CALIBRATION OF BBC2005 YIELD CRITERIA USING PLANE STRAIN YIELDING RESULTS FROM A BULGE TEST

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ABSTRACT: The accuracy of the simulation predictions of the sheet metal processes is strongly influenced by the constitutive law implemented in the programme. In order to describe the anisotropic behaviour of the material, BBC2005 yield criterion has been used. The model has been calibrated using eight material parameters. The paper presents two computational strategies for determining the BBC2005coefficients. The first set of mechanical parameters used in the identification consists in the yield stresses and the anisotropy coefficients determined at 0º, 45º and 90º from the rolling directions as well as the equibiaxial yield stress and equibiaxial anisotropy coefficient. The second set of mechanical parameters contains the same uniaxial mechanical parameters, and the equibiaxial parameters have been replaced by two yield stresses determined in plane strain conditions on samples cut at 0º and 90º from the rolling direction. A novel experimental methodology used for determining the yielding under plane-strain regime is proposed. The method is based on hydraulic bulge process and the tests are performed on universal Erichsen sheet metal testing equipment. The validation of the procedure using finite element method and comparison with the experiments is considered as a future work.

KEYWORDS: Mechanical parameters, yield criterion, identification procedure, finite element method.

1 INTRODUCTION

The yield criterion describes the inelastic behaviour of metallic materials. With the development of the finite element method the researchers focus their attention on advancing reliable and complex formulations of equivalent stress. Modern models use in their identification procedure more and more mechanical parameters, which have to be experimentally determined. Sometimes the experimental procedure can be time consuming and the laboratory equipment very expensive. But having a good description of the material behaviour, the accuracy of the simulation predictions can be improved and the volume of rejected parts can be minimized. Several anisotropic yield criteria are described in the literature. In general, they belong either to Hill's or Hosford's classes of yield criteria. The BBC2005 model [1] used in this paper belongs to the Hosford's class. BBC2005 is part of the BBC group of yield criteria developed along the last 15 years [2-6]. A review of published yield criteria can be found in [7]. According to a series of papers [8,9,10] published by ThyssenKrupp Steel Europe AG, Research and Development Department Group, the accuracy of the simulation predictions is strongly influenced not only by the mathematical formulation of the yield criterion but also by the identification strategy. In this paper, the BBC2005 yield criterion has been tested using two strategies based on different sets of mechanical parameters. In the first approach, the conventional one, three uniaxial yield stresses and anisotropic coefficients together with the equibiaxial yield stress and anisotropic coefficient have been used for calibrating the model. In the second identification procedure, the biaxial mechanical parameters have been replaced by two plane strain yield stresses determined at 0º and 90º from the rolling direction. A similar approach regarding to the usage of the yield stress in plane strain regime instead of the equibiaxial mechanical parameters in the identification procedure can be found in Ref. [11]. An experimental strategy for determining the plane strain yield stresses based on bulge tests will be presented in the next chapter. From the experimental point of view, it's should be mention the fact that for all mechanical parameters involved in both identification strategies, two equipment are used. The experiments for determining the uniaxial mechanical parameters as well as equibiaxial anisotropic coefficient are carrying out on Zwick-Roell 150kN tensile test machine.

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The equibiaxial yield stress as well as the achievement of the plane strain state is obtained by means of bulge tests performed on ERICHSEN 140-20.

2 THEORETICAL FRAMEWORK

2.1 YIELD CRITERION

The yield criterion describes the anisotropic behaviour of the sheet metal. Under this circumstance the yield criterion represents the kernel of the mathematical modelling of the forming processes. The equivalent stress of the BBC2005 yield criterion has the following formulation [1]:

$$\bar{\sigma}=\begin{bmatrix} a\left(\Lambda+\Gamma\right)^{2k}+a\left(\Lambda-\Gamma\right)^{2k}+ \\ +b\left(\Lambda+\Psi\right)^{2k}+b\left(\Lambda-\Psi\right)^{2k} \end{bmatrix}^{\frac{1}{2k}} \quad (1)$$

where $k \in N^{\geq 1}$ and $a, b > 0$ are material parameters, while Γ, Λ and Ψ are functions depending on the planar components of the stress tensor:

$$\begin{aligned} &\Gamma=L\sigma_{11}+M\sigma_{22} \\ &\Lambda=\sqrt{\left(N\sigma_{11}-P\sigma_{22}\right)^2+\sigma_{12}\sigma_{21}} \\ &\Psi=\sqrt{\left(Q\sigma_{11}-R\sigma_{22}\right)^2+\sigma_{12}\sigma_{21}} \end{aligned} \quad (2)$$

Nine material parameters are involved in the expression of the BBC2005 equivalent stress: $k, a, b, L, M, N, P, Q,$ and R. The integer exponent k has a special status and depends only on the crystallographic structure of the material:

- $k=3$ for BCC materials
- $k=4$ for FCC materials.

