THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAŢI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 1221- 4566, 2009

EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF ERICHSEN TEST. APPLICATION TO IDENTIFICATION OF SHEET METALLIC MATERIAL BEHAVIOUR

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ABSTRACT

This paper proposed a method for determining the plastic behavior for the metal sheets based on inverse analysis. The identification of the material coefficients is performed with a finite element simulation using a minimization procedure starting from a least squares cost function expressed in terms of the experimental forces and of the numerical ones. In fact, the input data for the automatically identification is: the geometrical model, the mathematical form of the flow curve equation and the force-displacement curve obtained experimentally. The output data represented the parameters which defined the material flow curve.

KEYWORDS: inverse analysis, numerical simulation, Erichsen test

1. INTRODUCTION

The design and monitoring of industrial material processes depends on the degree of accuracy of material characteristics, of the conditions that may arise from the interface between tool and product, of the plastic deformation phenomena, of the equipment and technology used and of the conditions imposed to the final product [1, 2]. These factors influence the choice of the tool geometry, the material of the product, and the conditions of plastic deformation: speed, temperature, stresses and degree of the plastic strain developed in the piece and in the tools. Achieving performances raised and extending enforceability processes of plastic deformation require continuous development of research in this field and a well knowledge of all operating parameters [3-5].

The proposed work introduces a new method for determining the plastic constitutive behavior of metallic materials. The main idea is to apply this new method in industry improving the practical knowledge required to industrial implement. This method based on the Inverse Analysis [6] requires a finite element model in order to simulate the plastic deformation process. In parallel with the numerical model, undergoing similar condition that the physical one, an optimization algorithm finds the correct parameters values which minimizes the numerical response of the finite element model and the response of the physical one. The constitutive parameter identification principle is then to determine the coefficients of the material behavior that decreases the "cost" function which expresses the difference between the numerical values of global responses and the measured ones.

In fact, in a first step, this paper proposes to compute all the rheological characteristics of the sheet material starting from conventional tensile tests, using a combined optical extensometer to perform the anisotropy of the material [7, 8]. In a second step, the sheet behavior will be analyzed using the Erichsen test [9, 10].

The material parameters resulting from the analysis of the tensile test will be the input data for a finite element simulation of the test [11, 12]. Numerical simulation of the Erichsen test will be add together with experimental recording of the force-displacement curve and of the deformation immediately before the occurrence of the material failure. Since the numerical simulation results and those obtained experimentally have some differences, an inverse analysis must be used to minimize the differences between the force-displacement curves [13, 14]. Then will be identified more precisely the parameters of the material flow curve: K – the strength coefficient and n – the hardening coefficient. Anisotropic coefficients determined from the tensile test will remain unchanged.

2. COMPUTATION OF PLASTIC MATERIAL PARAMETERS FROM TENSILE TESTS

The most used method for the sheet material testing is the uniaxial tensile one [8]. The sample is fixed at the both ends and deformed at a constant speed until the failure occurs. The applied force is measured using a load cell and the plastic strains are measured using an optical extensometer. The obtained data can be represented graphically as the force-displacement coordinates. However, they are generally converted into the true stress - strain curves. In addition, for determination of deformability, the normal practice is to measure the width of the sample during the test. This is measured either intermittently by stopping the test or either continuously with an extensometer. To determine the material data, a tensile device type INSTRON 5587 (fig. 1) is used and the experimental protocol is based on the following steeps:

- were chosen two types of materials: a DC04 sheet with a thickness of 0.4 mm and a DC02 one with a thickness of 0.8 mm;

