MODELLING OF DAMAGE IN METAL FORMING PROCESSES

Smain Bezzina [1]

1: Assistant professor, Production department, Jeddah College of Technology, KSA

E-mail: ibezzina@yahoo.fr

ABSTRACT

Fracturing by ductile damage occurs quite naturally in metal forming process due to the development of microcracks associated with large straining or due to plastic instabilities associated with material behavior and boundary conditions. This paper deals with the numerical simulation of the shear cutting process. Using the framework of the thermodynamics with internal state variable at finite deformation, an isothermal elastoplastic model accounting for the hardening and the isotropic continuum damage for the fracture is developed. Thus the coupling between elastoplasticity and damage lead to a fully description of the degradation of the material mechanical properties. The full constitutive equations of this model are presented , then the simulation by finite elements of sheet cutting is analyzed and compared to experimental results.

Keywords: *Continuum Damage Mechanics, Finite Elastoplaticity, Sheetmetal Cutting, Finite element Analysis, Numerical Simulations.*

الملخص

إن ضاهرة الإنكسار بالضرر في المعادن تحدث طبيعيا بسبب نمو و تطور الشقوق الداخلية المصاحبة لـلإ جهادات الداخلية الكبيرة أو بسبب عدم الاستقرار المصاحب لتفاعل المواد و شروط الحواف. في ورقتنا هذه, و باستخدام إطار الديناميكا الحرارية للمتغيرات الداخلية في حالة التشوه المحدود, طور نموذج لدونه للأخذ في الإعتبار التصلد و ضاهرة الضرر المستمر أثناء عملية الكسر. و بالمزاوجة بين اللدونة و الضرر المستمر نصل إلي وصف كامل لتدهور الصفات الميكانيكية للمواد.

1. INTRODUCTION

During metal forming, the main causes of fracture result either from plastic instabilities associated with localization phenomena (necking in sheet metal forming, surface fracture observed in bulk metal forming,….) or from the development of damage due to large staining of the material (sheet metal cutting, internal fracturing in cold forging).

Numerical modeling of metal forming processes has now gained the industrial stage, and it became possible to simulate metal deformation and to calculate stress and strain states for complex processes, see as example the increasing interest in the Numiform and Metal

Forming Conferences in terms of variety of processes that can be analyzed [Chenot, J. L. et al, 1992].

At present, both fracture and plasticity theories as well as other phenomenological material modeling approaches cannot treat material constitutive relations differently from virgin and damaged parts of a material constitutive at the same time. In circumstances where the defects are distributed in a statically homogenous manner, it is advantageous to model the mechanisms associated with material degradation within continuum damage mechanics (CDM).

In CDM, damage is principally a reduction of the net area and may be regarded as a continuous degradation measure of material degradation. Many material models with stiffness using CDM have been proposed during the last two decades, A literature review on damage mechanics has been made by [Chaboche, J. L., 1988] and the reference therein.

The approach proposed in this paper use the continuum damage mechanics to simulate the cuttings process. First a fully coupled elastoplastic-damage model is presented. The large plastic deformation with strain hardening, the isotropic ductile damage and the contact with friction are taken into account. Secondly, the obtained constitutive equations are implemented in the general purpose finite element Code developed at Compiegne University of Technology (France). To prove the validity of this approach some examples of numerical simulation are presented and compared to experimental results.

2. ELASTOPLASTIC DAMAGED MODEL

In this section, the formulation of the basic equations of the constitutive model is considered, based on the thermodynamics of irreversible processes with internal variables. This damage-elastoplasticity model adopts the following hypothesis: i) linear, isothermal and isotropic elastic behavior, iii) isotropic plastic flow of Mises type with non-linear isotropic and kinematic hardening. iv) isotropic plastic (ductile) damage. All these phenomena are represented by the following couples of state variables:
The observable State Variables (OSV):

$(\varepsilon_{ij}, \sigma_{ij})$ the total strain tensor and the associated Cauchy stress tensor.

