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VALIDATION OF A NEW METHODOLOGY FOR DETERMINATION OF STRESS-STRAIN CURVES THROUGH BULGE TEST

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Abstract: *This paper is focused on determining the stress-strain curve of sheet metal by bulge test. The first part of the paper describes a methodology recently developed by the authors, for effective and accurate determination of stress-strain curve by bulge test. This methodology is based on the continuous measurement of hydraulic pressure and polar height of the specimen during the test, and on an analytical approach that is able to take into account the non-uniformity of the specimen thickness in the meridian section during bulging. Further the FE -simulation of bulge test is used in order to evaluate the accuracy of the hardening law obtained using the new methodology. This evaluation is done by comparison between the FE- simulation results and experimental data. As comparable results were used the distribution of the specimen high and the distribution of the wall thinning as function of the position in the meridian section. The experiments were performed on samples made from rolled steel sheets DC04 using a 3D optical measurement system ARAMIS. By comparison of the results a good agreement between finite element simulation data and experimental result was found.*
Key words: *Bulge test, Analytical approach, Stress-strain curve, Thickness reduction, FE-Simulation.*

1. INTRODUCTION

The successful implementation of the finite element simulations in the design phase of sheet metal forming processes depends on the accuracy of the material characteristics. From this point of view, the hardening law defining the relationship between the flow stress and the plastic strain has a major influence on the quality of the numerical results. The use of bulge test for the determination of the stress-strain curve gains more and more attention from the sheet metal forming industry. The most important advantage of the bulge test is its capability to attain very high levels of straining [1]. The main problem of using the bulge test for the determination the stress-strain relationship is the measurement of the bulge radius and polar thickness of the specimen. This data is required to calculate the stress based on the membrane theory. Extensive efforts have been made to develop analytical models for the calculation of the dome radius and thickness. Hill [2] developed an analytical model of the bulging process. He admitted the spherical shape of the dome and neglected the influence of the fillet radii located at the entrance of the insert die. Panknin [3] also proposed a formula for the calculation of the curvature radius. This relationship takes into account the effect of the fillet radius on the dimensional characteristics of the dome. By comparing the analytical results with experimental data, Panknin noticed deviations less than 10% of the calculated curvature radius as compared to the experimental value. Chakrabarty and Alexander [4] improved the accuracy of the formulas previously proposed by Hill by taking into account the hardening effects. Gologranc [5] noticed that the values of the polar thickness predicted by Hill’s formula were considerably different from his own experimental results. Shang [6] extended the analytical models developed by Hill in order to take into account the fillet radius of the die insert. According to his experimental observations, the value of the fillet radius has a small influence on the polar strains. Atkinson [7] also tried to improve the accuracy of the analytical predictions referring to the polar thickness and dome radius. Kruglov [8] developed a formula for the calculation of the polar strains. This formula is based on the assumption that the meridian strain is uniformly distributed on the dome surface. Analytical models for the computation of the pressure-time relationship were developed by Banabic [9] for the bulging of both strain hardening and superplastic materials trough elliptical dies and by Vulcan [10] and Banabic [11] for superplastic forming of aluminium sheets using the cone-cup testing method.

The paper is focused on the determination of the biaxial stress – strain curves by bulging tests with circular die. First, a recently proposed methodology for the accurate and efficient determination of the biaxial stress – strain curves is presented [12], [13]. Second, the material parameters determined using the new methodology is used to simulate the bulge test. The validation of the new methodology is done by comparison of the FE-simulation results with the experimental data.

2. METHODOLOGY FOR THE DETERMINATION OF STRESS-STRAIN CURVES

The methodology used to determine the stress-strain curve is based on a modified version of Kruglov's formula for calculation of the polar thickness. The modification consists in taking into account the non-uniform distribution of the strains on the specimen surface by means of a correction coefficient. This approach is briefly described below but more details can be found in [12] and [13].

2.1 Analytical modelling

Figure 1 shows the geometric configuration of the deformed specimen used for the analytical modelling of the bulging test. Table 1 summarizes the notations in Fig. 1.

The current value of the biaxial surface stress (σ_b) is defined by Laplace's formula:

$$\sigma_b = \frac{p\rho}{2s}, \qquad (1)$$

where (p) is the pressure.

