STATE OF STRESSES PREDICTED BY A NUMERICAL MODEL BASED ON DIFFERENT PLASTICITY CRITERIA

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Abstract: State of stresses within formed parts has a significant influence on their accuracy. The analysis of the stresses distribution may be performed by simulation with finite element method. In order to obtain accurate results, as close as possible to experimental ones, a significant attention should be paid to description of material behaviour into the simulation code, especially when anisotropy is considered. The aim of this paper is to analise the state of stresses within virtual parts obtained when two plasticity criteria are used to describe the material anisotropy in the case of a deep-drawing process. To validate the numerical model an experimental test was performed. The results obtained with the two investigation technics fit well, demonstrating the effectiveness of FEM analysis.
Key words: stresses distribution, plasticity criteria

1. INTRODUCTION

It is well known that the stresses distribution within the formed parts is the main cause of material springback after unloading which, in turn, influence the accuracy of the final parts. In order to investigate the state of stresses of the formed parts, different experimental methods can be used but they are often limited by the part geometry and are costly enough because they impose the use of expensive devices and equipments.
This is why the specialists are using frequently the finite element analysis to study the mechanics of the forming processes and their afferent phenomena. But to attend this task, intensive efforts have been made in order to obtain into a simulation code a descryption as close as possible to reality of the material behavior during the forming process. In this sense, different plasticity criteria were elaborated by specialists [1-7]. Some of these criteria take into account the material anisotropy while others are based on the hypothesis of isotropic material.
The aim of this paper is to analyze the state of stresses within virtual parts obtained when two plasticity criteria - transversal anisotropy of Hill and Ferron's theory of plastic anisotropy – are used to describe the material anisotropy in the case of a deep-drawing process. Further a comparison between numerical and experimental results is made to asses the suitability of the proposed numerical model.

2. SIMULATION OF DEEP-DRAWING PROCESS

2.1 Condition and methodology of simulation

The numerical analysis of the deep-drawing process was performed by using the 3D numerical model presented in figure 1. Analytical rigid surfaces were used to model the punch, die and holder, whose motion was governed by the motion of a single node, known as the rigid body reference node. Therefore, only the sample (200 mm diameter x 0.8 mm thickness) was considered deformable with a planar shell base. The elements used to mesh the sample were of S4R type, with 5 integration points through the sheet thickness.
In order to describe the anisotropic characteristics of the sheet metal into the simulation programme (ABAQUS/Explicit), two criteria of plasticity were used with the help of the VUMAT subroutine: Ferron's criterion and transversal anisotropy of Hill that could be obtained as a particular case of the plasticity criterion proposed by Ferron et al. [8]:

$$g(\theta,\alpha)^{-m} = g(\theta)^{-m} + 2a\,\sin\theta\cos^{2n-1}\theta\cos 2\alpha + b\sin^{2p}\theta\cos^{2q}2\alpha \quad (1)$$

where:
- θ is the polar angle, that define the orientation of the main axes reported to the orthotropic axes;
- α is the rolling direction;
- m, n, p, q are positive constants;
- a, b are adimensional coefficients that characterise the material anisotropy.

The Hill's criterion is obtained for the exponent n, p, q egual with 1. The coefficients which intervene into the equations of the used criterion are given in table 1 and were calculated with the help of the FORTRAN programme, on the base of the anisotropy coefficients experimentally determined.