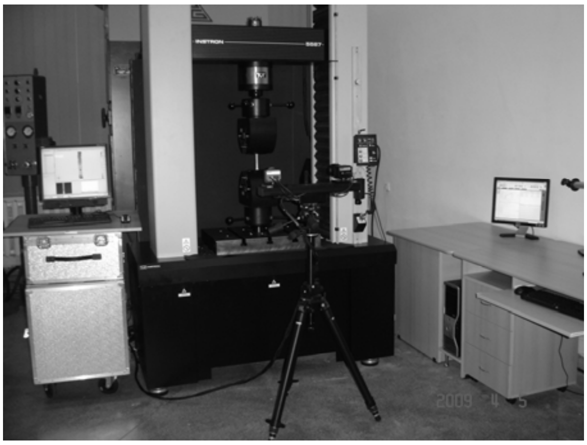

Fig. 1. Experimental layout

- have made a set of five samples for each thickness of material. Due to the variation of properties, depending on the direction with respect to the rolling one, the samples are done in the longitudinal direction (parallel to the rolling direction of the sheet), transverse (perpendicular to the direction of plate rolling) and oblique (inclined at 45^0 from the direction of plate rolling). Shape and size of the specimens are taken in accordance with SR EN 10002-1/1995.
- testing method uses the language's own machine according to the INSTRON type one and will be established at this stage: the type of the test (traction), the material (specimen geometry, thickness of the material, the width of the sample, the distance between the landmarks which defines the measurements), the tensile speed, the limits values, the rate of the experimental acquisition (200 points/s), the type of the output file (ASCII or DIFF, a file format that can be retrieved by any programs for statistical data processing) and the type of the output data to be collected;
- the output data are: the longitudinal modulus of elasticity or the elastic shear modulus, maximum stress of the material, relative elongation corresponding to the maximum stress in the material, K_Y – the strength coefficient and n – the strain hardening exponent;
- outside the data specified above, is used an optical extensometer system ARAMIS which permits to measure the displacements of a diffuse points of the sample (fig. 2). It is then possible to compute the strains values and the corresponding principal values.

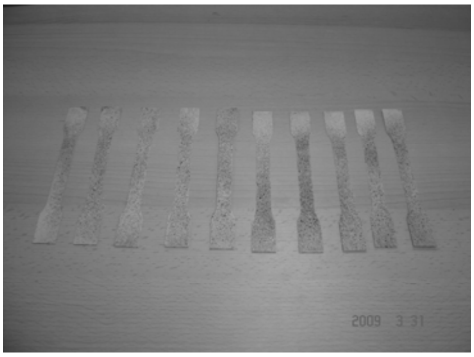

Fig. 2. The prepared specimens which have the useful part defined by L = 75 mm and l = 12.5 mm

In Figures 3 and 4 are shown curves of true equivalent stress – true plastic strain obtained from the tensile tests, at the direction parallel to the rolling one, for the sheet with the thickness of 0.4 mm (fig. 3) and for the sheet with the thickness of 0.8 mm (fig. 4).

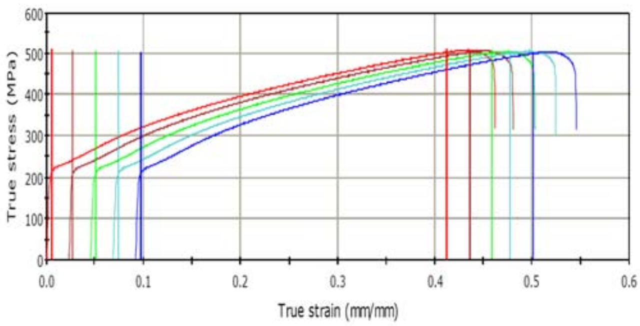

Fig. 3. The stress-strain curve for DC04 sheet steel

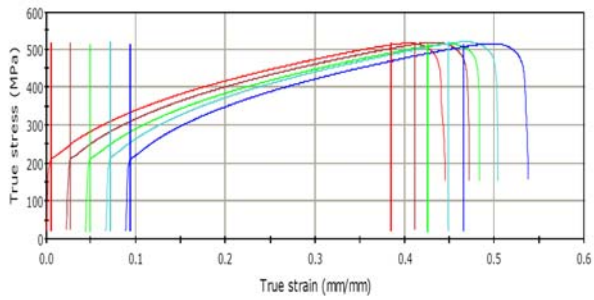

Fig. 4. The stress-strain curve for DC02 sheet steel

For a classical hardening exponential law, the stress of the plastic flow is defined by the following Swift relationship:

$$\sigma_Y = K_Y(\varepsilon_0 + \varepsilon)^n \qquad (1)$$

where K_Y is the strength coefficient, ε_0 is appropriate initial elongation corresponding to limit of elasticity, ε is the corresponding plastic strain and n is the hardening coefficient.

Concerning the ε_0 value, it can be computed from the Yield tensile stress σ_{00} using the formula:

$$\varepsilon_0 = \left(\frac{\sigma_{00}}{K_Y}\right)^{1/n} \qquad (2)$$

All the material parameters were computed from the INSTRON software and are presented in the Table 1 and the Table 2.