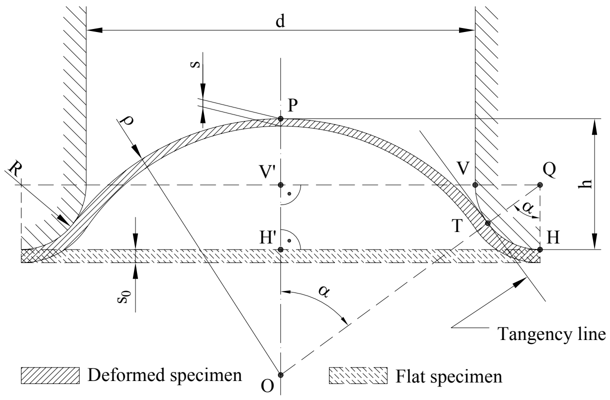


Fig. 1. Schematic representation of the specimen subjected to bulging

The corresponding thickness strain (the so-called biaxial strain ε_b) can be evaluated as follows:

$$\varepsilon_b = \ln\frac{s_0}{s}. \qquad (2)$$

Equations (1) and (2) can be used to obtain a biaxial stress - strain diagram only if the quantities p, ρ and s are either measured or derived from other experimental data. The pressure p can be easily measured using a sensor connected to the hydraulic chamber of the experimental device. The other process variables, namely the curvature radius ρ and the polar thickness s are less accessible to the direct determination. It is more convenient to obtain their values in an indirect manner, using approximate formulas that involve the current value of the polar height h.

Table 1

Geometric parameters for sheet metal bulging

Parameter	Description
d	Diameter of the bulging orifice
R	Fillet radius of the bulging orifice
s_0	Initial thickness of the specimen
s	Current thickness of the specimen in the polar region (point P)
ρ	Current radius of the dome surface
h	Height defining the current position of the pole P

The curvature radius ρ can be evaluated with Panknin's formula [3]

$$\rho = \frac{1}{2h}\left(\frac{d}{2}+R\right)^2 + \frac{h}{2} - R. \qquad (3)$$

The experimental studies performed by other researchers [14] proved that amongst the numerous relationships that can be used to compute the current value of the polar thickness s Kruglov's formula [8] provides the best results. This relationship reads

$$s = s_0 \exp(-\varepsilon_b) = s_0 \left(\frac{\alpha}{\sin\alpha}\right)^{-2}, \quad (4)$$

where (α) can be calculate using the dome height h and the dimensional characteristics of the experimental device (i.e. diameter and the fillet radius of the bulging orifice)

$$\alpha = \arcsin\left[\left(\frac{d}{2}+R\right) \Big/ \left(\frac{1}{2h}\left(\frac{d}{2}+R\right)^2 + \frac{h}{2}\right)\right]. (5)$$

The accuracy of Kruglov's formula is still improvable if Eq (4) is modified as follows:

$$s = s_0 \exp(-\varepsilon_b) = s_0 \left(\frac{\alpha}{\sin\alpha}\right)^{-2(1+c\alpha)}. \quad (6)$$

The coefficient c is a strictly positive constant that takes into account the non-uniformity of the meridian strain distribution on the dome surface. More details about the development of the analytical expression of the coefficient c can be found in [12]. The calculation of the parameter c can be done using the following formula

$$c = \left(\ln\sqrt{\frac{s_0}{s_{min}}} - \ln\frac{\alpha_{max}}{\sin\alpha_{max}}\right) \Big/ \left(\alpha_{max} \ln\frac{\alpha_{max}}{\sin\alpha_{max}}\right), (7)$$

where s_{min} is the final value of the polar thickness and α_{max} is the angle spanned by the dome surface. Both quantities correspond to the final stage of the bulging process. The angle α_{max} can be calculated using the equation

$$\alpha_{max} = \arcsin\frac{\frac{d}{2}+R}{\frac{1}{2h_{max}}\left(\frac{d}{2}+R\right)^2 + \frac{h_{max}}{2}}, \quad (8)$$

where h_{max} is the maximum polar height measured at the end of the bulge test.

