Damage and crack propagation theories applied to sheet metal cutting.

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ABSTRACT: Sheet metal cutting is widely used in industry and the numerical modeling of such a process can be very helpful in order to improve the quality of the final product as well as the productivity of the process. During sheet metal cutting, the material undergoes elastic and plastic deformation with high shearing, damage and fracture. We propose here to focus on the two most critical stages of the process: damage and fracture. To do so, a 2D finite element software dealing with large deformation of elastic-plastic materials is presented. A coupled damage model, based on the Lemaître theory, is used to model the evolution of damage. Numerical tools have also been developed to model the stages of crack initiation and crack propagation up to fragment creation. Special attention will be paid to the computation of the crack extension direction and to the mesh structure at the crack tip. The aim of these techniques is to model the complete separation between the final part and the skeleton, and to study the tool wear due to the punch raising.

INTRODUCTION

Sheet metal components are widely used in many industrial fields such as the car industry, household appliances or consumer electronics. Despite the importance of the sheet metal cutting process, improvements of process parameters are mainly due to trial and error tests or knowledge-based procedures. The modeling of sheet metal cutting remains very difficult to carry out since the part undergoes elastic and plastic deformation, high shearing, damage and fracture during the process. Moreover, after the complete separation between part and skeleton, it is not yet possible to study the raising stage of the punch and consequently the tool wear which has a strong influence on the edge morphology.

Common criteria to assess the accuracy of a finite element simulation of the process are the comparison of load-displacement curves and the study of the sheared edge morphology. The load-displacement curve of the process may be decomposed in different steps (Figure 1).

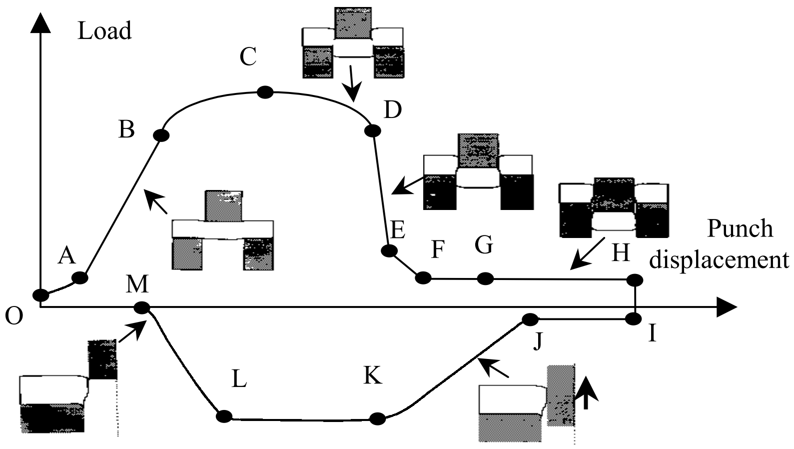


Figure 1: Load-displacement curve of the cutting process.

Up to this day, numerical modeling has been restricted to the first steps: clearance catch up (OA), elastic deformation (AB), plastic deformation (BC), damage (CD).

More recently, some developments have been performed to model crack propagation in the sheet width (DE). However, an important issue of the process is not modelled yet: the complete separation of the part and the skeleton (GH) and the punch raising (JK). These two steps are very important in order to study:

- **The part quality**: a complete separation of the part would enable to study the elastic springback of the part after cutting;
- **The tool wear**: the punch raising involves an important friction between the external side of the punch and the skeleton. The wear induced by this friction is an important parameter to estimate the tool life.

In this article, we present two techniques to model the stages of damage and crack propagation. The finite element software FORGE2 Multimateriaux [1] is used. It can take into account elastic, elastic-plastic and elastic-viscoplastic behavior for large plane strain or axisymmetric deformation. A Newton-Raphson based algorithm is used to deal with non linearities. The main strength of the code is its advanced mesher and automatic remesher presented in [2]: they can deal with multiple materials and internal holes.

Figure 2 shows a fully automatic simulation of the first stage of the cutting process without any damage or fracture during the simulation.

