Int J Mater Form (2008) Suppl 1:5–8
DOI 10.1007/s12289-008-0058-4

An inverse analysis approach of the Erichsen test starting from a finite element model

A. Gavrus[1], M. Banu[2], E. Ragneau[1], C. Maier[2], V. Oleksik[3]

[1]LGCGM, INSA de RENNES – 20 Av. des Buttes de Coesmes, 35043 RENNES Cedex, France
URL: www.insa-rennes.fr e-mail: adinel.gavrus@insa-rennes.fr

[2] UNIVERSITY "Dunarea de Jos" of GALATI- 111 Str. Domneasca, 80008 Galati, Romania
URL: www.ugal.ro e-mail: mihaela.banu @ ugal.ro

[3] ULBS, UNIVERSITY "Lucian Blaga" of SIBIU, 2-4 Emil Cioran , 550025, Sibiu, Romania
URL: www.ulbsibiu.ro e-mail: valentin.oleksik@ulbsibiu.ro

ABSTRACT: During the deep drawing process the deformation history is different as compared to the tensile one where the constitutive equation can be identified only for small values of the plastic strain. More accurate values of the constitutive parameters can be obtained using the Erichsen drawing test. In this work we propose to use the inverse analysis principle to identify the rheological parameters directly from the Erichsen test. Results obtained for classical steel will be analyzed using an identification numerical high board (OPTPAR) automatically coupled with a commercial finite element code charged to simulate numerically the experimental test. Application to a DC03 sheet steel alloy will be presented.

Key words: Deep Drawing Process, Finite Element Model, Inverse Analysis, Erichsen Test

1 INTRODUCTION

The deep drawing process is one of the most important sheet metal forming process [1]. Erichsen test is a very popular test which gives an excellent account of current metallurgical practice in producing pressed and deep drawn components. In order to understand the whole complexity of the process and to optimize the forming conditions, a numerical modeling must be used [2-4]. This simulation requires available constitutive equations and accurate rheological parameters values that characterize the sheet material behavior. In order to identify the material rheological behavior, the uniaxial tensile test is generally used and the parameters values are obtained approximately by an analytical analysis which uses same restricted hypothesis: homogeneity of the strain and small influence of the necking area [5]. In this case the stress-strain curve is available only for small plastic deformations. Moreover the problem is that during deep drawing process the deformation history is different as compared to the uniaxial tensile one and the constitutive equation can be wrong identified. Generally, for the determination of the sheet metals properties we can use two different experimental tests which as the Olsen and the Erichsen one [6-7]. For the both cases, as an indicator of deformability, it is used the height of drawn sheet by deforming with a spherical punch until the fracture of the material corresponding to a fissure, of a length approximately equal to 5 mm, occurs. In several cases it is recorded the maximal values of the force corresponding to the necking of the sheet. Using the inverse analysis [8-9] of a finite element model more accurate values of the constitutive parameters can be obtained directly from the drawing experimental device like as the Erichsen one. The principal experimental data can be represented by the recordings of the evolution of the drawing force with the depth of the deformed sheet. Results obtained for a classical steel will be presented using an identification high board (named OPTPAR) automatically coupled with a commercial finite element code (FORGE2®) charged to simulate numerically the Erichsen test.

2 EXPERIMENTAL SET-UP

The experimental Erichsen test used in the Europe has a hemispherical punch of steel with the diameter of 20 mm, an active die with the diameter of 27 mm, a restraint plate with the diameter of 33 mm and a blank with the diameter of 90 mm. The radius of the die is 0.75 mm (see Fig 1).