2.2 Methodology

An overview of the methodology for determination of stress-strain curve is described by the flow chart shown in Fig. 2. This methodology consists in the following steps:

Step 1: During the bulging experiments the pressure and dome height are recorded continuously until the end of the test.

Step 2: The dome height and the dimensional characteristics of the experimental device (i.e. diameter of the die aperture, and the fillet radius of the die) will be used to calculate the dome radius (Eq (3)).

Step 3: The maximum dome height h_{max}, the minimum polar thickness s_{min}, the initial thickness of the specimen and the dimensional characteristics of the experimental device will be used to calculate the correction coefficient c (Eqs (8) and (7)).

Step 4: The dome height, the correction coefficient, the initial thickness of the specimen and the dimensional characteristics of the experimental device will be used to calculate the polar thickness s (Eqs (5) and (6)).

Step 5: The biaxial stress and strain will be calculated on the basis of pressure, polar radius, polar thickness and initial thickness of the specimen (Eqs (1) and (2)).

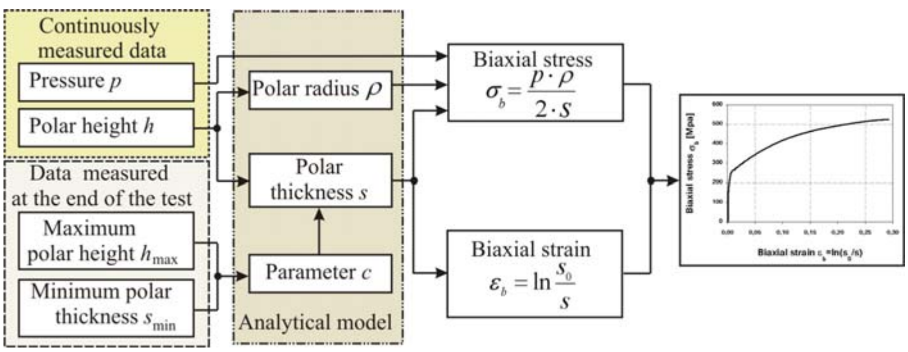


Fig. 2. Methodology used for the determination of the biaxial stress-strain curve

3. MATERIAL

A DC 04 low carbon steel with a thickness of 0.85 mm, mostly used for automotive components and body panels, and defined by the EN 10130 was chosen for the experiments in this work. The mechanical properties of the specimen are shown in Table 2.

Table 2

Mechanical properties of the DC04 steel

Parameter		Value
Ultimate tensile strength, σ (MPa)		310
Initial yield stress, σ_Y (MPa)		183,86
Young's modulus E (MPa)		207000,0
Total elongation, A (%)		41,5
Poisson's ratio, ν		0,28
Strength coefficient, K (MPa)		715,27
Initial plastic strain ε_0 (-)		0,004165
Hardening exponent, n		0,2478
Lankford parameters	$r_{0°}$	1,864
	$r_{45°}$	1,361
	$r_{90°}$	2,345

4. EXPERIMENTAL PROCEDURE

The experiments have been performed using a bulging device and a 3D optical measurement system ARAMIS shown in Figure 3. The geometric dimensions of the tool are (see Fig. 1): diameter of the die aperture d = 80 mm; fillet radius of the die R = 7 mm. The pressure and polar height has been recorded continuously by a pressure sensor and two CCD cameras, respectively.

Fig. 3. Experimental set-up for the bulge test

Figure 4 shows the dependence of the hydraulic pressure as function of time. An example of the bulged specimen before fracture is presented in Figure 5. The experimental data has been used for the determination of biaxial stress – strain curves using the ARAMIS software and the new methodology, respectively.

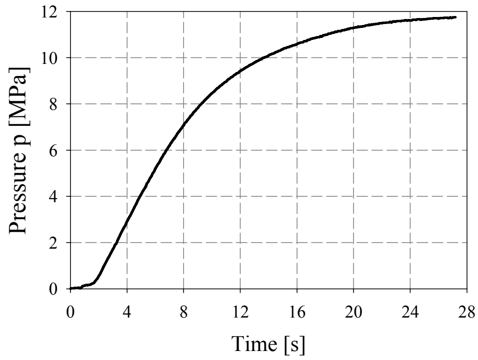


Fig. 4. The relationship between pressure and time during bulge test

Fig. 5. Specimen before fracture

5. FINITE ELEMENT SIMULATION OF BULGE TEST

The aim of the FE-simulation of bulge test was to evaluate accuracy of stress-strain curve determined using the new methodology. This evaluation is done by comparison between results of finite element simulation and experimental data. As parameters for comparison of the results, the displacement Z and thickness reduction of the wall in meridian section, as function of the X-coordinate are used (Fig. 6).