The other eight coefficients are calculated by forcing the constitutive equations associated to the BBC2005 yield criterion to reproduce a set of experimental data. A flexible identification procedure based on the input data you may find in [7].

2.2 DETERMINATION OF THE MAJOR YIELD STRESS IN PLANE STRAIN CONDITIONS

In order to determine the major yield stress in plane strain at 0° and 90° from the rolling direction, a bulge test is performed and Laplace equation has been used:

$$\frac{\sigma_{11}}{\rho_{RD}}+\frac{\sigma_{22}}{\rho_{TD}}=\frac{p}{s} \quad (3)$$

where σ_{11} and σ_{22} are the principal stresses along rolling direction (RD), transverse direction (TD) respectively; ρ_{RD} and ρ_{TD} are the bulge radius along RD and TD; p is the pressure of the hydraulic oil and s is the current thickness of the deformed specimen in the polar zone.

For convenience, the following notations have been adopted:

$$\alpha=\frac{\sigma_{22}}{\sigma_{11}}, \quad \gamma=\frac{\rho_{TD}}{\rho_{RD}} \quad (4)$$

If the rolling direction of the specimen is coincident with the major strain direction, Eq. (3) may be written in the following form:

$$Y_0^{PS}\left(1+\frac{\alpha_0}{\gamma_0}\right)=\frac{p\rho_{RD}}{s} \quad (5)$$

where Y_0^{PS} represents the plane strain yield stress along RD. The index 0 indicates that the elongation is associated to the rolling direction. The right term of Eq. (5) is expressed in [MPa], therefore it represents a stress. In the following we denote that quantity as “pseudo-sigma”.

If the rolling direction of the specimen is perpendicular to the major strain direction, the plane strain along TD has been considered and Eq. (3) has the following formulation:

$$Y_{90}^{PS}\left(1+\alpha_{90}\gamma_{90}\right)=\frac{p\rho_{TD}}{s} \quad (6)$$

where Y_{90}^{PS} represents the plane strain yield stress along TD. The index 90 indicates that the elongation is associated to the transverse direction. As in the previous case, the right term of Eq. (6) is expressed in [MPa] and is also denoted as “pseudo-sigma”.

One may notice that the left term of Eqs. (5) and (6) are related to the stress ratio This means that both minor and major plane strain yield stresses are depending to the adopted yield criterion.

The current thickness has been computed according to the plane strain condition $\left(\varepsilon_2=0\right)$ and assuming the constancy of the material volume $\left(\varepsilon_3=-\varepsilon_1\right)$:

$$s=s_0\exp\left(-\varepsilon_3\right) \quad (7)$$

where s_0 is the initial thickness of the specimen.

3 EXPERIMENTAL FRAMEWORK

3.1 MATERIAL

The material used for investigation is an AA6016-T4 aluminium alloy with 1mm thickness. The uniaxial mechanical parameters used in the identification procedure of the BBC2005 yield criterion are:

yield stresses (Y_0, Y_{45} and Y_{90}) and anisotropic coefficients (r_0, r_{45} and r_{90}). The values of these parameters result from tensile tests. The subscripts denote the direction of the tensile load with respect to the rolling direction. The parameters of the hardening law have been obtained by performing a tensile test on a sample cut along the rolling direction. The hardening has been described by the Hollomon's power law.

The equibiaxial parameters such as the yield stress and the anisotropy coefficient have been obtained from bulge and compression tests, respectively. One may assume that in the polar zone of the bulged specimen the principal stresses along the rolling and transverse directions are approximately equal. The deformation behaviour of the sample is recorded using an optical strain measurement system. Based on a methodology proposed by Barlat in [12], the equibiaxial yield stress has been computed. The method consists in equating the plastic work dissipated in equibiaxial and uniaxial traction regimes. The method is detailed in [13].

As mentioned above, a compression test has been used in order to determine the equibiaxial coefficient of anisotropy. The methodology is similar to that presented by Barlat in [14]. The initial diameter of the specimen has been set to 10mm.

