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# Numerical simulation of easy opening lids for food cans using fully coupled advanced constitutives equations with ductile damage

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ABSTRACT: This paper presents the modelling and numerical simulation of the easy opening process (indentation, perforation and tearing) of food lids. The objective is the virtual prediction of the tearing load by using 3D finite element analysis accounting for the mixed isotropic and kinematic hardening together with the ductile damage effect. The different materials parameters are identified using experimental tensile tests conducted until the final fracture. The overall process is numerically simulated and the results compared to the experimental measurement of the load-displacement curves.

Key words: Ductile damage, FEA, indentation process, easy-opening can lid, plasticity

## 1 INTRODUCTION

Today the food industry is locking to develop attractive market products with a simple and useful packaging. Particularly, for the sterilized food cans the so called easy-opening lids are developed as an attractive commercial product. This consists to open the can without using utensils thanks to the effect of a score line along the circumference of the lid. This score line acts as local stress concentrator and facilitates the crack initiation and its propagation along the circumference. An optimal easy-opening lid for food cans, consists to obtain a complete opening using a minimum applied force and avoiding any inadvertent opening. Many parameters influence the performance of the easy-opening as: geometrical parameters (residual thickness after indentation, angle of indent, geometries of the panel ...) and the mechanical properties of the steel (ductility, hardening, …) [1, 2].

This work aims to propose FEM based numerical methodology able to 'optimize' the easy-opening lids using advanced constitutive equations accounting for non linear isotropic and kinematic hardenings strongly coupled with ductile isotropic damage. The coupling between the ductile damage and the elastoplastic constitutive equations is formulated in the framework of the thermodynamics of irreversible processes together with the Continuum Damage Mechanics (CDM) theory. The associated numerical aspects are discussed and implemented into ABAQUS/Explicit using the Vumat user's subroutine.

## 2 THERMO MECHANICAL DAMAGE CONSTITUTIVE EQUATION

The fully coupled elasto-plastic behaviour is modelled in the framework of the thermodynamics of irreversible processes with state variables ([3-4]) assuming the small elastic strain hypothesis with large plastic strain. According to the first gradient formulation, the 'external' state variables: ($\underline{\varepsilon}$, $\underline{\sigma}$) for total strain tensor and the Cauchy stress tensor. The 'internal' state variables and their conjugate forces are : ($\underline{\varepsilon}^e$, $\underline{\sigma}$) for small elastic strain tensor and the Cauchy stress tensor; ($\underline{\alpha}$, $\underline{X}$) for the back-strain and back-stress deviator tensors that describe the kinematic hardening (i.e. translation of the yield surface centre); ($r$, $R$) equivalent plastic driving strain and stress representing the isotropic hardening (i.e. variation of the yielding surface size) and ($D$, $Y$) for isotropic ductile damage and its conjugate force, which is also known as a damage strain energy release rate.

The fully coupled constitutive equation formulated in the rotated configuration according to the objectivity requirement using the above defined state variables ([3, 4]):

The state relations:

$$\underline{\sigma} = \left(g_1(D)\right)^2 \underline{\underline{\Lambda}} : \underline{\varepsilon}^e \tag{1}$$

$$\underline{X} = \frac{2}{3}\left(g_1(D)\right)^2 C\underline{\alpha} \tag{2}$$

$$R = \left(g_2(D)\right)^2 Qr \tag{3}$$

$$Y = Y_e + Y_r + Y_a \tag{4}$$

$$Y_e = -g_1(D)\frac{dg_1(D)}{dD}\begin{pmatrix}\left(\frac{3\lambda_e + 4\mu_e}{3}\right)\left(\left\langle \mathrm{tr}\left(\varepsilon^e\right)\right\rangle\right)^2 + \\ 2\mu_e \underline{\mathrm{dev}}\left(\varepsilon^e\right) : \underline{\mathrm{dev}}\left(\varepsilon^e\right)\end{pmatrix} \tag{5}$$

$$Y_a = -\frac{2}{3} g_1(D)\frac{dg_1(D)}{dD} C\underline{\alpha} : \underline{\alpha} \tag{6}$$

$$Y_r = -g_2(D)\frac{dg_2(D)}{dD} Qr^2 \tag{7}$$

Evolution Equation :

$$\underline{D}_p = \dot{\delta}\underline{n} \ , \ \ \underline{n} = \frac{3}{2}\frac{1}{g_1(D)}\frac{\underline{s} - \underline{X}}{\left\|\underline{\sigma} - \underline{X}\right\|} \tag{8}$$

$$\dot{\underline{\alpha}} = \dot{\delta}\left(\underline{n} - a\underline{\alpha}\right) \tag{9}$$

$$\dot{r} = \dot{\delta}\left(\frac{1}{g_2(D)} - br\right) \tag{10}$$

$$\dot{D} = \left(\frac{\langle Y - Y_0 \rangle}{S}\right)^s \frac{\dot{\delta}}{(1-D)^\beta} \tag{11}$$