The Internal State Variables (ISV):

(α_{ij}, X_{ij}) the kinematic internal strain tensor and the associated internal stress tensor representing the kinematic hardening. (r, R) the isotropic internal strain tensor and its associated internal stress representing the isotropic hardening. (D, Y) the isotropic damage and its associated internal force representing the isotropic damage. Since the effect of the damage in the elastoplastic behavior can not be neglected, the hypothesis of total energy

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equivalence is used to define the following so-called effective state variables $(\tilde{\sigma}_{ij}, \tilde{\varepsilon}^{e}_{ij}), (\tilde{X}_{ij}, \tilde{\alpha}_{ij})$ and $(\tilde{R}, \tilde{r})$. These effective state variables are used in the state and dissipation potentials to derive the constitutive equations fully coupled with damage. The detailed calculations to derive these coupled constitutive equations can be found in [Saanouni, K.et al, 1994]; here are given only the final forms of the state and the evolution laws

2.1 The State Laws

$$\sigma_{ij} = \left(\frac{\nu\tilde{E}}{(1+\nu)(1-2\nu)}\right)\varepsilon_{kk}\delta_{ij} + \frac{\tilde{E}}{(1+\nu)}\varepsilon_{ij} \tag{2.1}$$

$$X_{ij} = \frac{2}{3}\tilde{C}\alpha_{ij} \tag{2.2}$$

$$R = \tilde{Q}r \tag{2.3}$$

$$Y = Y_{\sigma} + Y_{X} + Y_{R} \tag{2.4.a}$$

$$Y_{\sigma} = \frac{1}{2}\frac{J_2^2(\sigma_{ij})}{E(1-D)^2}\sigma^* \tag{2.4.b}$$

$$Y_{X} = \frac{1}{2\tilde{C}}J_2^2(X_{ij}) \tag{2.4.c}$$

$$Y_{R} = \frac{1}{2\tilde{Q}}R^2 \tag{2.4.d}$$

with:

$$\tilde{E} = (1-D)E, \tilde{C} = (1-D)C, \tilde{Q} = (1-D)Q \text{ and } \sigma^* = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{J_2(\sigma_{ij})}\right)^2$$

where, C and Q are the kinematic and isotropic hardening moduli, a and b are material coefficients characterizing the non-linearity of the hardening and S, s and α are the material coefficients of the damage evolution. σ_H is the hydrostatic stress. E and ν are the classical elastic properties of the isotropic medium. $J_2^2(Z_{ij})$ represents the Von-Mises norm defined in the stress space by:

$$J_2^2(Z_{ij}) = \frac{3}{2}Z^{d}_{ij}Z^{d}_{ij} \tag{2.5}$$

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where, $Z^{d}_{ij} = Z_{ij} - \frac{1}{3} Z_{kk}\delta_{ij}$ is the deviatoric part of the stress tensor Z_{ij}.

2.2 The Evolution Laws

If $(s_{ij} - X_{ij})\dot{\varepsilon}_{kl} \leq 0 \Rightarrow$ elastic behavior

$$\dot{\sigma}_{ij} = L^{\sigma e}_{ijkl}\,\dot{\varepsilon}_{kl} \tag{2.6}$$

with,

$$L^{\sigma_p}_{ijkl} = L^{\alpha}_{ijkl} = L^{r}_{ij} = L^{D}_{ij} = 0$$

if $(s_{ij} - X_{ij})\dot{\varepsilon}_{kl} > 0 \Rightarrow$ damage-plastic loading

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{p}_{ij} \tag{2.7}$$

$$\dot{\sigma}_{ij} = L^{\sigma}_{ijkl}\,\dot{\varepsilon}_{kl} \tag{2.8}$$

$$\dot{\alpha}_{ij} = L^{\alpha}_{ijkl}\,\dot{\varepsilon}_{kl} \tag{2.9}$$

$$\dot{r} = L^{r}_{ij}\,\dot{\varepsilon}_{ij} \tag{2.10}$$

$$\dot{D} = L^{D}_{ij}\,\dot{\varepsilon}_{ij} \tag{2.11}$$

where the final forms of the operators $L^{\sigma}_{ijkl}, L^{\alpha}_{ijkl}, L^{r}_{ij}, L^{D}_{ij}$ and the tangent elastoplastic module H (strictly positive) are defined as :