Table 1. The material characteristics obtained by uniaxial tension test for DC04 sheet steel

Specimen no.	G Shear modulus	Yield Tensile stress	Maximum Tensile stress	Tensile strain at Maximum Tensile stress	n Strain Hardening Exponent	K_Y Strength Coefficient
	[MPa]	[MPa]	[MPa]	[%]	-	[MPa]
1	73533,1	208,7	335,5	42,3	0,248	591
2	74384,9	207,9	335,8	42,05	0,248	591
3	75872,2	206,1	335,4	41,55	0,248	590,6
4	73122,1	204,7	334,8	41,55	0,249	589,9
5	76671,5	205,8	334,7	41,75	0,249	589,1
Average	**74716,76**	**206,64**	**335,24**	**41,84**	**0,2484**	**590,32**

Table 2. The material characteristics obtained by uniaxial tension test for DC02 sheet steel

Specimen no.	G Shear modulus	Yield Tensile stress	Maximum Tensile stress	Tensile strain at Maximum Tensile stress	n Strain Hardening Exponent	K_Y Strength Coefficient
	[MPa]	[MPa]	[MPa]	[%]	-	[MPa]
1	67565,8	205,9	350,9	38,55	0,254	626
2	71332,6	205,7	350,2	39,05	0,252	622,7
3	68037,3	206,8	349,3	38,75	0,249	618,7
4	65214,6	207,8	353,7	38,55	0,25	627,9
5	67554,3	205,9	349,2	37,55	0,249	618,2
Average	**67940,92**	**206,42**	**350,66**	**38,49**	**0,2508**	**622,7**

Starting from the experimental data a Ludwick law has been identified. The mathematical form of this law is the following:

$$\sigma_Y = \sigma_{00} + K\varepsilon^n \qquad (3)$$

Parameters obtained from the software OPTPAR are presented in the Table 3.

Table 3. The material characteristics obtained from OPTPAR for the Ludwick law

Specimen Sample no 1	σ_{00} [MPa]	K [MPa]	n	R^2
DC04	208.97	542.8	0.67	0.99
DC02	204.34	569.3	0.62	0.99

In order to determine the material anisotropy, was used an optical measurement system ARAMIS. It allows the principal strains values and the Von Mises plastic strain ones, and, if the test allows a real-time transmission of the loads, it can be determined the corresponding Von Mises stress values. In Figures 5 ... 8 are presented the minor and the major strains immediately before the failure of the specimen.