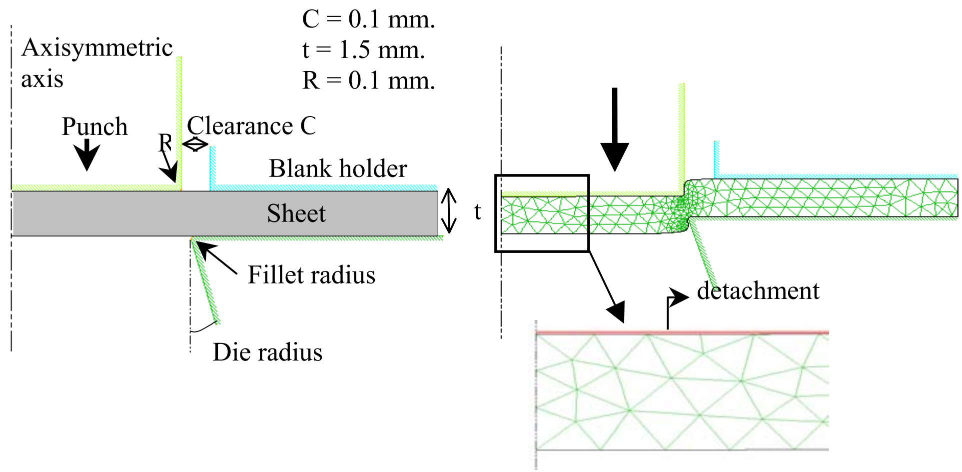


Figure 2: Numerical simulation of the cutting process

The first part of this article is devoted to the coupled damage model developed in the software and its application to the cutting process. Then we focus on the modeling of crack propagation during the cutting process. A particular attention is paid to fracture criteria in mixed mode configuration.

COUPLED DAMAGE MODELING

Continuum damage mechanics is a constitutive theory that describes the progressive loss of material integrity due to the propagation and coalescence of microcracks, microvoids, and similar defects. Beyond a certain value of strain, void nucleation and void growth appear in the material: this phenomenon, called damage, enables to model the ductile fracture of materials. When these voids reach a critical size, they coalesce and give raise to instabilities or cracks propagation. A state of the art of different models used to model the cutting process is proposed in [3].

The model implemented in FORGE2 Multimateriaux is based on the Lemaître theory [4]. It is a coupled damage model, which means that damage and mechanical properties are directly linked and the material fracture is modeled by a progressive decrease of the global response of the structure. Contrary to the uncoupled approach, coupled damage models are quite difficult to introduce in numerical software, but are closer to the physical phenomenon of micromechanical fracture of ductile materials. The evolution of damage is taken into account through the damage parameter *D* which is 0 for a material without damage and 1 for a fully damaged material. We also introduce the notion of effective yield stress $\tilde{\sigma}_0$ and effective Young's modulus $\tilde{E}$:

$$\begin{cases} \tilde{\sigma}_0 = \sigma_0(1-D) \\ \tilde{E} = E(1-D) \end{cases} \tag{1}$$

where σ_0 represents the yield stress of the material and E its Young's modulus. The following incremental form [4] is used to take into account the damage evolution:

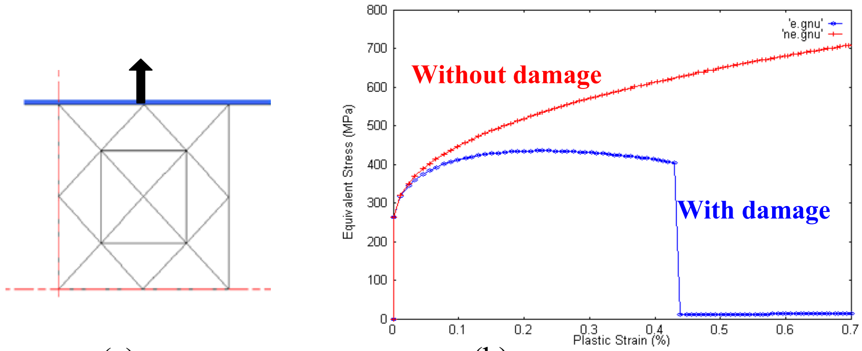
$$\begin{cases} dD = 0 \quad for\ \bar{\varepsilon}_p \leq \varepsilon_D \\ dD = \dfrac{D_c}{\varepsilon_R - \varepsilon_D}\left[\dfrac{2}{3}(1+\upsilon) + 3(1-2\upsilon)\left(\dfrac{\sigma_H}{\sigma_{eq}}\right)^2\right] d\bar{\varepsilon}_p \quad for\ \bar{\varepsilon}_p > \varepsilon_D \end{cases} \tag{2}$$