3.2 PLANE-STRAIN HYDRAULIC BULGE TEST

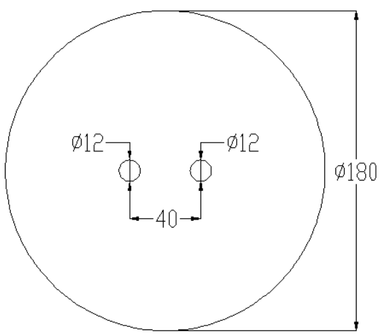

Fig. 1 *Geometry of the sample (dimensions in mm) used to achieve the plane strain conditions*

The classical manner to determine the plane strain yield stress consists in performing a tensile test on wide samples [15]. Malo [16] proposed a bending test in order to attained plane strain condition. The authors adopted an alternative approach based on the bulging process. More about the principle of bulge tests you may find in [17].

The geometry of the sample is presented in Fig. 1. One may notice that the circular specimen is pierced by two circular holes. Under the sample, a carrier plate from the same material has been placed. Under the action of the oil pressure, both the specimen and the carrier deform in the same time.

Fig. 2 shows the major and minor fields of strain as well as the thickness reduction in the central region of the specimen, i.e. between the circular holes. One may notice that zero contraction along the holes direction has been observed. The deformation behavior of the samples is recorded using an ARAMIS optical strain measurement system.

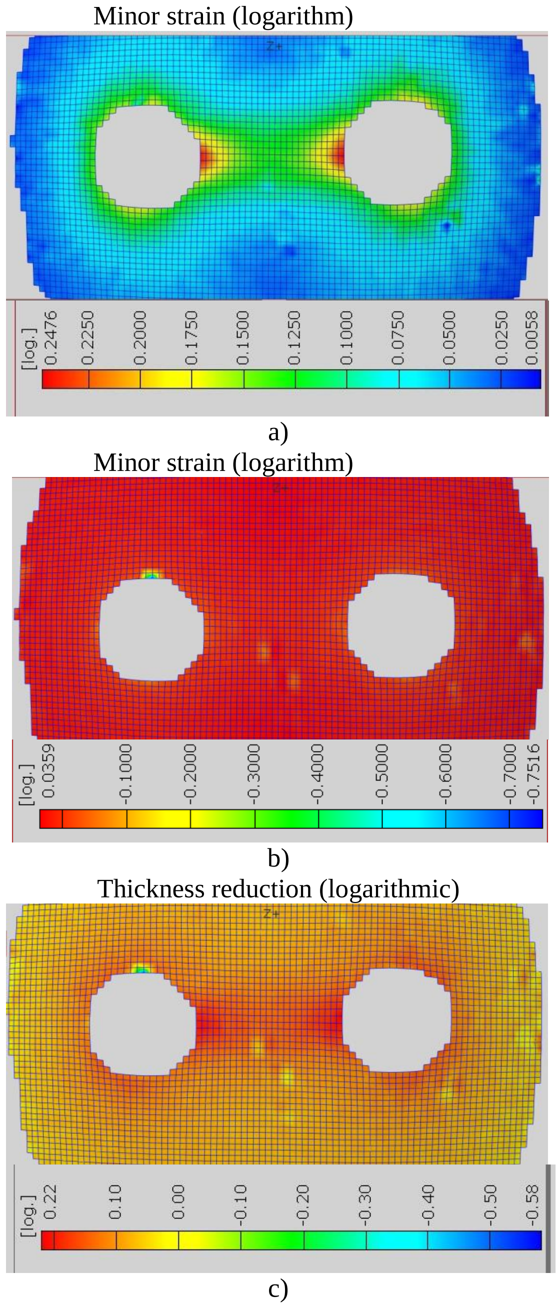

Fig. 2 *Major a), minor b) strain fields and thickness reduction c) on the specimen obtained at the same stage*

Fig. 3 shows the determination of the radii along RD and TD using the ARAMIS Software. The software allows the user to select the area used for calculating the best circular approximation. The radii automatically determined during the bulge process have been used to build the diagrams presented in Fig. 4 and 5, respectively. One may notice a linear evolution of the radii leading to the possibility of calculating the slope of the regression line. It has been notice that the bulge process tends to stabilization after 0.045 logarithmic thickness reductions.