In these equations $\underline{\underline{\Lambda}}$ is the fourth order symmetric elastic properties tensor $\underline{\underline{\Lambda}} = 2\mu_e \underline{\underline{1}} + \lambda_e \underline{1} \otimes \underline{1}$; C is the kinematic hardening modulus and Q is the isotropic hardening modulus; a and b characterize the non linearity of the kinematic and isotropic hardening respectively; $Y_0$ (Threshold), S, $\underset{\cdot}{s}$ and $\beta$ characterize the ductile damage evolution. Finally the Macaulay brackets $\langle \mathbb{Z} \rangle$ are used to define the positive part of $\mathbb{Z}$.

The deviatoric second order tensor $\underline{n}$ is the outward normal to the isotropic Mises yield surface f with damage effect defined by:

$$f = \frac{\left\|\underline{\sigma} - \underline{X}\right\|}{g_1(D)} - \frac{R}{g_2(D)} - \sigma_y = 0 \tag{12}$$

in which $\sigma_y$ is the limit yield stress in uniaxial tension i.e. the initial size of the yield surface in the stress space. The function $g_1(D)$ and $g_2(D)$ are positives and decreasing function of damage variable D representing the effect of the ductile damage on the mechanical behavior. Various forms can be taken for these damage effect functions as:

$$g_i(D) = \sqrt{1 - D^\omega} \tag{13}$$

In this work, the case with $\omega$=1 is used. Finally, the friction between the tools and the sheet is taken as the classical Coulomb model with the friction parameter $\eta$=0.1.

## 3 IDENTIFACTION METHODOLOGY

The identification of the materials parameters is based on experimental results of tensile tests conducted until the final fracture. The gage length of the specimen is discretized with hexahedral trilinear elements (C3D4R from Abaqus element library) with a constant size of 0.2 mm. The dimensions of the specimen gage length are 80x20x0,17 mm.

The identification procedure gives the following values of the material parameters: E=210 GPa, $\nu$=0.35, $\sigma_y$=285 MPa, Q=704 MPa, b=1.3, C=2000 MPa, a=80, S=80 MPa, s=1.3, B=10, $Y_0$=0

As shown in figure 1 the damage zone localizes inside along one shear band giving the final fracture of the specimen.

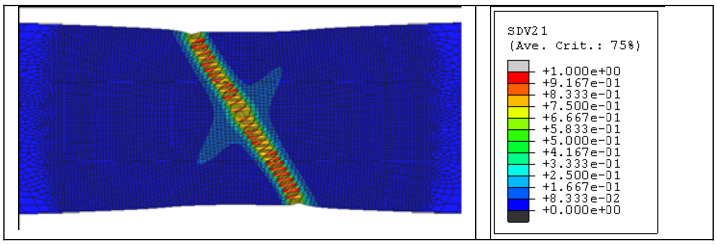


Fig. 1. Damage distribution after 30 mm displacement

The global force-displacement curve predicted by the model is shown in figure 2 compared to the experimental data.

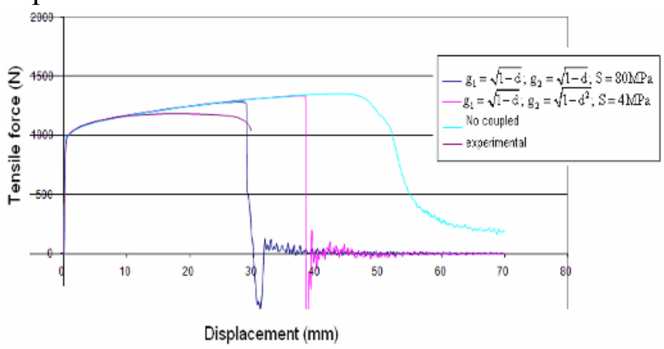


Fig. 2. Comparison between the numerical and experimental global force-displacement curves.

## 4 THE SCORE LINE FORMING

The goal of the indentation is to weaken the zone of drilling and opening in order to facilitate the crack propagation during the opining. This operation consists to form a score line along the circumference of the lid (see figure 5). The sheet is placed between the indent and the cylindrical anvil tools; the displacement of the indent deforms the sheet and the score line with a certain residual thickness. In certain case, a large displacement of the indent leads to a traversing cracks.

The figure 3 shows some micrography of score line with different indent tools without any traversing crack.