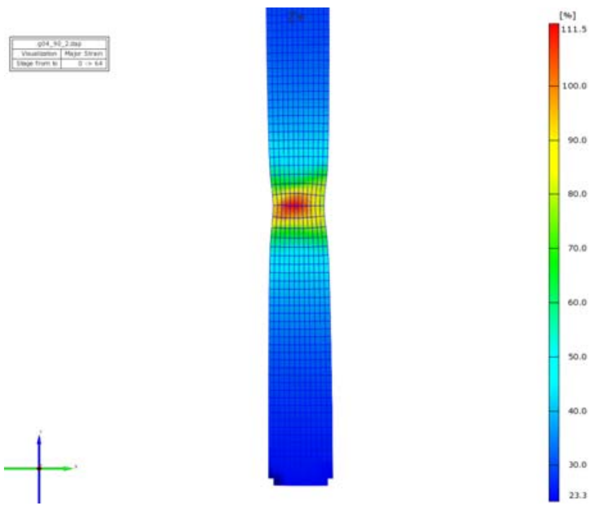

Fig. 5. Major strain for g = 0,4 mm

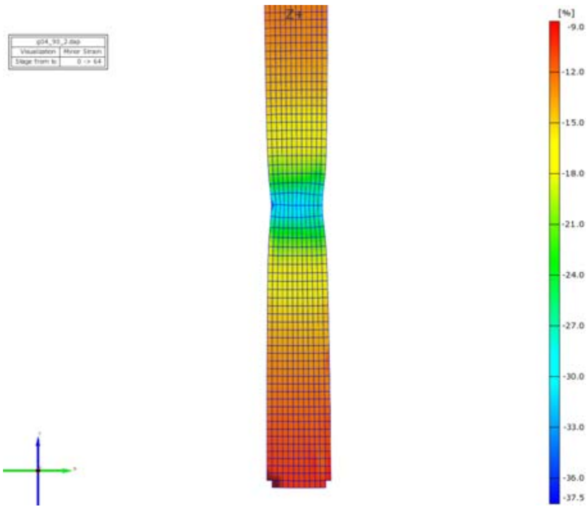

Fig. 6. Minor strain for g = 0,4 mm

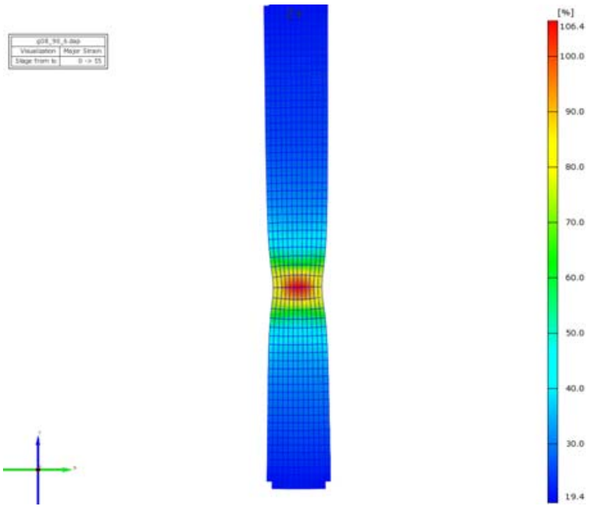

Fig. 7. Major strain for g = 0,8 mm

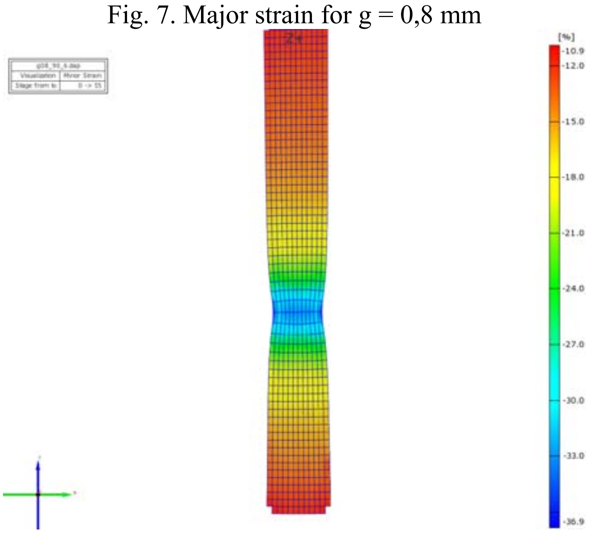

Fig. 8. Minor strain for g = 0,8 mm

After calculating the anisotropic coefficients were obtained the following results. For the plate with g = 0.4 mm: R_{00} = 0,92; R_{45} = 0,87; R_{90} = 0,9, $\overline{R} = 0.815$, $\Delta R = 0.02$ and for the plates with g = 0.8 mm we have R_{00} = 0,98; R_{45} = 0,94; R_{90} = 1,07, $\overline{R} = 0.98$, $\Delta R = 0.04$. Because the values of $\overline{R}$ are close to 1 and of ΔR close to 0, it can be concluded that anisotropy can be neglected and all the sheets can be considered to be isotropic.

3. EXPERIMENTAL ANALYSIS OF THE ERICHSEN TEST

The Erichsen test is widely accepted in the industrial world to determine the drawing ability of thin metal sheets [10]. The material is deformed using a hemispherical punch pressed into the sheet until material fracture occurs. At this point the test is stopped immediately and the depth of the bulge is recorded. This depth expressed in millimeters obviously gives a measure of the ductility of the sheet under biaxial stress conditions in the plane of the drawing. In a pure stretching forming the sheet is totally clamped. The experimental device (fig. 9) consists of a punch 1, designed so as to be able to be mounted on an INSTRON machine, a port-pill 6, which is attached to the machine layer 7, an active pill 5 and a retention plate 2. The material sheet 3 is clamped between the restrain plate and active pill 5 through the screws 4.

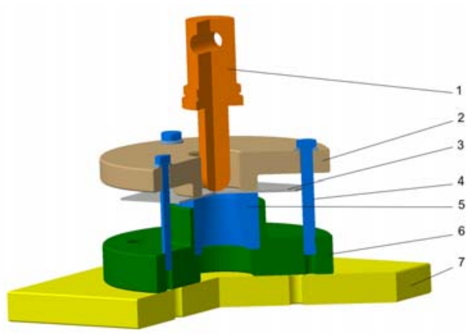

Fig. 9. An isometric view of the Erichsen test

The Erichsen test, used in Europe, has a steel punch with a diameter of 20 mm and an active plate with a diameter of 27 mm and 0.75 mm radius (see Figure 10).