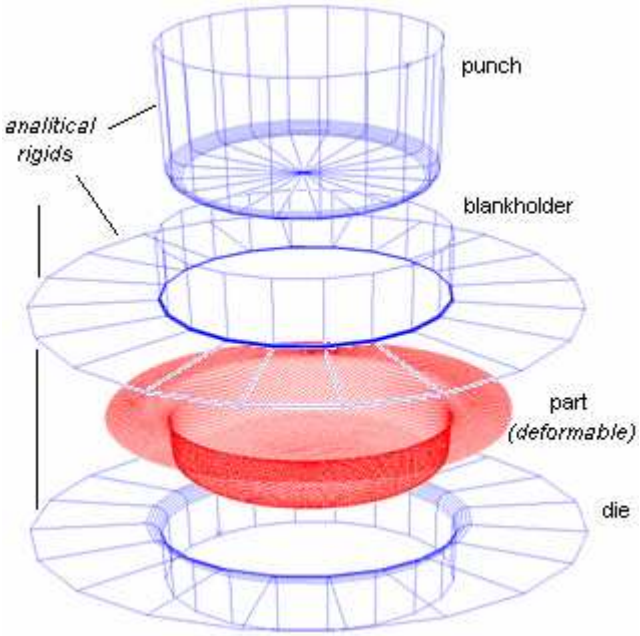


Fig. 1. Numerical model used in simulation

The material used in simulation was FEPO 5MBH steel, whose mechanical characteristics are presented in table 2. They were determined by uniaxial tensile tests on a universal testing machine equipped with Hottinger cell force of 25tf and an electronic data acquisition system - Spider 8. The measurement of specific strains for determination of the stress-strain curve used in simulation (fig. 2) was performed using an uniaxial extensometer and Hottinger electric resistive wire strain gauges.

Data acquisition, processing and visualisation were performed by using the Catman - Professional software. The used rate of data acquisition was of 5 points/sec for a crosshead-rate of 10 mm/min. The specimens were cut as a function of the rolling direction being achieved sets of specimens corresponding to the directions of 0º, 45º and 90° and were worked by milling and grinding in order to obtain the prescribed dimensions. The reference length of the specimen was equal to 50 mm. To obtain a good accuracy of the results, 3 specimens were tested for each determination.

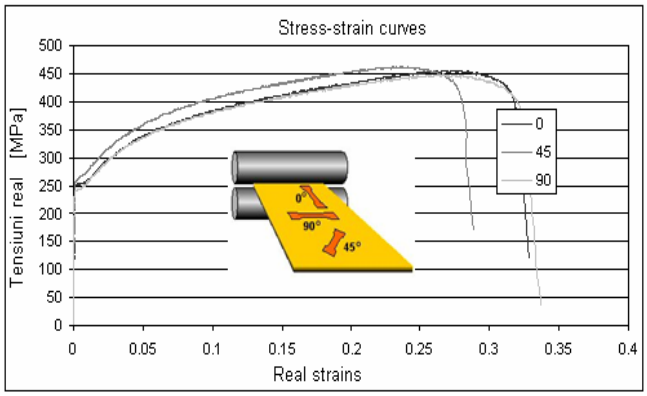


Fig. 2. The stress-strain curves for FEPO 5 MBH steel

Table 1. Coefficients corresponding to the used plasticity criteria

Coefficients	Ferron criterion	Hill criterion
A	2.953	4.128
B	8.859	9
k	0.2	0
m	2	2
n	2	1
p	2	1
q	1	1
a	-0.07264	-0.12848
b	0.87256	0.60729

Table 2. Mechanical characteristics of the FEPO 5MBH steel

Orientation against rolling direction	Young's modulus	Yield strength [MPa]	Total Elongation [%]	Anisotropy coefficient r	Hardening coefficient n
0^o	198000	306	34.7	0.82	0.234
45^o	200000	360	44.1	0.77	0.232
90^o	200000	375	26.1	0.81	0.233

The process parameters used in simulation were as follows: punch velocity = 18 mm/min, the coefficient of friction = 0.1, blankholder force = 25, 50, 75, 100, 125 kN.

3. DISTRIBUTION OF STRESSES WITHIN VIRTUAL PARTS

Because the number of elements used to discretizise the part was very big (9600 elements) it was quite impossible to graphical represent on a clear way the stresses within the formed part. Nevertheless, in order to analise the variation of stresses in the case of using the two plasticity criteria, a median band of the part was chosen (figure 3) and the stresses corresponding to the elements from that area were plotted.

The stresses distribution within virtual parts obtained as result of simulations by using the two criteria of plasticity and the above mentioned process parameters are present in figure 4 (stresses at the end of forming process) and figure 5, respectively (state of stresses after springback).