where $\bar{\varepsilon}_p$ is the equivalent plastic strain, σ_{eq} the equivalent stress, σ_H the hydrostatic stress and ν the poisson ratio. D_c , ε_R and ε_D are materials parameters that can be identified by means of a tensile test [4]. They correspond respectively to the critical damage value at fracture, the strain value at fracture and the threshold strain at which damage initiates. When D reaches Dc its value is directly set to D_r (very close to 1) in order to represent the complete fracture. More details about the model and its implementation in Abaqus may be found in [5].

Uniaxial tensile loading

A validation of the model has been done on a simple uniaxial test, with the following damage parameters: ε_D=0, ε_R=0,43, D_c=0,35 and D_r=0,98. D_r represents the damage value for a fully damaged material and is not equal to 1 in order to avoid a 0 value denominator when computing the yield stress with respect to the effective yield stress.

Figure 3.a shows the coarse mesh for the tensile test simulation and Figure 3.b shows equivalent stress versus plastic strain curves for a simulation with and without damage. It is interesting to see the progressive decrease of equivalent stress due to damage evolution and the complete fracture when the plastic strain reaches ε_R.



(a) (b)

Figure 3: Uniaxial tensile test with coupled damage

Modeling of the cutting process

The same mechanical parameters are used to model the cutting process. Figure 4.a represents the damage concentration in the shearing area during the process. Figure 4.b shows the comparison of numerical load-displacement curves for simulations with and without taking into account damage. We can see that the curve corresponding to the simulation with damage is closer to experimental curves. It shows the progressive loss of rigidity of the material and the final fracture when D reaches D_c.

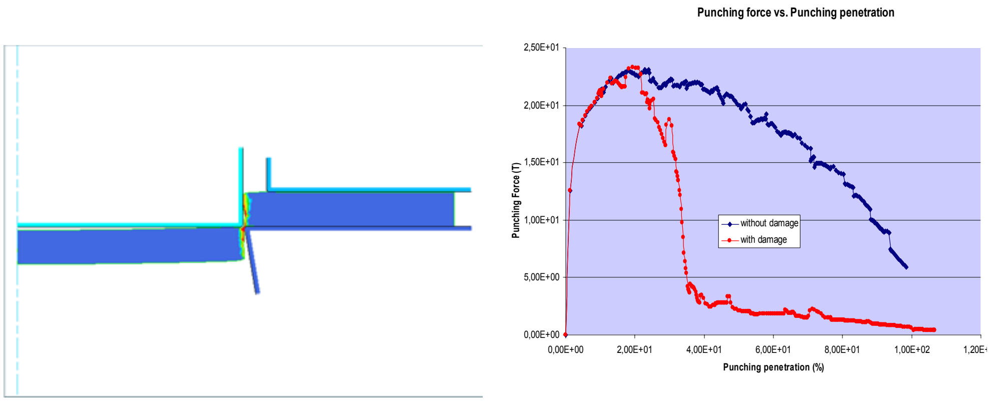


Figure 4: a) damage concentration during the cutting process b) comparison of load-displacement curves.

Some comparisons have also been performed on the influence of the tool sharpness on the cut edge morphology. We can see in figure 5 that a blunt tool involves the presence of an important burr on the cut edge morphology.

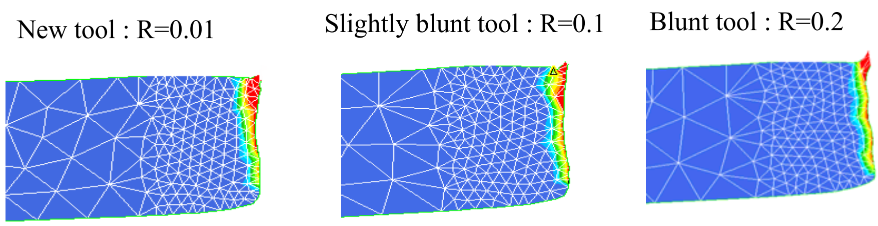


Figure 5: influence of the sharpness of the cutting tool on the cut edge morphology.