The forth order operators :

$$L^{\sigma}_{ijkl} = L^{\sigma_e}_{ijkl} + L^{\sigma_p}_{ijkl} \tag{2.12}$$

$$L^{\sigma_e}_{ijkl} = \frac{\nu\tilde{E}}{(1+\nu)(1-2\nu)}\delta_{ij}\delta_{kl} + \frac{\tilde{E}}{(1+\nu)}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) \tag{2.12.a}$$

$$L^{\sigma_p}_{ijkl} = -\frac{3}{2}\frac{1}{H}\frac{E}{(1+\nu)J_2}\left[\frac{3}{2}\frac{\tilde{E}}{(1+\nu)J_2}(s_{ij} - X_{ij})(s_{kl} - X_{kl}) + \frac{Y^*}{\sqrt{1-D}}(\sigma_{ij} - X_{ij})\sigma_{kl}\right] \tag{2.12.b}$$

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$$L^{\alpha}_{ijkl} = \frac{9}{4}\frac{1}{H}\frac{E}{(1+\nu)J_2}\left[\frac{(s_{ij}-X_{ij})(s_{kl}-X_{kl})}{J_2} - \frac{a}{C}\frac{(s_{ij}-X_{ij})X_{kl}}{\sqrt{1-D}}\right] \tag{2.13}$$

The second order operators:

$$L^{r}_{ij} = \frac{3}{2}\frac{1}{H}\frac{E}{(1+\nu)}\left[1-\frac{bR}{Q\sqrt{1-D}}\right]\frac{(s_{ij}-X_{ij})}{J_2} \tag{2.14}$$

$$L^{D}_{ij} = \frac{3}{2}\frac{1}{H}Y^{*}\sqrt{1-D}\frac{E}{(1+\nu)}\frac{(s_{ij}-X_{ij})}{J_2} \tag{2.15}$$

with:

$$H = Y^{*} = \frac{1}{(1-D)^{\alpha}}\left[\frac{-Y}{S}\right]^{s} \tag{2.16}$$

and s_{ij} is the deviatoric part of the stress tensor σ_{ij}.

$$H = Q + C + \frac{3}{2}\frac{E}{(1+\nu)} - \left[b\tilde{R} + \frac{3}{2}a\frac{(s_{ij}-X_{ij})X_{kl}}{J_2}\right] + \frac{Y^{*}}{1-D}\frac{\sigma_y}{2} \tag{2.17}$$

So that the equations (2.1) to (2.17) define completely the elastoplastic behavior with damage.

3. NUMERICAL STUDIES AND APPLICATIONS

3.1. At Gauss point level

The theoretical model presented above was implemented in the general purpose Finite element code SIC (systeme interactif de conception) developed at Compiegne University of Technology (France). Under the of assumption of plane strain, the simple case of axial traction with imposed displacement is considered. Material parameters correspond to a mild steel material and provided by [Saanouni, K, .et al, 1994].: E= 200000 Mpa, $\nu = 0.3$, k= 264 Mpa, Q= 1000 Mpa, b = 16, C=10000 Mpa, a= 20, S=1, s= 1, α=1. Full implicit time integration scheme is used for the integration of the constitutive equations (generalized midpoint rule). Calculations without coupling to damage show the classical stabilized response. In the coupling case, figure 1 shows the variation of the Cauchy stress equivalent versus the accumulated plastic strain. We note that the presence of damage generates continuous degradation of the mechanical properties until the total failure of the volume element. attains his critical value D = 1).

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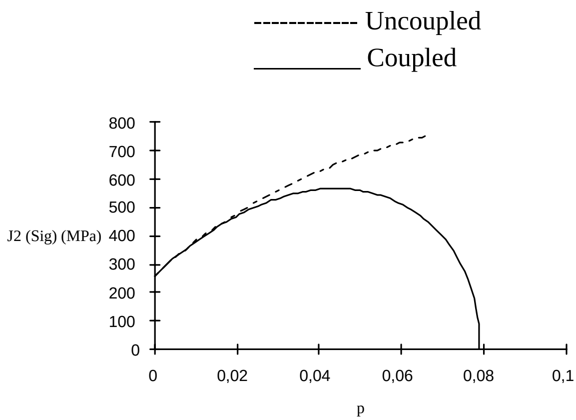

Figure 1. Cauchy stress equivalent versus the accumulated plastic.strain

Figure 2 shows the predicted variation of the stress equivalent back-stress versus the accumulated plastic strain: The response indicates that the value of the internal variable starting from zero, increases with increasing hardening, reaches a maximum value and goes to zero when damage approaches D = 1. Fig 3 and fig 4 show respectively the variation of the isotropic hardening R and the internal damage variable. Note that this is not the case in the theory used by [Chaboche, J. L., 1988] and by other authors where the internal stresses X and R remain unaffected by the damage.