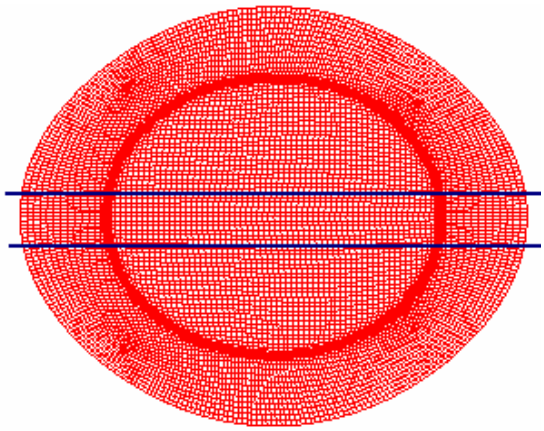
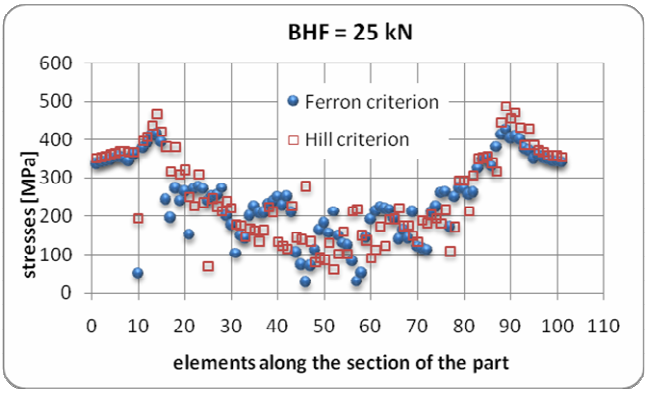
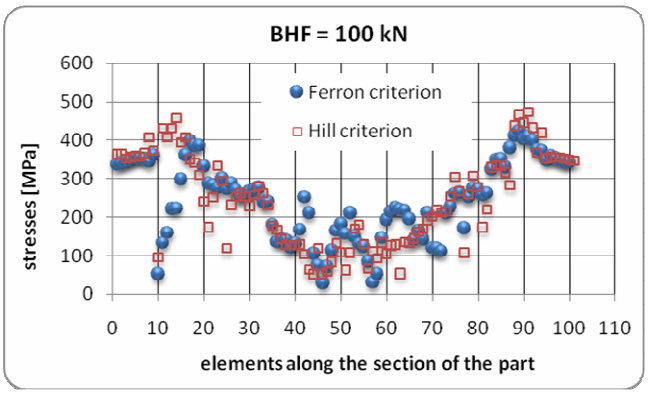
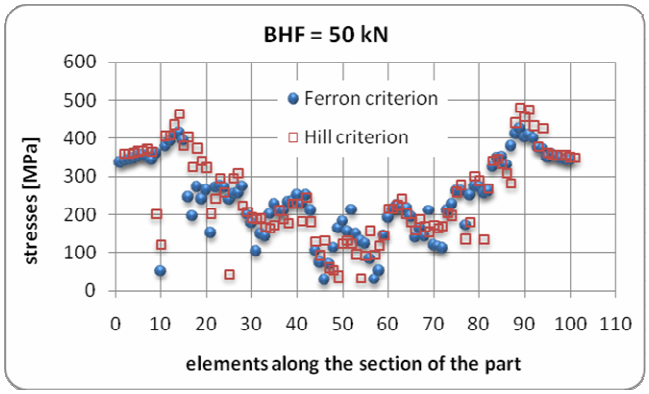