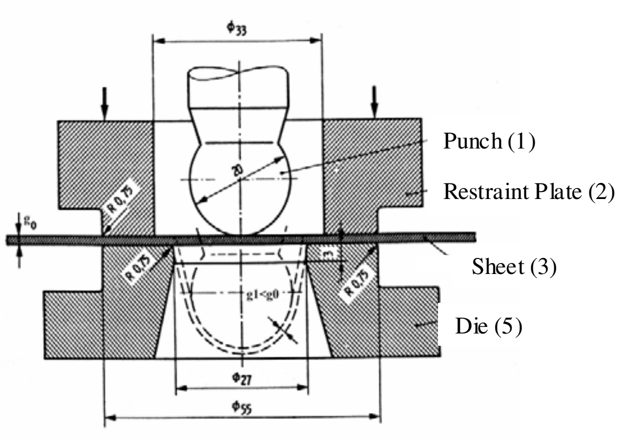

Fig 1: Experimental Erichsen test: axisymmetric view.

In the Erichsen test, a hemispherical punch is pressed into the sheet until fracture occurs, at which point the test is stopped immediately and the depth of the bulge is measured. This depth (mm) gives the *Erichsen indices* and obviously gives a measure of the ductility of the sheet in the plane of drawing under biaxial stress conditions. In a pure stretch forming the sheet is totally clamped and is deformed by the punch. This test is used for comparative purposes of sheet metals. Measurement of the axial punch force variation can be added and considered as the experimental data points.

3 NUMERICAL MODELLING AND ANALYSIS

The experimental device of the Erichsen test can be modeled by the finite element method. We consider a steel sheet with the thickness of 3 mm and diameter of 90 mm. The punch, the restraint plate and the die are considered to be rigid tools and the sheet is meshed using three nodes linear triangular axi-symmetric elements. Remeshing procedure is activated during the process computation in order to eliminate numerical problems linked to the possible appearance of degenerate elements. The contact between the sheet and the restraint plate or the horizontal part of the die is chosen to be glued. Coulomb friction law with a friction coefficient of 0.1 is used between the sheet and the punch or active part of the die.

Considering the rheological law of the sheet material we choose two different descriptions: a Ludwick one (1) and a Voce one (2) (see Fig 2):

$$\bar{\sigma} = \sigma_{00} + K\bar{\varepsilon}^{n} \qquad (1)$$

$$\bar{\sigma} = \sigma_{00} + K\left[1 - \exp\left(-n\bar{\varepsilon}\right)\right]^{n_a} \qquad (2)$$

where σ_{00} is the elastic limit of the equivalent Von-Mises stress, K is the hardening stress and n is the hardening parameter.

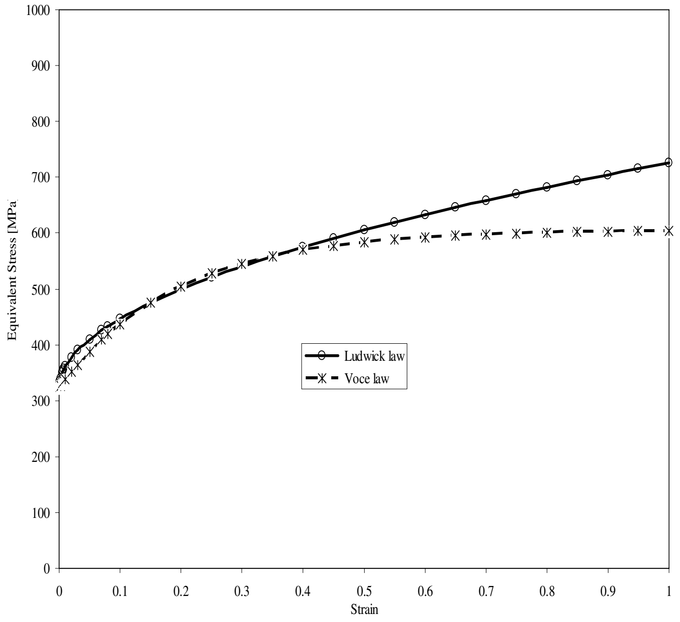

Fig2: Rheological laws used for the numerical simulation

The values of the elastic material properties and of the plastic parameters are presented in the Table 1.