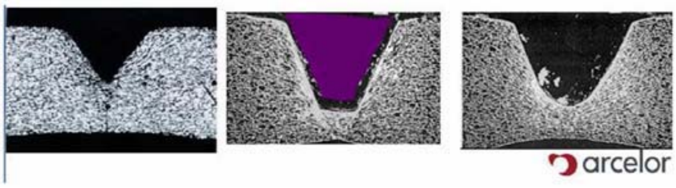


Fig. 3. Micrographs of different indentation

A 2D adaptive meshing is developed to enhance the prediction of the numerical model [5]. In this case, the configuration of plane strain is choosen. The description of this test is shown in figure 4. The initial thickness of the flange is equal to 0.17 mm.

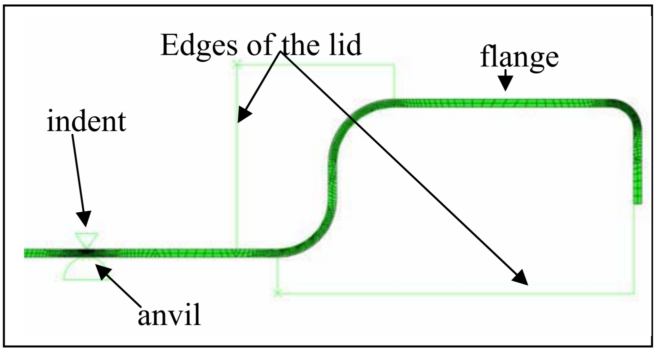


Fig. 4. Geometry of the score line forming

The distribution of the damage for different residual thickness “h” is summarized in figure 5. One can verify that no traversing cracks develop along the thickness of the flange.

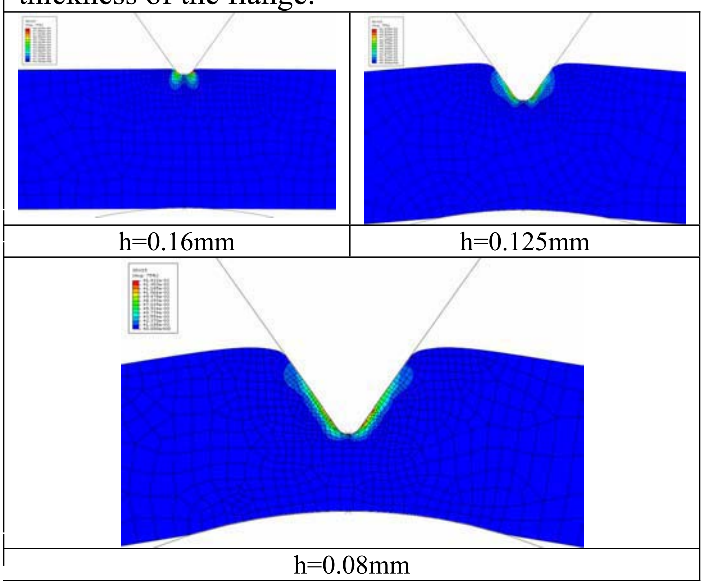


Fig. 5. Damage distribution at different indent tool displacement values (h is the residual thickness)

The same operation is realized in the case of a 3D real geometry of a lid. To save the CPU time only five elements are put along the thickness in the score line zone. The result is described in figure 7.

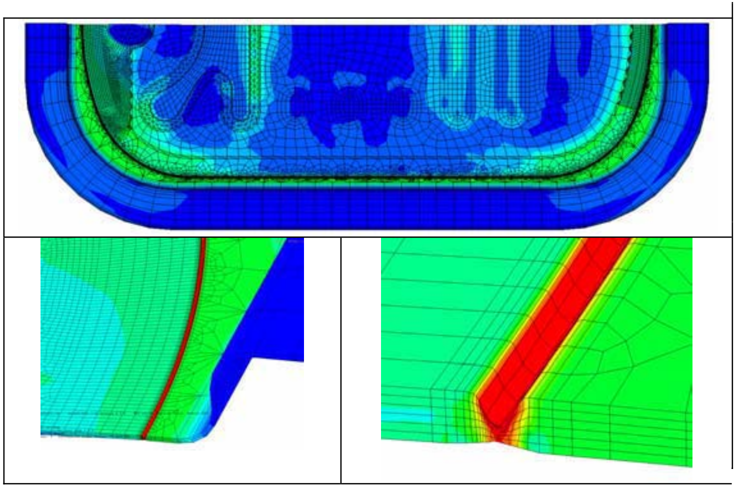

Fig. 6. 3D forming of the score line

## 5 NUMERICAL SIMULATION OF EASY OPENING LIDS

The first step consists to perforate the lid with a special form of a ring tool. This operation generates generally the maximum of opening force. The ring tool is supposed as rigid body and only the symmetric part of the sheet is considered (see figure 7)

