Deep drawing process with different elasto-plastic laws

P. de Montleau[1], L. Duchêne[1], S. Bouvier[2], P. Flores[1], A-M. Habbraken[1]

[1]*University of Liège, dep. M&S – Bât. B52/3, 1 chemin des chevreuils, 4000 Liège-1, Belgium*
URL: www.ulg.ac.be e-mail: *p.demontleau@ulg.ac.be*

[2]*LPMTM-UPR9001, University Paris 13, 99 av. J.B. Clément, 93430 Villetaneuse, France*
URL: www-lpmtm.univ-paris13.fr e-mail: *salima.bouvier@lpmtm.univ-paris13*

ABSTRACT: Recently, a combination of a texture based yield locus and of the Teodosiu's hardening model has been implemented in the Finite Element code LAGAMINE of the department M&S of the University of Liège. The yield locus is able to take into account the texture updating during a FE simulation. The texture evolves with respect to the crystalographic rotations due to the plastic deformations. Two hardening models are considered: the classical Swift istropic hardening model and the Teodosiu's hardening model that is a physically-based microstructural model. It takes into account intergranular heterogeneity due to the evolution of dislocation structures, that affects the isotropic and the kinematic hardening. The aim of the paper is to compare the influence of the hardening with the influence of the yield shape updating due to the texture evolution, on the final plastic anisotropy, for a deep drawing simulation. The tests are performed for the steel FeP06t that presents a non negligible initial anisotropy.

Key words: Steel Anisotropy, Texture Evolution, Microstructure-based Hardening Model, Deep Drawing.

1 INTRODUCTION

In view to perform accurate finite element simulations of sheet metal forming, sufficiently developed constitutive description of anisotropic materials is required. From a numerical point of view, the plastic anisotropy results from the shape of the yield locus that depends on the crystallographic texture, from the yield locus size or isotropic hardening which is related to the dislocation density and from the kinematic hardening that changes the position of the yield locus. This last phenomena is associated with the process of dislocation pile-up.

In order to take into account these two behaviours, a combination of a texture based yield locus and of the Teodosiu's hardening model has been implemented in the Finite Element code LAGAMINE of the department M&S of the University of Liège.

The Teodosiu's hardening model (C. Teodosiu (1995), S. Bouvier (2002)) is a physically-based microstructural model. Basically, it is able to describe both kinematic and isotropic hardening taking into account the influence of the dislocation structures and their evolutions, at a macroscopic scale. It allows to describe complex hardening behaviours induced by strain-path changes. The classical Swift isotropic hardening is also available, to be able to isolate the influence of the size and of the position of the yield locus.

The description of the yield locus is based on the texture via the Taylor's model. An original local description called MINTY has been developed by L. Duchêne (2003,2004). It presents the advantage to be able to take into account the texture updating during a FE simulation, without dramatic computation time. The texture evolves with respect to the crystalographic rotations due to the plastic deformations.

The aim of this paper is to compare the influence of the hardening with the influence of the yield shape updating due to the texture evolution, on the final plastic anisotropy induced by forming processes, for a deep drawing simulation. The tests are performed for the FeP06t steel that presents a non negligible initial anisotropy.

2 DESCRIPTION OF THE MODELS

2.1 Hardening model

The model is described by 13 material parameters $C_p, C_R, C_{Sd}, C_{SL}, C_X, R_{Sat}, S_{sat}, X_0, Y_0, f, r, n, n_L$ and depends on four state variables :

$$\mathbf{P}, \mathbf{S}, \mathbf{X}, R \qquad (1)$$

The variable $\mathbf{P}$ is a second order-tensor that depicts the polarity of the persistent dislocation structures (PDSs in S. Li and al. 2003) and $\mathbf{S}$ is a fourth-order tensor that describes the directional strength of the PDSs. The scalar R represents the isotropic hardening due to the randomly distributed dislocations and the second-order tensor $\mathbf{X}$ is the back stress. These state variables evolve with respect to the equivalent plastic strain rate $\dot{p}$ with the form $\dot{Y} = f(Y)\dot{p}$. A precise description of these evolution equations can be found in Salima and al. (2002). The yield condition is given by

$$\bar{\sigma} = \sigma_y = Y_0 + R + f\,|\mathbf{S}| \qquad (2)$$

where $\bar{\sigma}$ is the equivalent stress, function of $\boldsymbol{\sigma} - \mathbf{X}$, σ_y is the current elastic limit, Y_0 is the initial size of the yield locus and $R + f\,|\mathbf{S}|$ represents the isotropic hardening. The expression of $\bar{\sigma}$ depends on the definition of the yield locus.