Fig. 3. Selected area for stresses measurement







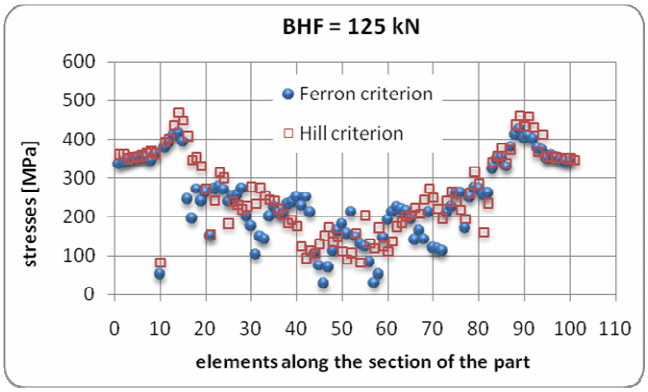
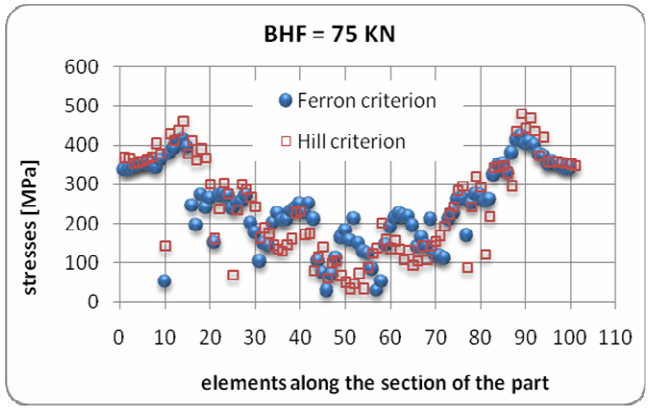
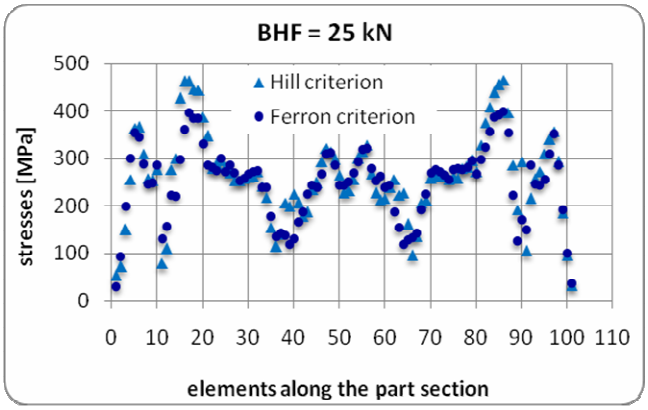
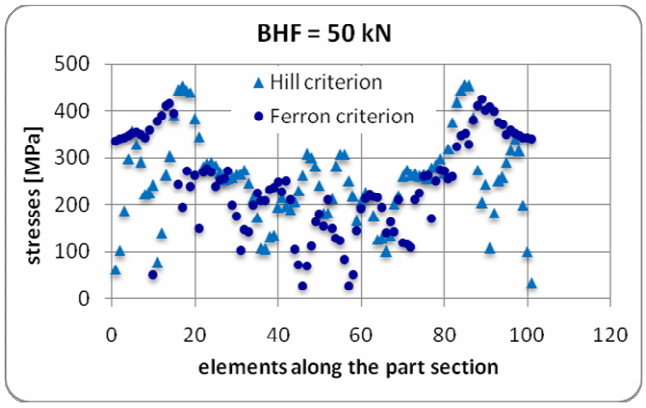
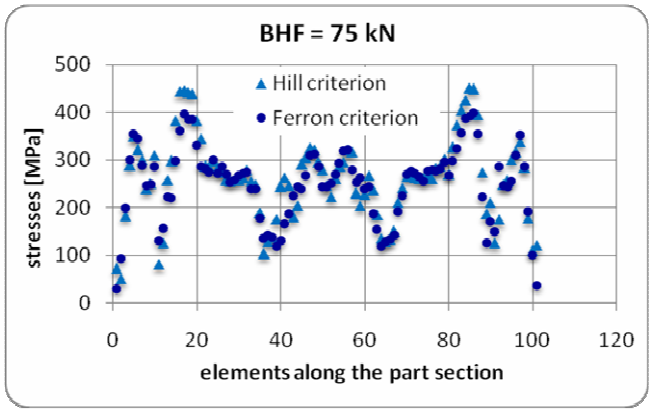