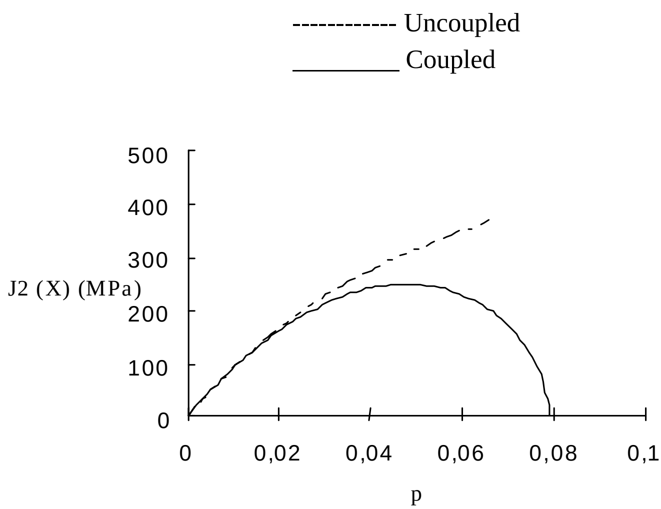

Figure 2. Back stress equivalent versus the accumulated plastic.strain

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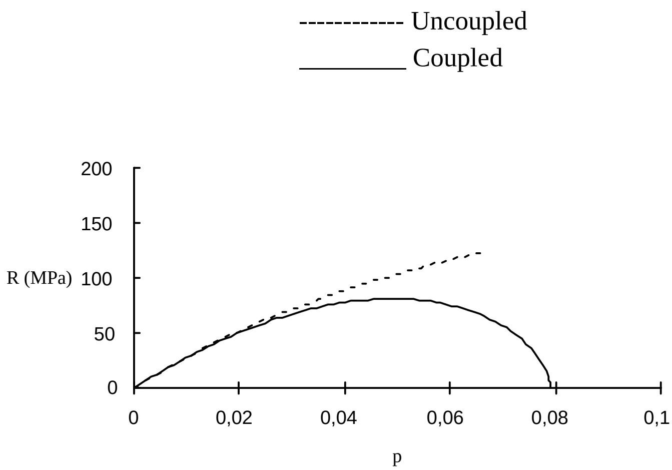

Figure 3. Isotropic hardening stress versus the accumulated plastic strain.

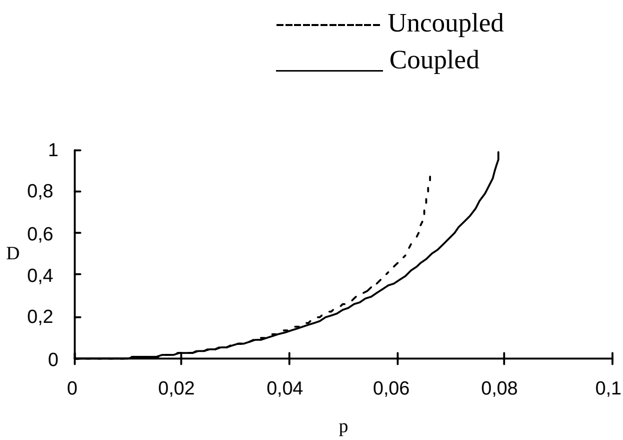

Figure 4. Damage versus the accumulated plastic strain

3.2 Numerical Simulation Of Sheet Cutting Process

The cutting or mechanical severing of thin plates is a metal forming process which consists in applying to the metal shear forces using a punch and die (Fig 5) When cutting during shearing process, the required force increases (hardening stage) until it reach a maximum value and then decreases (softening stage) until it attains zero force when cutting is completed.