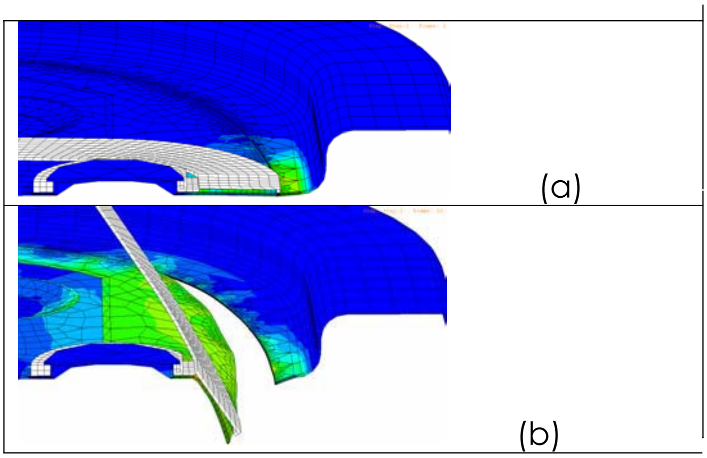


Fig. 7. The perforating operation of the sheet

An experimental procedure to measure the opening force versus the displacement during the easy-opening operation is performed by Arcelor Mittal Company. The experimental facility is shown in figure 8.

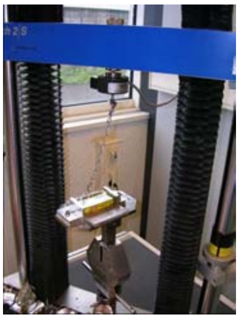

Fig. 8. Experimental apparatus for the opening test

In figure 9 are summarized different steps of the opening process. The comparison between the predicted and the experimental force-displacement curves is shown in figure 10. Clearly the predicted force is quite different from the experiment mainly at the beginning of the tearing operation. Also some oscillations of the force are obtained due to some numerical instability caused by a bad choice of the mass scaling factor. This aspect should be enhanced in the future.

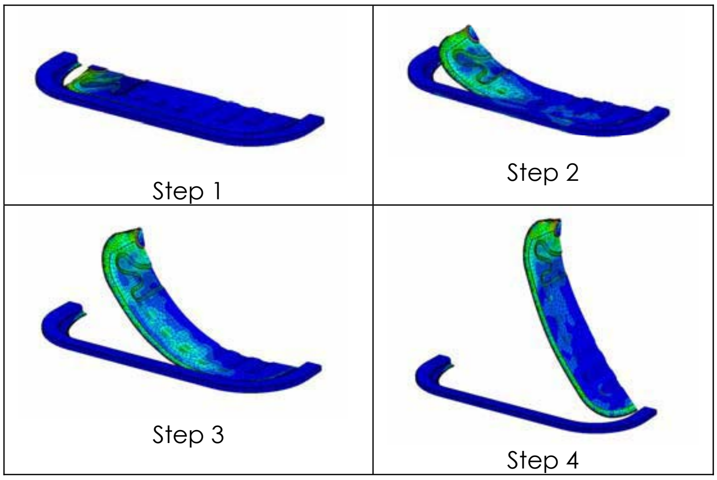


Fig. 9. The tearing operation of a lid for different steps

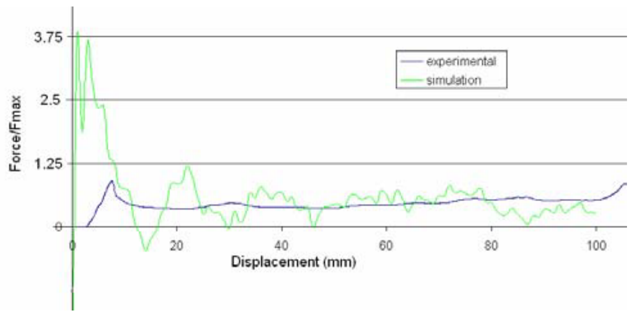


Fig. 10. Comparison between experimental and numerical tearing forces

## 6 CONCLUSION

An "advanced" elastoplastic model accounting for mixed non linear hardening fully coupled with ductile damage has been shown helpful to predict the opening force of a lid. A 2D adaptive remeshing methodology has been used to 'optimize' the easy-opening lids of cans by minimizing the opening force and avoiding the formation of any macroscopic crack during the score line simulation by indentation. However, some open aspects are still under progress and will be addressed in prospect as developing a 3D adaptive remeshing facility.

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