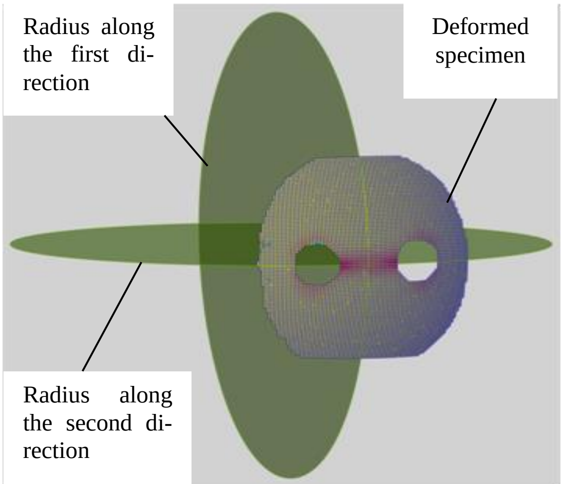

Fig. 3 *Automatic determination of the radii along RD and TD using a facility of the ARAMIS Software*

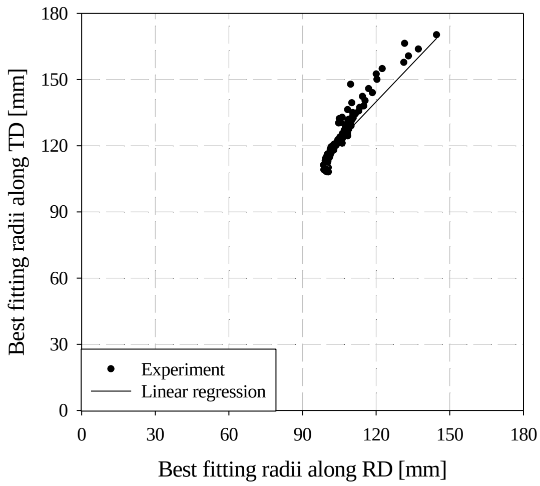

Fig. 4 *Evolution of best fit radii along RD and TD during the bulge process. Elongation along RD.*

Considering the initial thickness of the sample as being equal to the sum of the specimen and the carrier thicknesses, "pseudo-sigma" vs. logarithmic thickness reduction curves has been built (see Fig. 6 and Fig. 7).

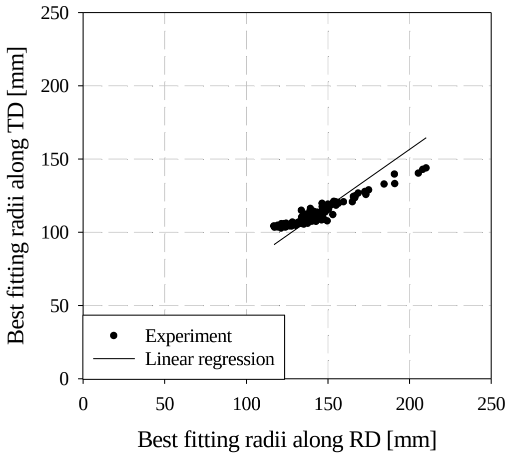

Fig. 5 *Evolution of best fit radii along RD and TD during the bulge process. Elongation along TD*

The experimental data sets offer the possibility to calculate the mechanical parameters of the Hollomon's hardening law. Based on the same energetic procedure as in the equibiaxial case, the yield stresses have been computed. One may notice that even if the curves are obtained in plane strain regime, are long enough to apply the procedure.

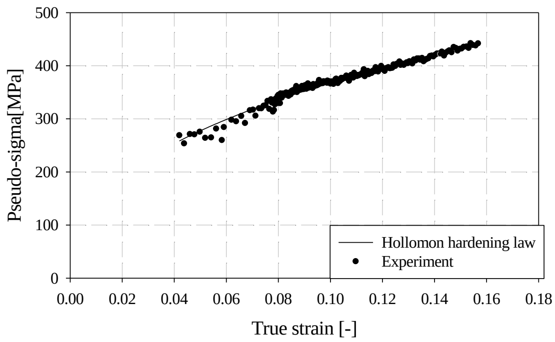

Fig. 6 *Pseudo-stress – logarithmic thickness reduction during the bulge process. Elongation along RD.*