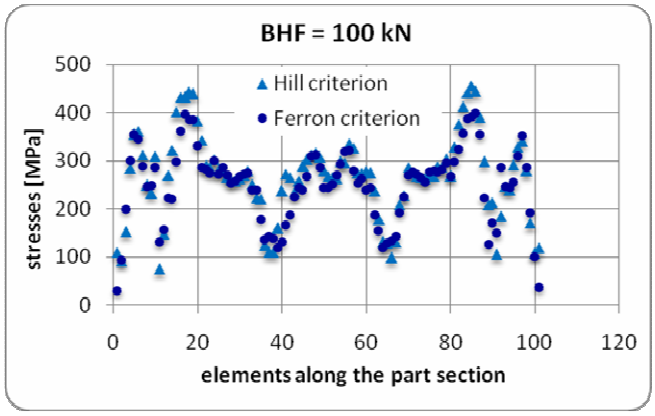
Fig. 4. Stresses distribution within the formed parts at the end of the forming process











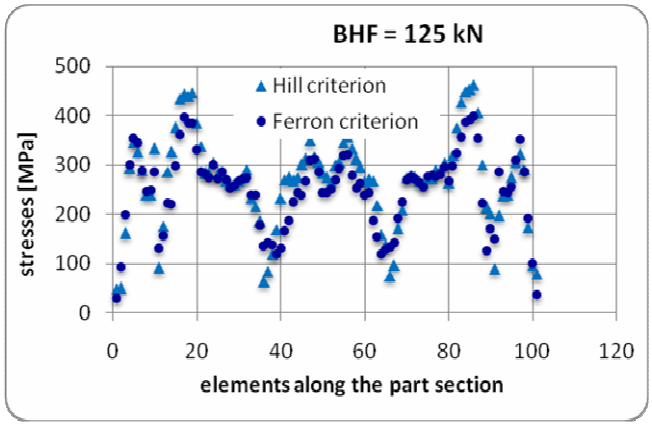


Fig. 5. Stresses distribution within the formed part after springback

4. EXPERIMENTAL ANALYSIS

4.1 Deep-drawing of part

In order to verify the suitability of the numerical model proposed in section 2, an experimental test was performed by using the following process parameters: blankholder force - 50 kN, drawing speed 18 mm/min, with lubrication. The blank dimensions were 200mm diameter per 0.8 mm in thickness.

The value of the blankholder force was achieved using a hydraulic device manually driven, the fluid pressure being indicated by a pressure manometer of 250bar. Measurement of the punch stroke was done with an inductive displacement transducer while the punch load was measured using a force cell of 25tf. The die components are presented in table 3.

Table 3. Die componentes

	Punch diameter (mm)	116
	Punch radius (mm)	6
	Inner diameter of die (mm)	118
	Die radius (mm)	4
	Blankholder diameter (mm)	220

4.2 Determination of residual stresses

4.2.1 Methodology and equipment

The residual stresses were measured by apllying the hole drilling method. This method consists in drilling a small hole in the part material at the centre of a strain gauge rosete. The hole is made using an air turbine that rotates at 400,000 rpm so that no residual stresses are added during drilling.

The residual stresses, in way of the removed material, are reduced enabling the surface strains to be measured by the strain gauges. A suitable mathematical model is then used to evaluate the reduced residual stresses from the strains measurements. The choice of back calculation method is very important in producing the most accurate representation of the real stress state. In our case the Integral method was used, because it provides a separate residual stress analysis at every holl drilling depth increment and the contribution to the total measured strain relaxations of the stresses at all depths are considered simultaneously, giving a high spatial resolution [10]. The equipment used to determine the residual stresses is presented in figure 6.