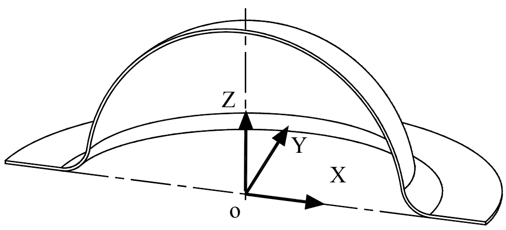


Fig. 6. The meridian section of a specimen

5.1 Material hardening behavior

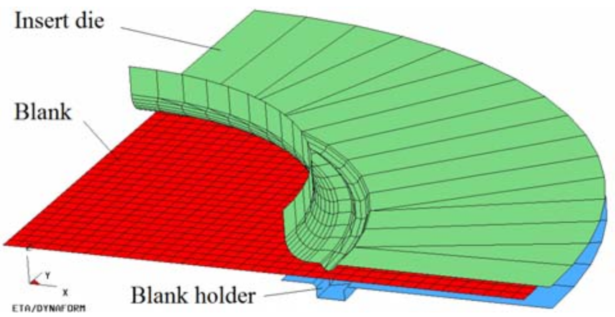
In order to describe the material hardening behavior during the simulation, the power law described by Swift's equation was used:

$$\sigma_y = K \cdot (\varepsilon_0 + \varepsilon_p)^n, \qquad (9)$$

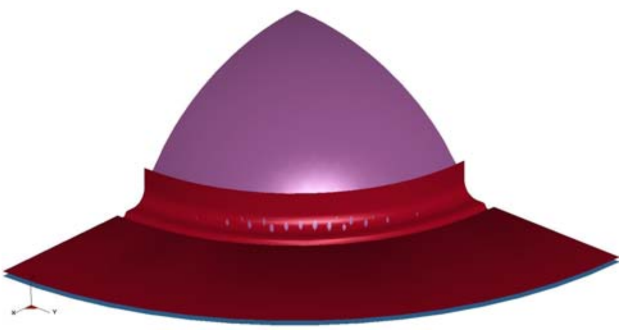
where: σ_y is the yield stress (in the plastic strain areea), and K, ε_0 and n are the material parameters to be identified by fitting the stress-strain curve obtained using the new methodology. These parameters are given in Table 2.

5.2 Finite element model of bulge test

In this study an elasto-plastic three-dimensional finite-elements model of bulge test is developed using a commercially available explicit finite element code eta/Dynaform. Figure 7 shows the finite element model of bulge test. The finite element model of bulge test includes two tools, namely, the insert die and the blank holder and the specimen. During the FE simulation of the bulging process, the blank material was modeled using a hardening elasto-plastic model. The material anisotropy was described by Barlat – Lian (1989) yield criterion [15].



a)



b)

Fig. 7. Explicit FE model for the bulge test: a)-initial position; b)-during bulging

The dies are defined as rigid bodies. The sliding between various pairs of surfaces (insert die-blank and blank holder-blank) was defined using a Coulomb friction model. The amount of implemented friction coefficient was 0.125.

6. RESULTS

The result of the bulge test using the new methodology is shown in Figure 8. In order to determine the parameters from Swift hardening law, the curve presented in Figure 8 is fitted using the equation (9). Figure 9 shows the experimental data obtained on the basis of the new methodology and the fitted curve using the Swift's hardening rule (Eq. (9)).