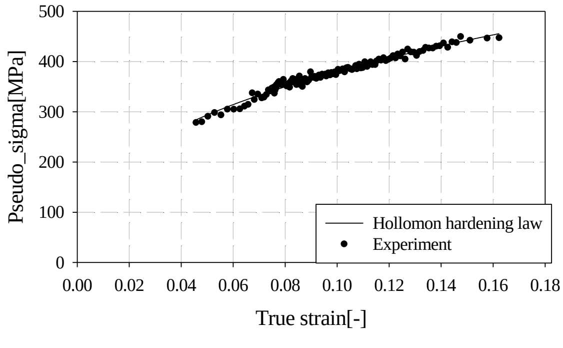

Fig. 7 *Pseudo-stress – logarithmic thickness reduction during the bulge process. Elongation along TD.*

3.3 RESULTS

Table 1 shows the uniaxial mechanical parameters determined by performing tensile tests on the specimens cut at 0º, 45º and 90º from the rolling direction. The parameters of the Hollomon hardening law results from a tensile test performed on specimen cut along rolling direction and there values are listed in the same table.

Table 1: *Uniaxial mechanical parameters of AA6016-T4 aluminium alloy (1mm thickness)*

Y_0[MPa]	139.26	r_0[−]	0.64
Y_{45}[MPa]	137.23	r_{45}[−]	0.53
Y_{90}[MPa]	136.30	r_{90}[−]	0.64
n[−]	0.25	K[MPa]	487.44

Table 2: *Experimental material parameters obtained from plane strain bulge tests*

Elongation direction	n [-]	K [MPa]	γ [-]	Y^{pseudo} [MPa]	Y^{PS} [MPa]
RD	0.406	936.265	1.166	184.38	146.051
TD	0.373	897.534	0.7826	185.216	143.976

Table 3: *Biaxial mechanical parameters of AA6016-T4 aluminium alloy (1mm thickness). Experiment and prediction*

Y_b[MPa]	140.76	r_b[−]	1.069
Y_b^{PS}[MPa]	130.23	r_b^{PS}[−]	1.05

Table 2 provides the computed parameters of the Hollomon hardening law (n and K), the regression slope (γ), the pseudo yield stresses (Y^{pseudo}) for both experiments.

The plane strain yield stresses (Y^{PS}) has been predicted by the BBC2005 yield criterion. Table 3 shows the biaxial parameters obtained experimentally as a result of bulge test and compression test respectively. In the same table the prediction of the biaxial parameters of the BBC2005 yield criterion identified with plane stress coefficients have been listed.

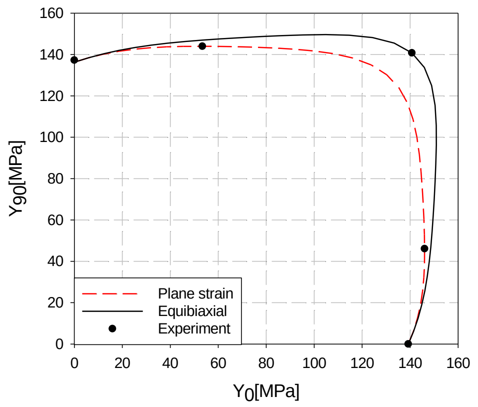

Fig. 8 *Predicted yield surfaces using two identification strategies of the BBC2005 yield criterion*

Finally, two sets of experimental data have been considered in order to predict the yield surface. The yield criterion used in this paper is BBC2005, as implemented in the AutoForm finite element programme. Fig. 8 shows the prediction of the yield surface for both identification cases. In the first approach, the following mechanical parameters have been used: three uniaxial yield stresses and the associated anisotropy coefficients, as well as the equibiaxial yield stress and the corresponding anisotropy coefficient. In the second calibration procedure, the same uniaxial mechanical parameters have been used in combination with the plane-strain pseudo-yield stresses. The experimental points have been plotted on the same diagram. One may notice that the values of the equibiaxial stress and equibiaxial anisotropic coefficient predicted from the second identification procedure are lower than the ones experimentally determined.

4 CONCLUSIONS

In this paper, an experimental strategy for determining the major yield stresses in plane strain along the rolling and transverse directions has been presented. The geometry of the specimen is simple and the laboratory equipment is based on principle of bulge test. The accuracy of the results demonstrates that the strategy is a good alternative to the tensile test performed on wide specimen.

By using the experimental data, an identification procedure of the BBC2005 yield criterion has been developed. The yield surface was compared with the one predicted with conventional experimental parameters.