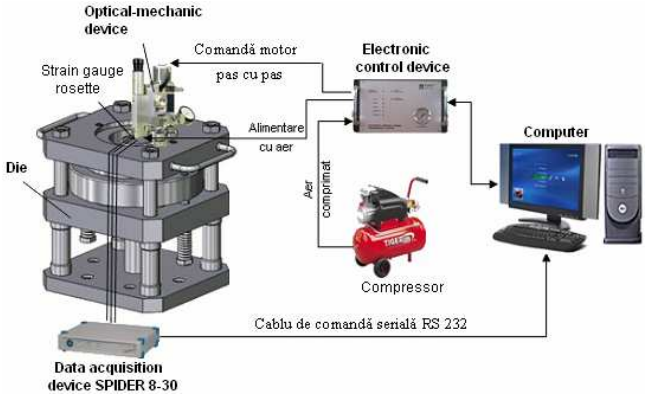


Fig. 6. Equipment for residual stresses determination

The so-colled 3-grid rosettes ($0^o/45^o/90^o$) were used for strain measurement. The principal normal stresses σ_1 and σ_2 for this type of rosette are calculated as follows [10]:

$$\sigma_{1/2} = \frac{E}{1-\nu}\cdot\frac{\varepsilon_a+\varepsilon_c}{2} \pm \frac{E}{\sqrt{2}(1+\nu)}\cdot\sqrt{(\varepsilon_a-\varepsilon_b)^2+(\varepsilon_c-\varepsilon_b)^2} \quad (2)$$

where: E - modulus of elasticity, ν - Poisson's coefficient, ε_a, ε_b, ε_c - strains measured by the 3-grid rosette.

Measurement of the residual stresses was possible only on the bottom of the part due to the restricted application zones of the strain gauges (only on the flat surfaces). Three positions were chosen for the strain gauges sticking: one in the center and two at the edge of part bottom, simetrically positioned from the centre (fig. 7).

Fig. 7. Pozition of the strain gauges

The sheet thickness was condisered equal to zero towards the part outside and 0.8 towards the part inside. The sheet was gradually drilled in 16 steps uniform distributed to the sheet thickness.

4.2.2 Obtained results

The residual stresses measured in the centre and at the edge of the bottom of part are presented in fig 8. Similar trends for the variation curves were found, but different as magnituted, the minimum stresses being encountered in the centre of the part bottom.

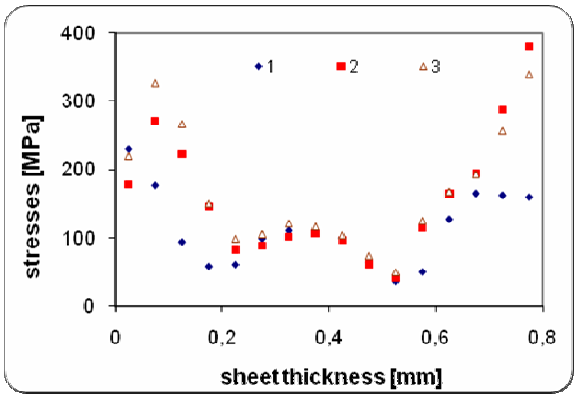


Fig. 8. Through thickness stresses at the bottom of part

5. COMPARATIVE ANALYSIS

The hole drilling method alows to measure the residual stresses through sheet thickness. In order to compare the stresses prescribed by the numerical model with the experimental stresses, they must be measured also through sheet thickness and not along the section of the part as described in section 3.

In this sense, three points from the mesh defining the part geometry were chosen, whose position coresponds with the position of the strain gauges in experimental test (nodes 981 in centre, 1980 and 2858, respectively at the edge, fig. 9), and the through thickness stresses were determined (fig. 10). The virtual stresses were measured only in the five integration points that were initially set through the sheet thickness (see section 2).