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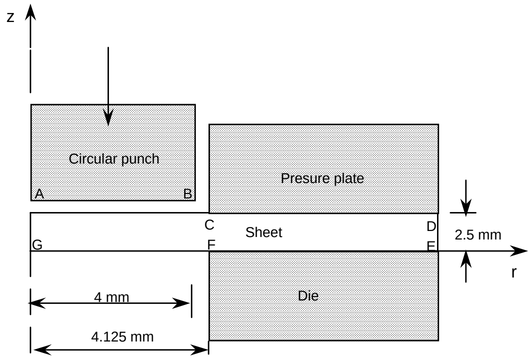

Fig. 5. Schematic representation of a meridian plan.

[Maillard, A., 1994] presented a series of pictures of blanking process as indicated in Fig. 6 where we show that the process of cutting is caused by the continuous degradation of a material along the shearing zone.

The hardening stage is due to the plastic deformation of the metal with large strain hardening, while the softening stage is mainly due to the initiation and growth of the micro-cracks which develop to give the macroscopic crack. Hence to analyze naturally the numerical simulation of this process, it is necessary to take into account a fully coupled plasticity-damage model which has been described in section 2. For this purpose, we compare the experimental results provided by [Maillard, A., 1994] with our numerical results.

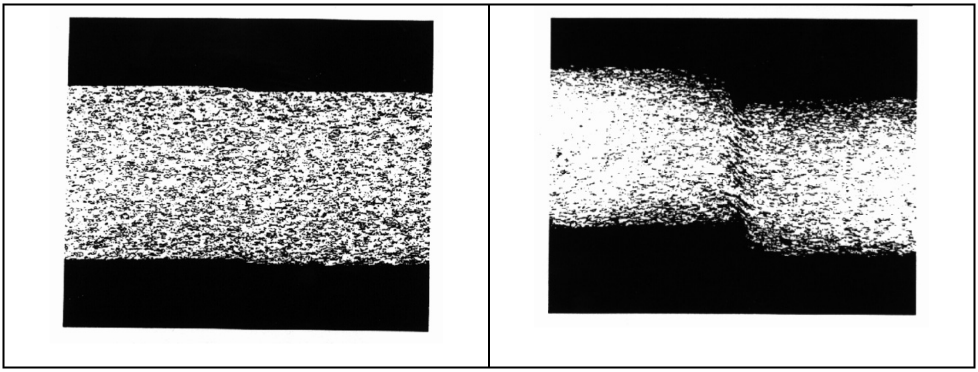

Fig.6. Partial cut of a ductile metal sheet.

The sheet work is made of a mild isotropic high ductile material steel (XES). For more description of the nature of the metal and the material constant see [Maillard, A., 1994] E = 200000 Mpa, $\nu = 0.29$, k = 150 Mpa, Q = 448 Mpa, b = 1, S = 100., $\alpha = 1$. The mesh of the sheet work considered contains 377 six-nodes triangular isoparametric continuum elements as shown in Fig. 7. Because all the phenomena of the cutting are concentrated in the central zone called the zone of sheared fracture [Bezzina, S., Saanouni, K., 1997].

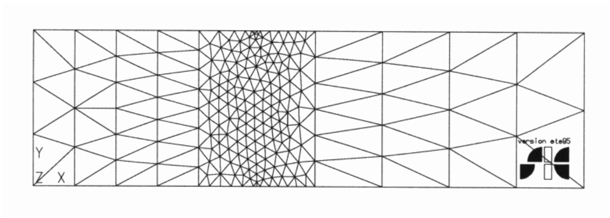

Fig. 7. Initial mesh of the sheet work.

In this case we take into account the moving contact conditions. We consider the same contact without friction as in the experimental data [Maillard, A., 1994] The model material is supposed elastoplastic without damage. The loading is applied by prescribing a displacement to the rigid punch. Fig 8 and Fig 9 show the successive deformed of the structure at different instants of the punch course. These deformed illustrate the path of deformation, and watch that the former is practically concentrated in the band. At the instant corresponding to u =1.1mm, say 45% of the thickness of the sheet work, we remark the presence of highly distorted elements near the punch and die. To continue the finite elements calculation after this time, procedure of remeshing is necessary**.** We notice that the plastic deformation is well concentrated in the sheared band. The recorded value examination shows that the former is very intense (exceeds 300 per cent) in the superior and inferior corners. That is probably unacceptable without taking into account of a procedure of remeshing.