CRACK PROPAGATION MODELING

The use of coupled damage gives good results when modeling the cutting process, however it does not take into account the real fracture of the material during the process. A real crack propagation technique would enable to locate accurately the crack tip and to take into account the influence of a sharp crack tip on the local mechanical fields. Several numerical developments have been made in FORGE2 Multimateriaux to model crack initiation and crack propagation [2,6]. These developments are based on an elaborate structure of the mesh at the crack tip and on a good automatic remeshing technique.

Several crack propagation criteria have been implemented: Maximum circumferential stress criterion, Minimum strain energy density criterion, Maximum strain energy release rate criterion. These criteria give good results on the direction of the crack propagation for mode I dominated applications. However, in applications with important shearing, we have shown in [7] that they give wrong crack path prediction (Figure 6).

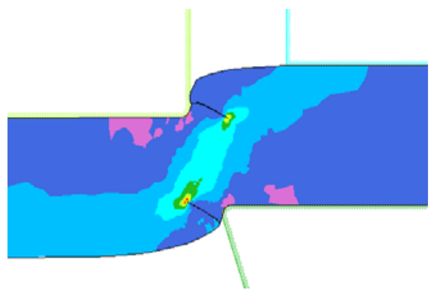


Figure 6: wrong crack path according to the maximum circumferential stress criterion during the cutting process.

Consequently, we have introduced a new crack propagation criterion, based on the shear stress, which states that the crack will naturally propagates along the maximum shear stress [7]. This criterion gives the right crack direction. However, when a crack propagates in a shearing area, the edges of the crack can get into contact. We are implementing a special contact algorithm which prevents the crack edges from interpenetrating if this occurs.

Sutton and coworkers [8] have shown on an aluminium alloy that classical crack propagation criteria were inappropriate when the mode mixity parameter α exceeds a material critical value.

$$\alpha = Arc\,tan\left(\frac{K_{II}}{K_I}\right) \tag{3}$$

where K_I and K_{II} are the stress intensity factors corresponding respectively to mode I and mode II.

For the cutting process, we have shown that the mode mixity parameter was greater than this material critical value. A numerical simulation has been performed using both Abaqus® and Franc2® software. Franc2®, developed in the Cornell Fracture group at Cornell University is a finite element software dedicated to the modeling of crack propagation. Abaqus®, developed by HKS, is used in this simulation to deal with non linearities due to elasticplastic deformation and contact between crack edges. Figure 7 shows that the maximum shear stress criterion predicts the right crack propagation direction and enables to model the process until complete fracture occurs.

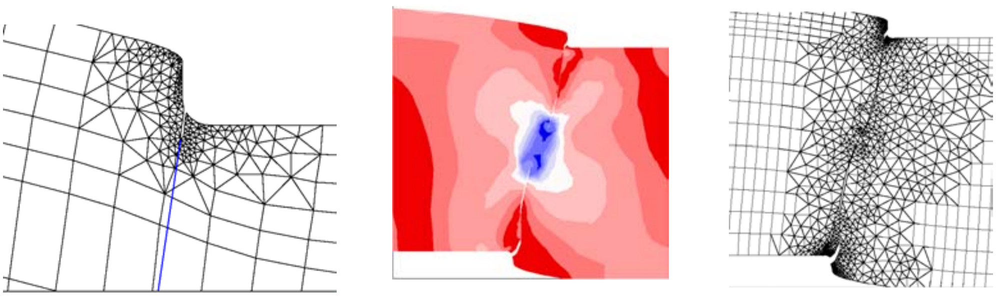


Figure 7: crack propagation during the cutting process, using the maximum shear stress criterion

CONCLUSION

We have presented two different techniques to model fracture during the cutting process:

- ♦ Coupled damage mechanics enables to model accurately the progressive loss of rigidity of the material leading to fracture.
- ♦ Crack propagation modeling enables to model the real fracture of the material, using a suitable crack propagation criterion.

In the future, a coupling between these two approaches is necessary if one wants to model accurately the complete sheet metal cutting process in which damage and fracture take place. From an experimental point of view, it would thus be important to develop criteria that can determine when we can switch from a damage approach to a fracture mechanics approach.

The final objective is to model accurately the whole process and the complete separation of the part and the skeleton. When the complete separation occurs, an elastic springback analysis may be performed on the part, and the punch raising stage can be modelled to study the tool wear.

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