On the other side, the expression of the Swift isotropic hardening is the classical one

$$\sigma_y = C\left(\varepsilon_0 + p\right)^n \qquad (3)$$

where p is cumulated equivalent plastic deformation, and C, ε_0 and n the material parameters.

2.2 Anisotropic yield locus

The yield locus developed by L. Duchêne during his Ph.D. thesis (2003) is called Minty. The interpolated yield locus (or local yield locus) is based on the following equation written in the 5D deviatoric space:

$$\boldsymbol{\sigma} - \mathbf{X} = \tau\ \mathbf{C}\mathbf{u} \qquad (4)$$

where $\boldsymbol{\sigma}$ is the computed yield stress, $\mathbf{X}$ the back stress, τ a scalar which is responsible of the isotropic hardening according to the hardening law, $\mathbf{u}$ is the 5D unit plastic strain rate direction for which the corresponding yield stress is investigated. The tensor $\mathbf{C}$ is the interpolation matrix (5x5). It is built on the basis of 5 points on the yield locus that are called the stress nodes. These 5 stress nodes are computed from the Taylor's model. The procedure is the following : 5 plastic strain rate directions $\mathbf{u}$ are chosen advisedly. The Taylor's model is used to compute the 5 corresponding yield stresses. The 5 couples of vectors are the stress nodes which define the vertices of the interpolation domain in the deviatoric stress space and in the plastic strain rate space. The matrix $\mathbf{C}$ can then be computed.

The definition of the equivalent stress is given by

$$\bar{\sigma} = M_{RD}\mathbf{u}^T\mathbf{C}^{-1}(\boldsymbol{\sigma} - \mathbf{X}) \qquad (5)$$

where M_{RD} is a proportionality coefficient such that $\bar{\sigma} = \sigma_{RD}$ for a tensile test in the rolling direction.

With this method, only a small part of the yield locus is known thanks to the $\mathbf{C}$ matrix. If another part of the yield locus is explored, a new matrix must be computed on the basis of new stress nodes computed by the Taylor's model.

This interpolation model is exactly in agreement with the Taylor's model only at the vertices of the domain (the stress nodes). Inside the domain, the model is only an approximation. It should be noted that the model does not define a plane (linear interpolation in Cartesian coordinates). It should rather be regarded as a linear interpolation in polar coordinates. If the Taylor's model is replaced by the Von Mises model, the yield locus would be an hypersphere in the 5D space and the interpolation model would be exactly superimposed to the hypersphere inside the domain, not only at the vertices.

The size of the interpolation domain is a very important parameter. A too large interpolation domain reduces the accuracy. On the contrary, a too small interpolation domain must be frequently updated because a new $\mathbf{C}$ matrix must be frequently computed, as the stress evolves and the computation time becomes prohibitive. The size of the domain is defined as the angle between the stress nodes. During deep drawing simulations, a size of 5° is generally used. It is a good compromise between accuracy and computation time. When texture evolution induces an updating of the yield shape, only the five stress nodes are computed by the Taylor's model to modify the yield locus.

2.3 Parameters fitting

The hardening parameters are generally fitted for a Von Mises yield locus. In the case of anisotropic yield locus, the elastic limit is not the same for a tensile test than for a shear test. However, the equivalent stress $\bar{\sigma}$ is defined such as $\bar{\sigma} = \sigma_{11}$ in the case of a tensile test. Because the Teodosiu's model parameters are fitted on Baushinger or orthogonal (tensile+shear) tests, a corrected factor k is introduce such that $k\bar{\sigma}_{VM} = \bar{\sigma}_{MINTY}$ for a pure shear stress state. The definition of the equivalent plastic strain rate is modified in the same way $\dot{p}_{VM} = k\dot{p}_{MINTY}$ such that the plastic dissipation power remains the same: $\dot{w} = \bar{\sigma}_{VM}\dot{p}_{VM} = \bar{\sigma}_{MINTY}\dot{p}_{MINTY}$. Subsequently, in an evolution equation of the form $\dot{Y} = C_Y\left(Y - Y_{SAT}\right)\dot{p}$, the hardening parameters C_Y and Y_{SAT} are multiplied by the factor k.