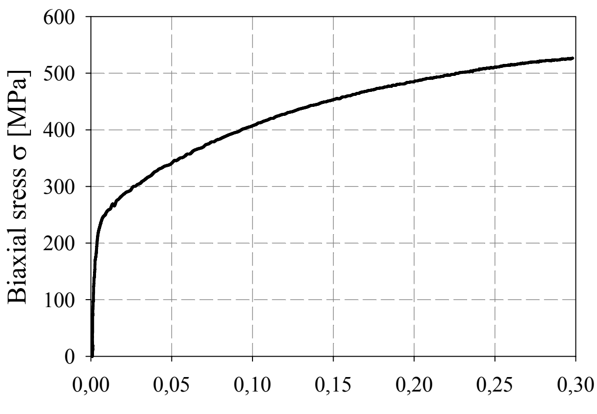


Fig. 8. Biaxial stress-strain curve

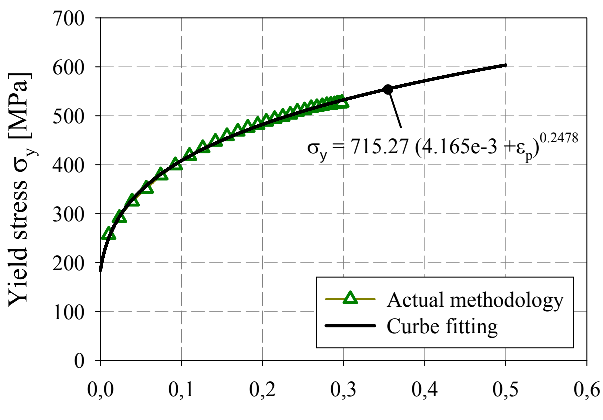


Fig. 9. Stress versus plastic strain

6.1 Wall Displacement of the specimen

Figure 10 shows a comparison between experimental and finite element simulation results of the displacement Z of the specimen at different values of pressure. From these figures can be observed the polar height reached during the three stages of the bulge test. A similar comparison is shown in Figure 11 in the case of wall thickness reduction.

It is important to mention that the maps of displacement Z and wall thickness reduction can only be used for a qualitative comparison of the results, since the figures shows an overall distribution.

In order to investigate the deformed shape, the specimen was sectioned in meridian plane both in the case of ARAMIS and FE-simulation (see Fig. 6). The displacement Z was plotted as function of location along the X coordinate for different values of pressure as shown in Figure 12.

