisation of damage ahead of the crack tip; a schematic representation is given in Fig. 1. Advantages are that

- crack initiation and propagation can be dealt with in a unified framework;
- no separate fracture criteria are therefore required;
- interactions between cracks and damage (e.g. pre-existing due to prior processing) can be accounted for in a natural fashion.

However, the practical implementations of the approach have become available only recently. They necessitated the development of, among other aspects, reliable and efficient localisation limiters and robust numerical strategies for crack propagation, such as remeshing–transfer operators [4,5].

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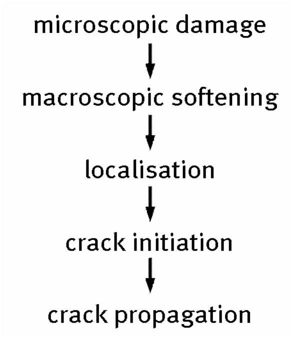

Fig. 1. Mechanism by which damage growth results in crack initiation and crack propagation.

A two-dimensional implementation of the concept which is specifically aimed at modelling forming processes has been developed in Ref. [6]. Salient features of the framework are

- an isotropic damage variable which describes the effect of damage in a continuum sense;
- a consistent constitutive model, formulated entirely in the current configuration;
- a gradient-type nonlocal damage formulation, resulting in a coupled system of partial differential equations and allowing a natural treatment of boundaries;
- an updated Lagrange implementation based on a two-field finite element discretisation;
- a monolithic, full Newton–Raphson solver using closed-form consistent tangents;
- an adaptive remeshing strategy to ensure a sufficiently accurate damage field to model crack growth and to at the same time avoid element distortion;
- a dedicated transfer algorithm for the remapping of history variables from one mesh to the next;
- a crack opening algorithm which ensures the robustness of simulations after remeshing and remapping.

The framework has been applied successfully to model a number of laboratory tests and forming processes, see e.g. [7]; one example is discussed in more detail below.

3 APPLICATION TO SHEET METAL SCORING

The computational framework as outlined above has been applied to the scoring of sheet metal. The process was studied experimentally by Boers et al. [8] in a configuration as sketched in Fig. 2. In it, a steel sheet is placed on an anvil and is subsequently penetrated to a certain depth by a trapezoidal indenter. Microscopic analysis revealed a considerable amount of damage in the material, particularly in and near the shear bands which are formed between the corners of the indenter and the bottom face of the sheet. A large number of elongated voids were observed, with aspect ratios as high as 10–20 and with their major axis aligned with the shear bands. For a sufficiently large penetration depth cracks were nucleated at the indenter corners as well as (slightly later) from the bottom surface of the sheet. Both propagated along the shear bands and ultimately met to completely separate the material.

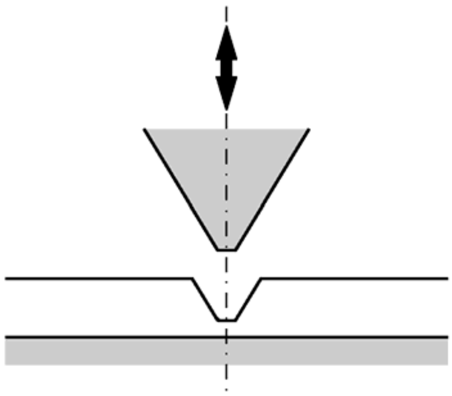

Fig. 2. Setup used for sheet metal scoring in the experiments of Ref. [8].

Fig. 3 shows the damage distribution predicted by a finite element simulation of the process and compares it with the experimental observation [9]. As a result of length scale introduced by the nonlocality of the damage modelling a shear band of finite width is observed in the simulation. At a certain stage of the damage development a crack is initiated at the corner of the indenter, which subsequently follows the shear band. A second crack is later initiated where the shear band meets the bottom face of the sheet and starts to grow towards the first crack. This sequence of events compares remarkably well with the experimental observation (Fig. 3).

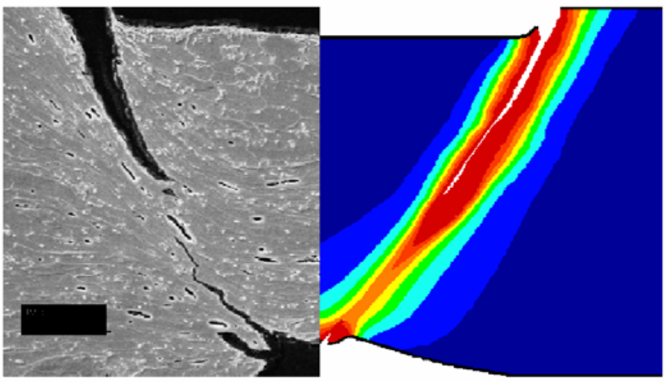

Fig. 3. Damage development during scoring: (left) as observed in the experiments, (right) as predicted by the damage–fracture modelling [9].

4 EXTENSION TO THREE DIMENSIONS

A limitation of the present implementation of the framework is that it is two-dimensional. This limits its application to problems which can be reasonably approximated by a plane-strain or axisymmetry assumption.
Extending the continuum damage modelling and its finite element implementation to three dimensions is relatively straightforward. Fig. 4 shows a result obtained for a cylindrical tensile bar loaded in tension; symmetry has been used to model only one-eighth of the bar. The interaction of plastic strain localisation and damage evolution leads to the formation of a neck at the centre of the bar. The highest level of damage, and therefore crack initiation, is predicted at the classical location at the centre of the bar due to the high stress triaxiality which arises here.