2.4 Implementation

From a FE point of view, three points must be noted. First, the constitutive equation is integrated in a local frame, at a constant and symmetric velocity gradiant so that Jauman corrections are not needed and the tensoriel state variables are always expressed in the local axes. Secondly, the integration shame is performed using a full implicit return radial method. Thirdly, the analytic tangent elastoplastic stiffness matrix is available.

3 DEEP DRAWING PROCESSES

3.1 Tests performed

The geometry of the deep drawing process is the one proposed by Li et al. (2001). It consists in an axisymmetric deep drawing process with a punch having a flat bottom. The diameter of the blank is 100mm, the punch diameter is 50mm (the drawing ratio is then 2.0), the punch fillet radius is 5mm, the matrix opening is 52.5mm and the matrix fillet radius is 10mm. The blankholder force is prescribed to 5 kN. The Coulomb friction coefficient between the blank and the tools obtained by the experimental lubrication method is μ=0.05. The punch travel is not stopped before the whole blank has passed along the matrix curvature. The flat part of the deformed cup which is clamped between the blankholder and the matrix is not present at the end of the process. The geometry is axisymmetric; but, as the steel sheet is orthotropic, a quarter of the process is considered. The sheet is meshed with a single element layer as shown in Figure 2.
The material studied is a FeP06T steel. The initial anisotropy is described hereafter by the Lankford coefficients

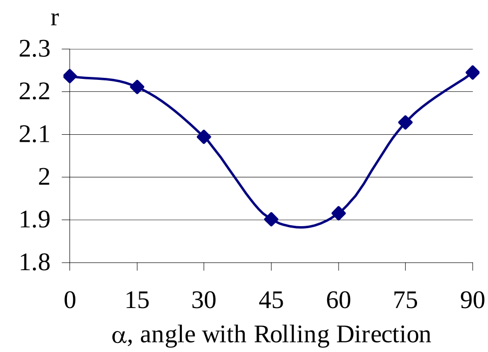

Fig. 1. Lankford coefficient computed from initial texture and the Taylor's model – steel FEP06T

Four tests are performed, using the Minty yield locus with or without texture updating, combined with two hardening models: isotropic Swift hardening for which the parameters values are $C = 530.4$, $\varepsilon_0 = 0.002524$ and n=0.277; Teodosiu's hardening model for which the parameters values are $C_p = 3.5$, $C_R = 50.8$, $C_{SD} = 6.9$, $C_{SL} = 6.67$, $C_X = 145.1$, $f = 0.859$, $n = 1.0$, $n_p = 48.9$, $r = 8.5$, $Y_0 = 114.9$ MPa, $R_{sat} = 29.7$ MPa, $S_{sat} = 245.8$ MPa, $X_0 = 16.0$ MPa.

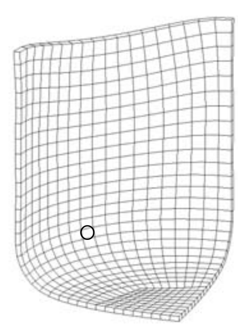

Fig. 2. Deep drawing simulation: final shape of the blank and identification of studied element.

3.2 *Results*

At the end of the process, anisotropy is estimated by the Lankford coefficients $r(\alpha)$ (Figure 3), for an element chosen such that it is in the lower vertical part of the cup at the end of the process (Figure 2). The black curve "EVOL_SWIFT" represents the initial anisotropy since it corresponds to a simulation without texture updating or kinematic hardening. Moreover, the earing profiles at the end of the process are exhibited in Figure 4.

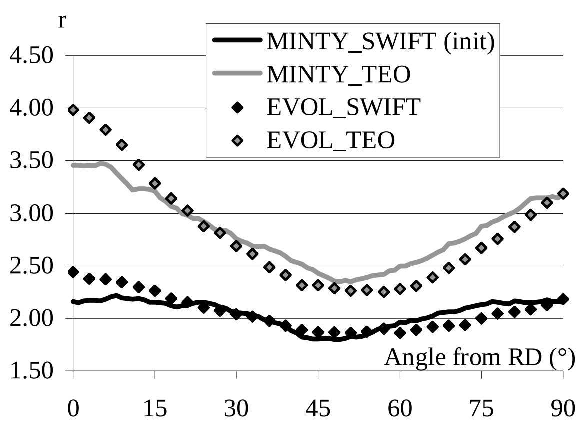

Fig. 3. Description of the final anisotropy by the Lankford's coefficients.