Table 1: Steel sheet material properties ($n_a = 1$)

Elastic Properties	E	υ	μ
	210000 MPa	0.3	0.1
Plastic Parameters	σ_{00}	K	n
Ludwick Law	324 MPa	401.76 MPa	0.514
Voce Law	324 MPa	281.46 MPa	5.14

Numerical simulation was made with FORGE2 (using an initial number of 947 elements) code and the MARC code (using an initial number of 346 elements). Results of the deformed mesh and of the equivalent plastic strain distribution, after 18 mm of the punch displacement, are pictured in Fig. 3.

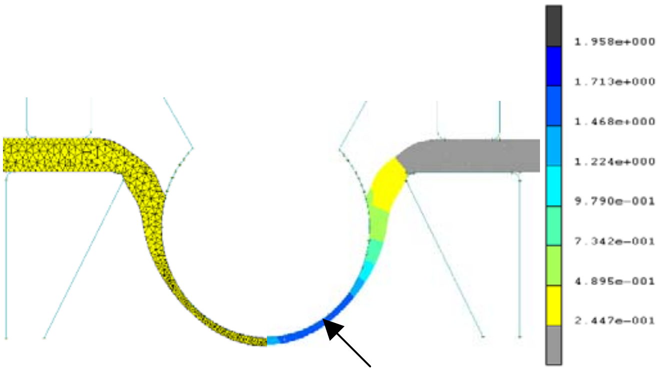

Fig 3: Numerical finite element results with MARC
(Mesh and cumulated plastic strain corresponding to t =18 s)

Similar results are obtained with the both numerical codes that confirm the availability of the numerical process description. It is possible to observe that necking phenomena occurs at approximately 30 degree under the punch. Moreover large values of the cumulated plastic strain are obtained (up to 150%) which allows to analyze the deformation history in conditions closed to the real stamping process. Results considering the variation of the axial punch force are plotted in Figure 4.

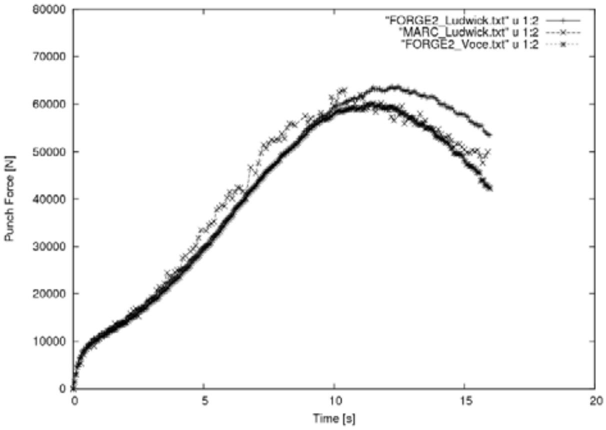

Fig 4: Results of axial punch force variation

These results show that we obtain similar shape curve between the FORGE2 code and the MARC one. The small differences are caused by the numerical treatment of the contact phenomena because different methods are used to regularize numerically the Coulomb law. Concerning the influence of the material rheological law we obtain a more pronounced softening with the Voce stress-strain curve. Using the extrapolation values for the stress from a classical Ludwick law can causes several problems in estimating of the process forces or of the deformation energies.

4 PARAMETER IDENTIFICATION BY INVERSE ANALYSIS

Accurate values of the constitutive parameters behavior can be obtained by an inverse analysis. The experimental data can be represented by the recordings of the evolution of the drawing force with the depth of the sheet [Fig. 4]. The identification of the material coefficients is performed with a finite element simulation of the Erichsen test using an optimization procedure (OPTPAR). The least squares cost function is expressed in terms of the experimental forces and of the numerical ones:

$$\Phi\left(P, F^{c}, F^{\exp}\right)=\frac{\sum_{i=1}^{N\exp}\left[F_i^{c}-F_i^{\exp}\right]^2}{\sum_{i=1}^{N\exp}\left[F_i^{\exp}\right]^2} \qquad [3]$$

where P is the parameter vector: $P=\{K,n\}$, *Nexp* is the number of the experimental points, F^c is the finite element computed punch forces and the F^{exp} is the corresponding experimental data. For a rheological identification problem an appropriate physical domain of parameters variation must be introduced and an optimization problem is obtained:

$$\begin{cases}\min\limits_{P\in D(P)} \Phi(P, F^{c}, F^{\exp}) \\ D(P)=\left\{P / P_{\min} \leq P \leq P_{\max}\right\}\end{cases} \qquad [4]$$