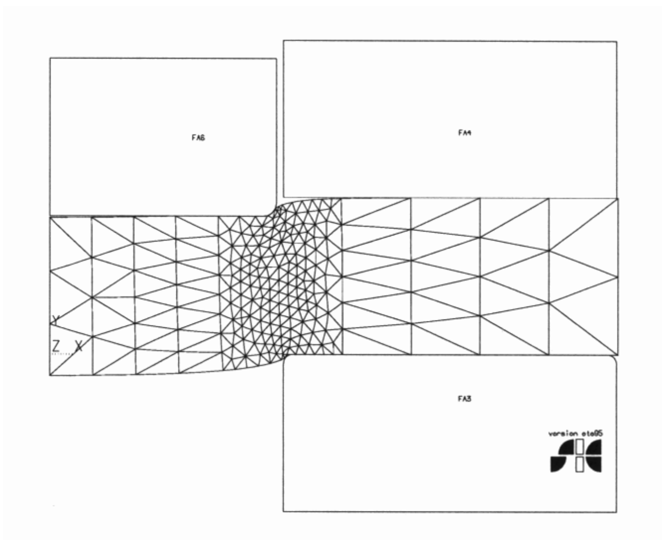

Fig 8. Deformed mesh at u = 0.3 mm

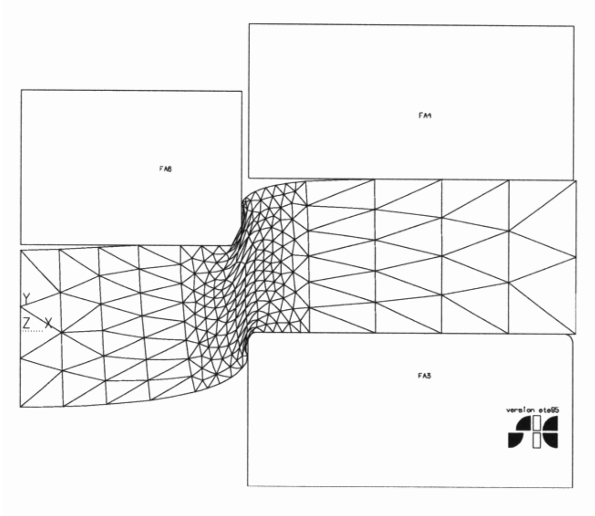

Fig 9. Deformed mesh at u = 1.1 mm

In Fig 10. we report the numerical load-displacement curve together with the experimental one. The introduction of the real limit conditions (condition of contact) lead to a small difference between the numerical and the experimental results.

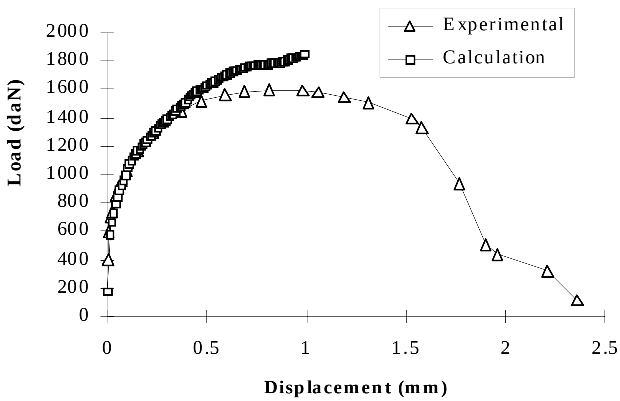

Fig 10. Load-displacement curve.

4. CONCLUSIONS

The main purpose of this work is to simulate the industrial process of cutting by punching. We have shown that the latter involved material non-linearities (elastoplasticity coupled to damage) and geometrical nonlinearities such as large deformation and contact with friction. To attain this, we presented a coupled elastoplastic damage model to describe a continuous degradation of the mechanical properties until the cut. This model is included in a general resolution scheme including large deformation and contact with friction. The present numerical results show that the introduction of remeshing is necessary for accurate the numerical simulation.

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