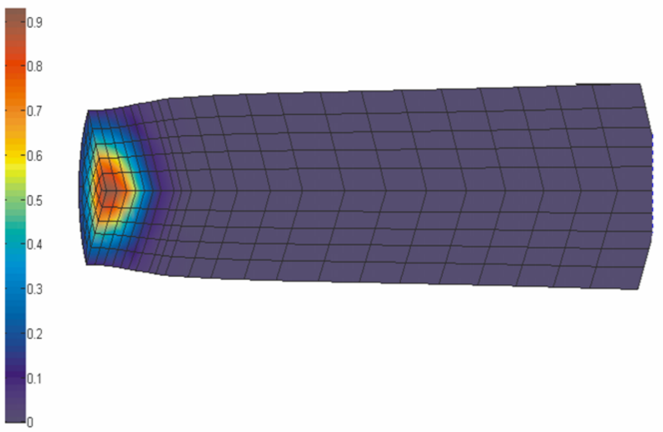

Fig. 4. Computed ductile damage evolution in a tensile bar; only one eighth of the bar has been modelled due to symmetry; the colour-bar indicates the level of damage.

The result shown in Fig. 4 was obtained using hexagonal elements with selectively reduced integration, which can be regarded as a direct extension of the quadrilateral elements used in Refs [6,7]. Automatic remeshers which can robustly mesh complex three-dimensional geometries, however, require the use of tetrahedral elements. For efficiency reasons and given the frequent occurrence of contact conditions in metal forming simulations, these elements should preferably be of a low order. Developing reliable low-order tetrahedral element formulations for combined damage and plasticity which avoid locking and instability issues is therefore one line of our current research.
A second, more fundamental difficulty in extending the available two-dimensional damage–fracture framework to three dimensions is the geometrical complexity which inherently results from three-dimensional crack growth, particularly in a large-deformation setting. Not only may the geometry of the workpiece evolve considerably due to large plastic strains, it may be simultaneously traversed by a complex three-dimensional crack surface. The combined effect is a shape of evolving complexity and topology. Tracing such an evolving geometry numerically in three dimensions is a challenge which is an order of magnitude more difficult than the corresponding two-dimensional problem. Developing the methods to do this, in the context of the damage-driven philosophy as explained above, is therefore another objective of our present research efforts.
A first result is illustrated in Fig. 5. It shows a cube containing an initial crack at one of its edges and which is vertically loaded in tension. The material model used is quasi-brittle and thus assumes small deformations and no permanent strain [10]; the deformations shown in the figure have been scaled for visualisation purposes. Shown is the damage distribution and crack opening near the end of the loading process, when the crack has almost traversed the cross section of the cube. Crack growth was driven by the growth of damage throughout the simulation. The computed damage field in each increment was used to predict the evolution of the crack surface, which was then included in the geometrical description of the problem and fed into a remesher. However, the algorithms developed are not yet sufficiently robust to be applied routinely in large-scale forming analyses and, in particular, do not yet take into account the geometry changes which may result from large plastic strains.

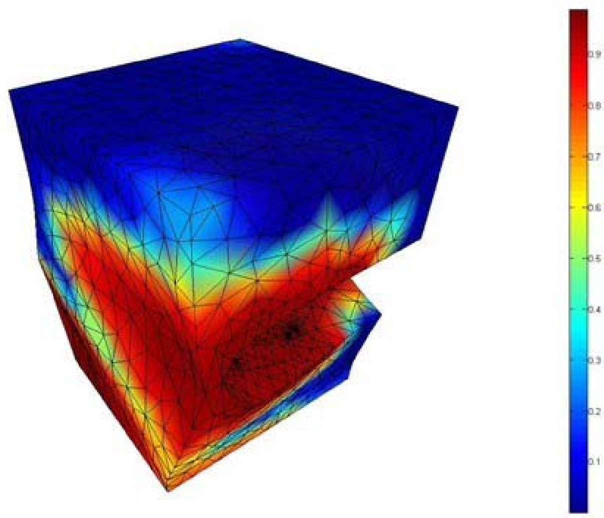

Fig. 5. Preliminary result of a three-dimensional damage-driven crack propagation analysis using a quasi-brittle damage model; the colour-bar indicates the level of damage; the deformation has been scaled for clarity.

5 CONCLUDING REMARKS

The computational results presented in this contribution illustrate the capabilities of the damage-based approach towards modelling fracture in sheet metal forming. However, the predictive power of the approach is currently limited by the predictive power of the underlying damage modelling, which so far is purely phenomenological. More predictive theories, with fewer fitting parameters, may be formulated on the basis of micromechanical modelling. Some progress has been made in this field in the past two decades or so, see e.g. [1,11]. However, some of the resulting formulations are so complex and nonlinear that their practical relevance is limited and they have therefore so far found little application.
Including more accurate, micromechanically-based damage models in the nonlocal damage-based approach to fracture followed in this contribution presents a further challenge for the future. Meeting this challenge may require significant modifications of the continuum damage formulation (particularly in the nonlocality) as well as of its finite element implementation, but will on the other hand result in a significantly increased predictive power.

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