The high nonlinearity of the objective function requires a robust numerical minimization algorithm based on the Gauss-Newton gradient method. In this case the evaluation of the first and second objective function derivatives are required. A direct differentiation method is used to compute the derivatives of the computed forces with respect to the constitutive parameters. To test the numerical convergences of the inverse analysis procedure, an artificial experimental data, based on the constitutive parameter values presented in Table 1, is used. The goal of convergence analysis is to verify the capacity of the identification algorithm to find the true rheological parameters starting from different initial estimations. The optimization procedure is started for the both laws using initial values sufficiently far from the real ones [see the Table 2].

Table 2: Numerical identified results obtained from a FORGE2 numerical finite element model

Parameters	Ludwick Law		Voce Law	
	Initial	Identified	Initial	Identified
σ_{00}	324.	324.	324.	324.
K	1000.	401.74	100.	281.38
n	0.1	0.514	10.	5.147
Φ	103%	0.004%	27%	0.07%
iterations	-	11	-	9

5 APPLICATION TO A REAL DATA

In order to test the inverse analysis of the Erichsen test in real conditions, a rheological parameter identification is made for a steel alloy DC03 with the initial thickness of 1 mm. The friction phenomenon and Coulomb parameter it is considered to be a priori know (μ = 0.1). The parameter identification analysis is presented in Table 4.

Table 4: Numerical parameter identification results

Parameters	Ludwick Law		Voce Law (n_a =1)	
	Initial	Identified	Initial	Identified
σ_{00}	150.	154.17	154.17	154.17
K	500.	516.52	500.	484.33
n	0.25	0.61	10.	2.47
Φ	19.8%	1%	34.7%	2.7%
iterations	-	6	-	4

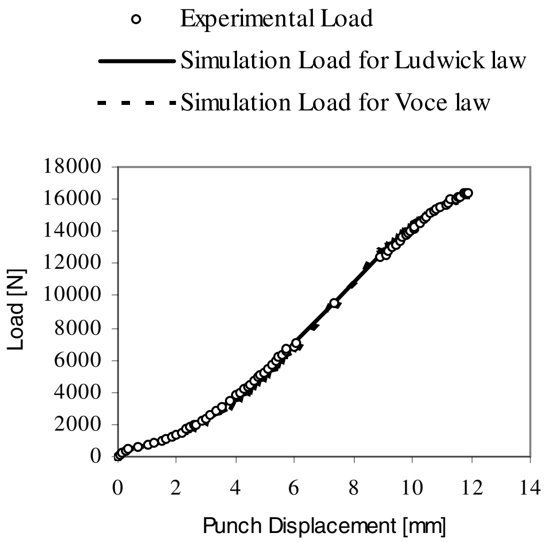

Fig. 5: Comparison between experimental and computed axial punch forces for the identified rheological laws.

The mesh of the numerical model has approximately 853 elements. The comparison between the experimental and computed loads is plotted in Fig 5.

6 CONCLUSIONS

The standard and advanced characteristics of the Erichsen test for sheet drawing analysis and also for stamping process optimization has been used to identify the rheological parameters. The main feature of this identification methodology is linked to the possibility to take into account the all complexity of the test. The finite element model permits to simulate the biaxial stress conditions together with a non-uniform distribution of the plastic strain and of the sheet thickness. It is then possible to obtain close deformations conditions as those which occur during a real stamping process.

ACKNOWLEDGEMENTS

The present project was elaborated until the bilateral research contract between INSA de RENNES - France and UNIVERSITY “Dunarea de Jos” GALATI – Romania and supported in financial terms by the research contracts CEEX 22/2005 and CEEX 24/2006.

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