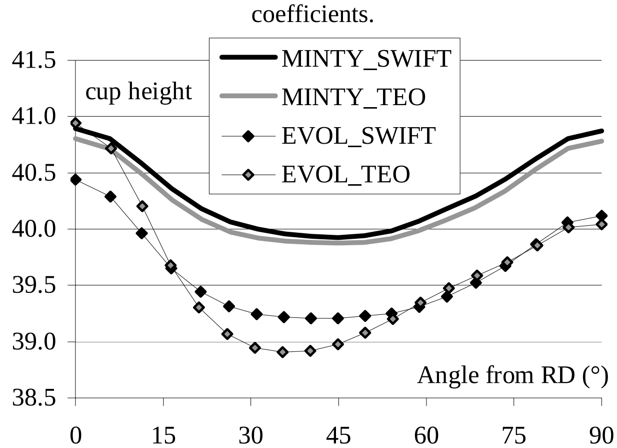

Fig. 4. Earing profile at the end of the process.

Figure 3 shows that the hardening model has a great influence on the final anisotropy of the material, compared with the updating of the shape of the yield locus from the texture evolution. At the contrary, the macroscopic anisotropic behavior of the forming process (Figure 4) is not so much influenced by the hardening (a similar result was observed by S. Li and all (2001)), except in the case where the yield shape is updated during the process.

These simulations have been performed using the parallelized code, on a SG3800, 64 processors machine. With four processors, a typical time length for an application is 30 hours.

4 CONCLUSIONS

The mean result presented in the paper concerns the achievement of a deep drawing numerical simulation coupling anisotropic yield locus based on texture evolution and microstructure-based hardening model. Further analysis and different material testing should give interesting results.

ACKNOWLEDGEMENTS

As Senior Research Associate of National Fund for Scientific Research, AM Habraken thanks this Belgian research fund for its support. This work has been performed in the programme "Belgian Science Policy", IAP 5/08. The authors are as well grateful to Saiyi Li and Shen He of the KUL for the texture database.

REFERENCES

1. S. Bouvier, C. Teodosiu, H. Haddadi and V. Tabacaru, Anisotropic Work-Hardening Behaviour of Structural Steels and Aluminium Alloys at Large Strains, In: *Proc. of the Sixth European Mechanics of Material Conference (EMMC6)*, S. Cescotto Eds (2002)329-336.
2. C. Teodosiu and Z. Hu , Evolution of the intergranular microstructure at modarate and large strains: modelling and computational significance, In: *Proc. NUMIFORM 95*, S.F Shen and P.R. Dawson Eds (1995) 173-182.
3. S. Li, E. Hoferlin, A. Van Bael, P. Van Houtte and C. Teodosiu, Finite Element Modeling of Plastic Anisotropy induced by Texture and Strain-path Change, *Int. J. of Plasticity* 19 (2003) 647-674.
4. L. Duchêne, FEM study of metal sheets with a texture based, local description of the yield locus, *Ph. D. Thesis*, Ulg, Liège, Belgium (2003).
5. A.M. Habraken and L. Duchêne, Anisotropic elasto-plastic finite element analysis using a stress-strain interpolation method based on a polycrystalline model, *Int. J. of Plasticity* (2004), to appear.
6. L. Duchêne, A. Godinas, S. Cescotto and A-M. Habraken, Texture Evolution during Deep-drawing Processes, *J. of materials Processing Technology,* 125-126(2002)110-118.
7. P. de Montleau, L. Duchêne, P. Flores and A-M. Habraken, Numerical shear tests for different elasto-plastic laws, *COMPLAS 2003*, Barcelone (2003).
8. S. Li, E. Hoferlin, A. Van Bael and P. Van Houtte, Application of a texture-based plastic potential in earing prediction of an IF steel, *Advanced Engineering Materials*, 3, N°12 (2001) 990-994.
9. P. Flores, L. Duchêne and A-M. habraken, Texture Analysis of Cylindrical Cup during Deep Drawing Process, In *Numisheet2002* , 1 (2002) 605-611.