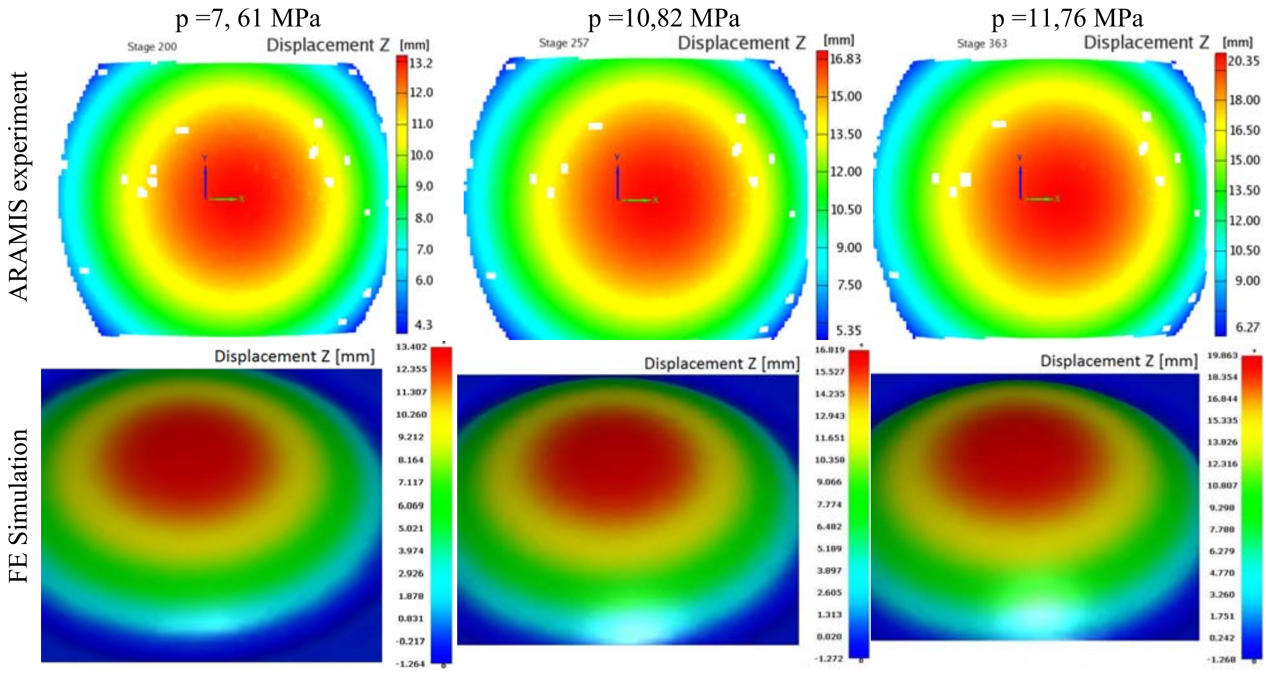


Fig 10. Comparison between experimental and FE-simulation displacement Z

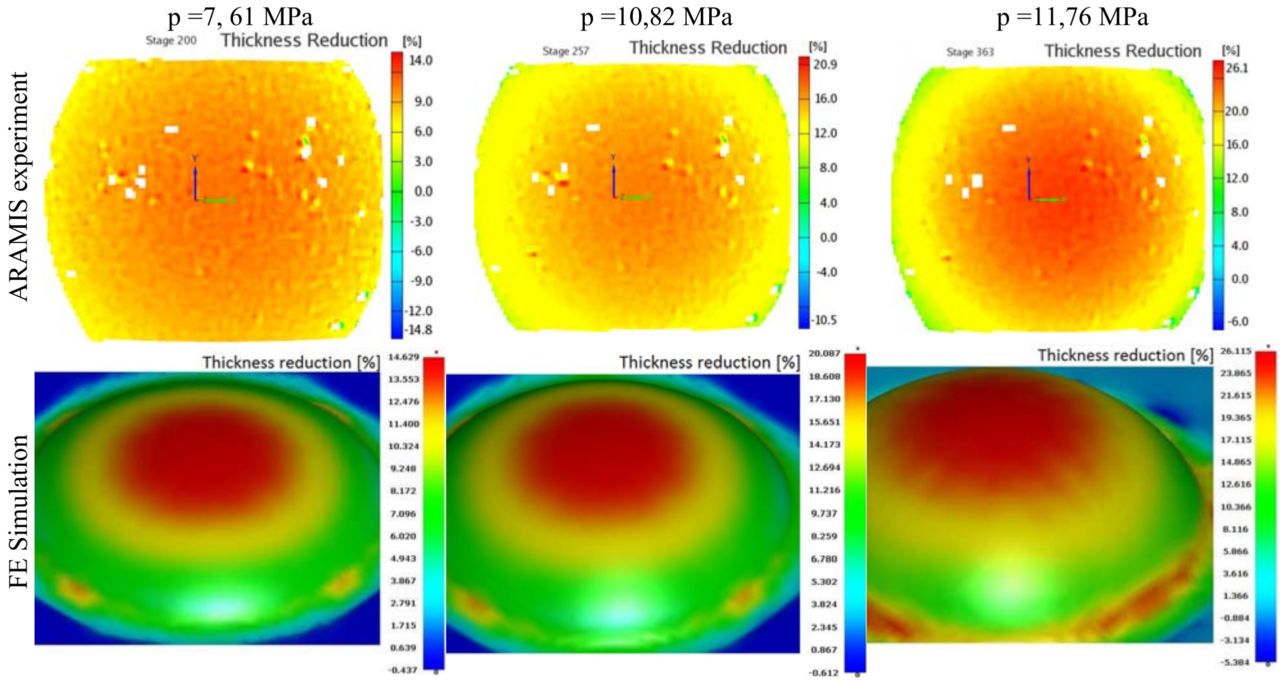


Fig. 11. The distribution of thickness reduction at different values of pressure

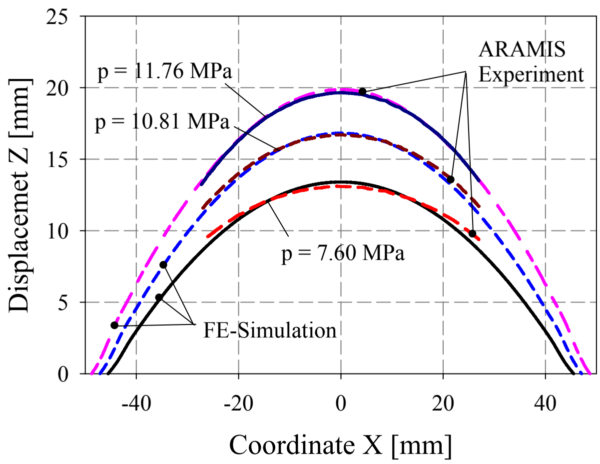


Fig. 12. The displacement Z vs. position X for different values of pressure

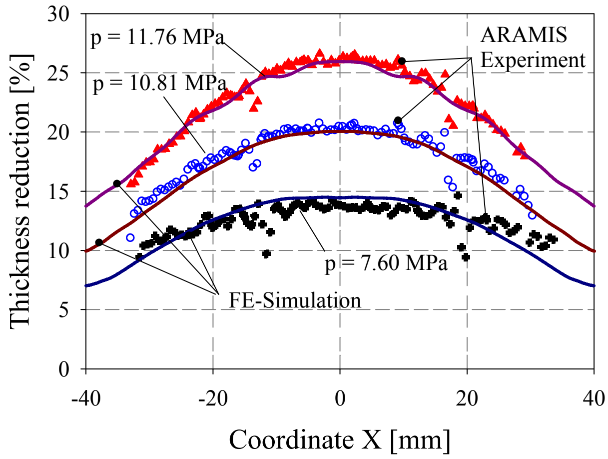


Fig. 13. Thickness reduction vs. position X for different values of pressure

As noticeable from Figure 12, the results obtained using the FE-Simulation is in good agreement with the experimental data provided by the ARAMIS system. The accuracy of the predictions using the FE-Simulation remains very good up to the end of the bulging experiment.

6.2 Thickness reduction

Figure 13 shows the thickness reduction plotted as function of location along the meridian section for different values of pressure. As noticeable from Figure 13, the results obtained using the FE-Simulation are also in better agreement with the experimental data provided by the ARAMIS system.

7. CONCLUSION

The paper presents a new methodology for the experimental determination of the biaxial stress – strain curves. This methodology is based on the continuous measurement of hydraulic pressure and polar height of the specimen during the test, and on an analytical approach of the bulge test that is able to take into account the non-uniformity of the specimen thickness in the meridian section during bulging. The comparison with experimental data provided by the ARAMIS system shows a good accuracy of FE-Simulation.