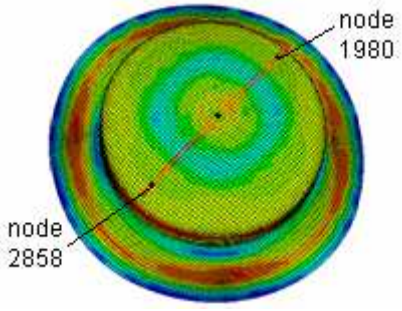
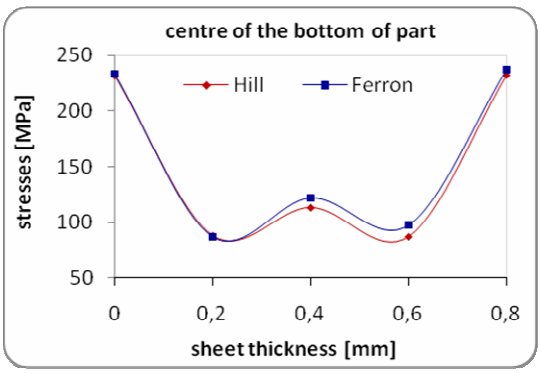


Fig. 9. Nodes where through thickness stresses were measured



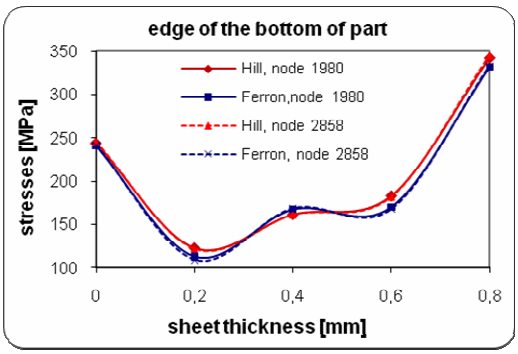


Fig. 10. Through thickness stresses at the bottom of part

Comparison of the experimental and numerical predicted through thickness stresses at the bottom of the part is given in figure 11.

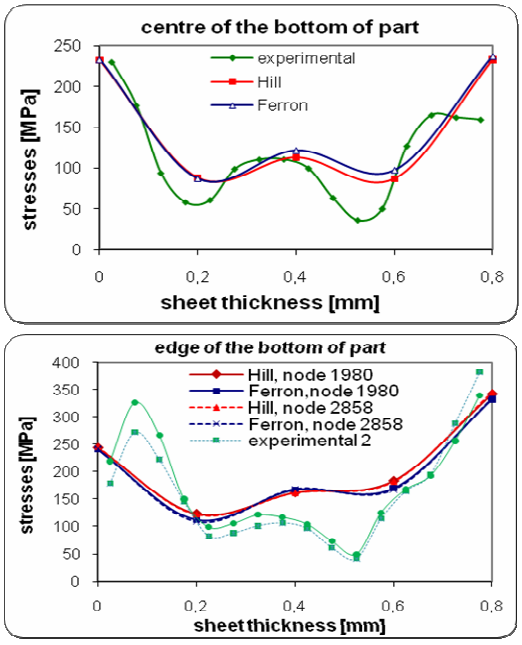


Fig. 11. Comparative analysis of results

6. CONCLUSIONS

By analysing the results obtained by simulation it seems that no significant difference between the states of stresses resulted when the two criteria of plasticity were used. Nevertheless, for higher blankholder forces (BHF > 50kN), some higher diferences between the amount of stresses could be observed at the level of the part bottom.

The stresses distribution obtained with the Hill's criterion is more uniform than in the case of Ferron's criterion. These results are in agreement with the results obtained in [9] according witch the part deviations resulted when the Hill's criterion was used were smaller than the deviations obtained in the case of Ferron's criterion.

After the material springback, the stresses distributions obtained with the two criteria of plasticity almost overlap, excepting the case when a blankholder force of 50 kN was used.

Comparing the results of the two investigation techniques, the following apects can be highlighted:

- in both cases stresses decrease towards the inner layers of the sheets, having minimal values around the neutral axis;
- in both cases stresses are bigger at the edge of the part bottom than in the centre;
- stresses determined by simulation are slighty higher than those experimentally determined; the differences may be due to the different number of measurements through the sheet thickness: 16 for experimental test and just 5 for simulation and also to the way the material properties were implemented into the simulation programe.

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