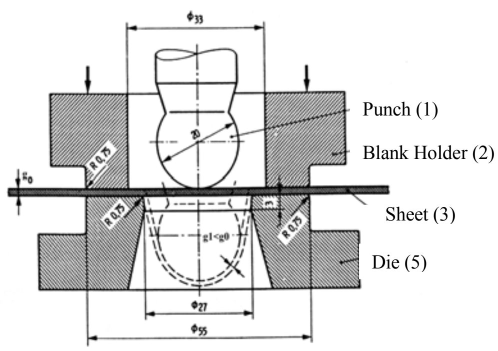

Fig. 10. The dimensions of the Erichsen test

The preferred criterion for determining when the material failure occurs is the maximum load. In order to highlight the peak time of the load, it is necessary to save, for each time, the pair of load-displacement points. Consequently, the Erichsen device was adapted and mounted on the tensile machine INSTRON 5587 (fig. 11).

Fig. 11. The Erichsen device mounted on the INSTRON machine

In all the following experiments were chosen the same two materials with the thicknesses of 0.4 mm and of 0.8 mm. There have been a number of four experiments for each thickness of material. The measured values were: the maximum depth before producing the first cracks, the maximum reached load and the pairs of force-displacement points that have been saved as an ASCII file and used as an input file data in optimization procedure. Figure 12 gives the force-displacement curves for the sample with the thickness g = 0.4 mm. It can be easy to see that the approximate value of the Erichsen Index is IE=8.5 mm.

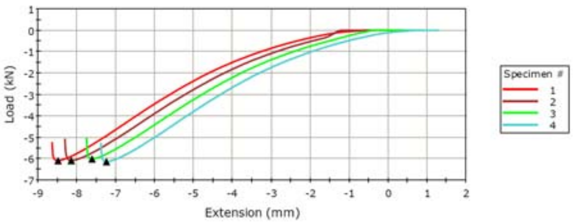

Fig. 12. The load-depth curves for g = 0,4 mm

Next, the sheet sample used in the Erichsen test is measured using an optical system ARGUS (fig. 13). The samples have been drawing with a network of circles with a diameter of 1 mm and with a distance between each one of 3 mm.

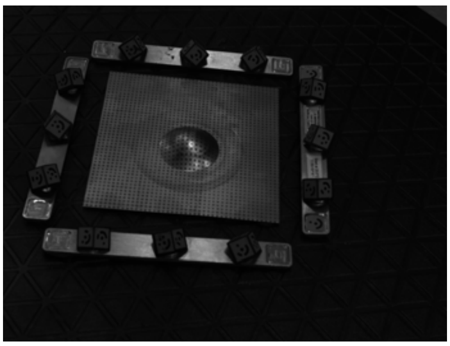

Fig. 13. Measured sheet sample with ARGUS system

In Figure 14 is presented the major principal strain ε_1 for the sheet sample with the thickness g = 0.4 mm.

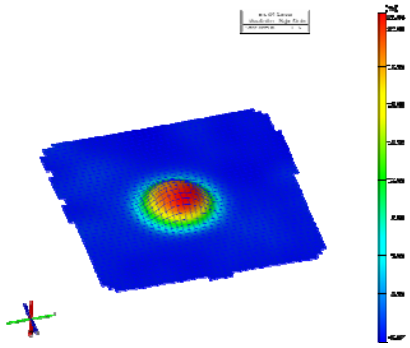

Fig. 14. The major strain corresponding to 7.5 mm displacement of the punch, measured with ARGUS

Concerning the thickness reduction, Figure 15 gives its distribution.