Due to its simplicity and accuracy, the methodology can be easily implemented in the industrial laboratories involved in the testing of sheet metals.

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VALIDAREA UNEI NOI METODOLOGII PENTRU DETERMINAREA CURBEI TENSIUNE-DEFORMAȚIE PRIN ÎNCERCAREA LA UMFLARE

Rezumat:
Această lucrare este focalizată pe determinarea curbei tensiune-deformație a tablelor metalice prin încercarea la umflare hidraulică. În prima parte a lucrării este descrisă o metodologie dezvoltată recent de către autori, eficientă şi precisă pentru determinarea curbei tensiune-deformație prin încercarea la umflare hidraulică. Această metodologie este bazată pe măsurarea continuă a presiunii hidraulice şi a înălțimii polare a epruvetei în timpul încercării, şi pe o abordare analitică a încercării care este capabilă să ia în considerare neuniformitatea grosimii epruvetei în secțiunea meridiană în timpul deformării. În continuare este folosită simularea cu elemente finite a încercării la umflare hidraulică pentru a evalua acuratețea legii de ecruisare obținută pe baza noii metodologii. Această evaluare este realizată prin comparația dintre rezultatele simulării cu elemente finite şi datele experimentale. Ca rezultate comparabile au fost utilizate distribuția înălțimii şi a reducerii grosimii epruvetei în funcție de poziția în secțiunea meridiană. Experimentele au fost realizate pe epruvete din tablă din oțel laminat DC04 cu ajutorul unui sistem optic de măsurare a deformațiilor ARAMIS. În urma comparării rezultatelor s-a constatat o bună concordanță între rezultatele simulării cu elemente finite şi datele experimentale.

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