As a future work, a sheet metal forming process will be simulated in order to validate the model. The test piece will be chosen so that the blank deformed mostly under the plane-strain condition. Under this circumstance, the calibration of the yield locus using plane-strain yield stresses will be emphasised. The obtained result will be compared with the ones determined using common calibration methodology.

5 ACKNOWLEDGEMENT

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REFERENCES

[1] Banabic D., Comsa D.S., Sester M., Selig M., Kubli W., Mattiasson K., Sigvant M.,: *Influence of constitutive equations on the accuracy of prediction in sheet metal forming simulation*. Numisheet, Interlaken, Switzerland, 37-42, 2008.

[2] Banabic D., Balan T., Comsa D.S.: *A new yield criterion for orthotropic sheet metals under plane-stress conditions*. Proceedings of the 7th Conference 'TPR2000', Cluj Napoca, Romania, 217–224, 2000.

[3] Banabic D., Kuwabara T., Balan T., Comsa D.S., Julean D.: *Non-quadratic yield criterion for orthotropic sheet metals under plane-stress conditions*. International Journal of Mechanical Sciences, 45:797–811, 2003.

[4] Banabic D., Kuwabara T., Balan T., Comsa D.S: *An anisotropic yield criterion for sheet metals*. Journal of Materials Processing Technology, 157–158:462–465, 2004.

[5] Banabic D., Aretz H., Comsa D.S., Paraianu L.: *An improved analytical description of orthotropy in metallic sheets*. International Journal of Plasticity 21:493–512, 2005.

[6] Comsa D.S., Banabic D.: *Plane-stress yield criterion for highly-anisotropic sheet metals*. In: Hora P (ed) Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes, NUMISHEET 2008, Interlaken, Switzerland, 43–48, 2008.

[7] Banabic D.: *Sheet Metal Forming Processes. Constitutive modelling and numerical simulation*. Springer, Springer-Verlag Berlin Heidelberg New York, 2010.

[8] Kessler L., Gerlach J., Beier T., Linnepe M.: *The impact of advanced material simulation parameters in press shop operations using mild steel grades*. Journal of Materials and Manufacturing, 3: 737-749, 2010.

[9] Aydın M.-S., Gerlach J., Kessler L., Tekkaya A.E.: *Yield locus evolution and constitutive parameter identification using plane strain tension and tensile tests.* Journal of Materials Processing Technology, 211: 1957-1964, 2011.

[10] Gerlach J., Beier T., Grass H., Heinle L., Kessler L.,Lipp A.: *Identification and validation of yield locus parameters with respect to industrial forming simulation needs*. In: 10th International Conference on Technology of Plasticity, Steel Research International, Special Edition, 732-737, 2011.

[11] Aretz H., Hopperstad O.S., Lademo O.-G.: *Yield function calibration for orthotropic sheet metals based on uniaxial and plane strain tensile tests.* Journal of Materials Processing Technology, 186: 221–235, 2007.

[12] Barlat F., Maeda Y., Chung K., Yanagawa M., Brem J. C., Hayashida Y., Lege D. J., Matsui K., Murtha S. J., Hattori S., Becker R. C., Makosey S.: *Yield function development for aluminum alloy sheets*. Journal of Mechanics and Physics of Solids, 45(11/12): 1727-1763, 1997.

[13] Comşa D.S.: *Numerical simulation of sheet metal processes using a new yield criterion*. PhD thesis, Technical University of Cluj Napoca, 2006 (in Romanian).

[14] Barlat F., Brem J.C., Yoon J.W., Chung K., Dick R.E., Choi S.-H., Pourboghrat F., Chu E., Lege D.J.: *Plane stress yield function for aluminium alloy sheets. Part 1. Theory.* International Journal of Plasticity, 19: 1297–1319, 2003.

[15] Vegter H., ten Horn C.H.L.J., An Y., Atzema E. H., Pijlman H. H., van den Boogaard T. H., Huétink H.: *Characterisation and modelling of the plastic material behaviour and its application in sheet metal forming simulation*. COMPLAS VII, 2003.

[16] Malo K.A., Hopperstad O.S., Lademo O.G.: *Calibration of anisotropic yield criteria using uniaxial tension tests and bending tests*. Journal of Materials Processing Technology, 80–81, 538–544, 1998.

[17] Koç M., Billur E., Necati Cora Ö.: *An experimental study on the comparative assessment of hydraulic bulge test analysis methods*. Materials and Design, 32, 272–281, 2011.