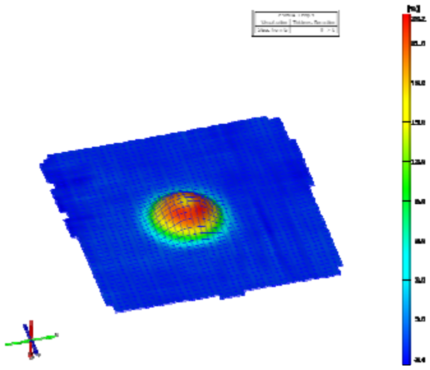

Fig. 15. The thickness reduction corresponding to 7.5 mm displacement of the punch, measured with ARGUS

It can be see that the main deformation is located approximately of 2/3 of crown height

4. NUMERICAL SIMULATION OF THE ERICHSEN TEST

The proposed numerical method is based on three-dimensional modeling of Erichsen test. A finite element model of the Erichsen test allows computing the stresses and the strains and permits to analyze critical issues that may occur during the drawing process [12-14]. The numerical analysis used for simulation in this paper is the LS-DYNA program, specific for cold plastic deformation. To define material properties an elasto-plastic flow law is used according to the Ludwich formulation (3). Active area of the experimental device was modeled numerically to determine the drawing ability. The numerical model of the test consists of a semi-circular thin sheet, sitting on the plate active area and also of a circular punch placed symmetrically and perpendicular to the plate. The network of finite elements, associated to the sheet geometry, is constructed so as to enable an ongoing analysis in good conditions, being required adaptive remeshing to avoid distortions and to minimize the hourglass energy. The used materials characteristics are those obtained from tensile test and have been presented previously. Were run two characteristic analysis of both types and thicknesses sheet. Stress and strains distribution are obtained by numerical simulation that indicates the possibility to obtain an important plastic state of the material (according to Von Mises plasticity criterion) in the punch area. The values of the equivalent stress and cumulated strain are higher in this area.

In Figure 16 is presented the major principal strain corresponding to the sheet thickness of g = 0.4 mm.

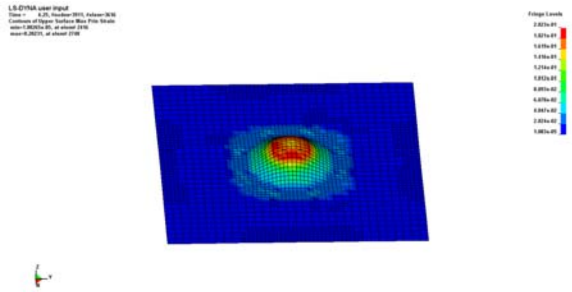

Fig.16. The major strain corresponding to 7.5 mm displacement of the punch, obtained from LS-DYNA

This corresponds to the maximum penetration of the punch before the material failure. The diminution of the sheet thickness is very important and can be shown in Figure 17.

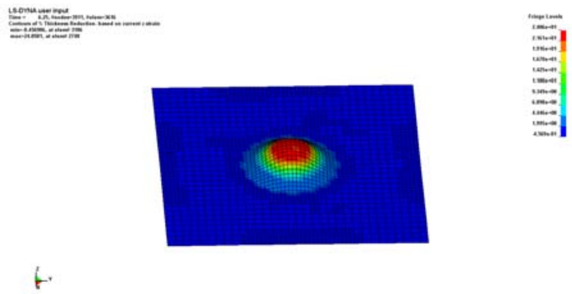

Fig. 17. The thickness reduction corresponding to 7.5 mm displacement of the punch, obtained from LS-DYNA

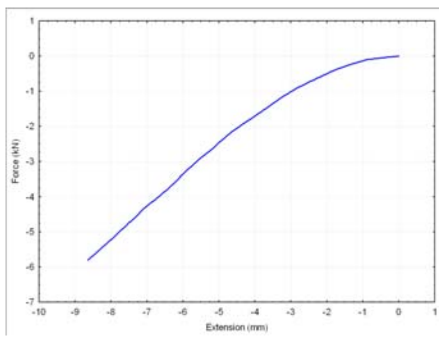

Fig. 18. The load-depth curve for sheet of g = 0,4 mm obtained from LS-DYNA

Compared with the experimental distribution, a good agreement is obtained and it is possible to conclude that the identification method of plastic material properties is correct. Moreover the curve of punch loads variation (pictured in Figure 18) shows a good agreement with the experimental one: IE = 8.5 mm and maximum load before the failure approximately of 6 KN.

5. CONCLUSIONS

In this paper was presented an analysis of steel sheet deformability using the tensile tests and the finite element simulation of the Erichsen test. A method based on inverse analysis has been used to identify all the material parameters. A new experimental technique, based on an optical system, was used to define the anisotropy of the sheet materials and to measure plastic strains and variation of the sheet thickness. In the future this method will be applied to improve the mathematical description of the anisotropy, coupling the tensile tests and the Erichsen ones. The function which must be minimizes by inverse analysis will include simultaneously the loads and the thickness reduction.

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