EFFECT OF THE CONSTITUTIVE LAW ON THE PREDICTION OF THE WALL THICKNESS DISTRIBUTION OF SQUARE CUP

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Abstract: *The output of the simulation is very sensitive to the constitutive equations that describing the anisotropic behaviour of the sheet metal. From this point of view, the mathematical formulation of the yield criterion as well as the number of the mechanical parameters used in the identification procedure has the most significant influence. The paper presents a comparative analysis referring to the quality of the wall thickness distribution of the square cup predicted by AutoForm finite element program if the anisotropy is described by one of the following yield criteria: Hill48, Barlat89 and BBC2005 with 6 and 8 parameters. The distribution of the thickness is studied along 0°, 45° and 90° from the rolling direction. The predictions are compared with the experimental data for AA6016-T4 aluminium alloy with 1 mm thickness.*

Key words: *Mechanical parameters, Yield criterion, FE simulation.*

1. INTRODUCTION

In order to be competitive in the automotive market, the industry was forced to increase the efficiency by decreasing the number of rejected parts. The deep-drawing process plays the most important role for obtaining the parts of the car body. The complex deformation observed on the squared deep-drawn part (Demerci et al. 2008, Huang et al. 2008) along a radius as well as corner zone constrained the authors to pay a special attention to this metal forming process. In the present study the quality of the squared deep-drawn part is analyzed due to wall thickness variation. A pronounced thinning leads not only to an anaesthetic part but also to rejection. The numerical results obtained from a deep drawing simulation are compared with the experiments. In order to describe the plastic behaviour of the sheet metal three yield criteria implemented in AutoForm finite element program are used.

The aim of this paper consists in evaluating the influence of yield criteria on the accurate predictions of the wall thickness of the squared deep-drawing part along 0°, 45° and 90° from the rolling direction (RD). Due to the fact that the BBC2005 yield criterion reduces to the formulations of Hill48 and Barlat89 yield criteria, it can be say that the influence of the number of the numerical mechanical parameters on the thickness predictions is analyzed.

A detailed description of the yield criteria are presented in (Banabic 2010).

2. PRESENTATION OF THE YIELD CRITERIA

2.1 Hill48

The equivalent stress of the Hill48 (Hill 1950) yield criterion has the following mathematical formulation:

$$\bar{\sigma}^2 = F\sigma_{22}^2 + G\sigma_{11}^2 + H\left(\sigma_{11} - \sigma_{22}\right)^2 + 2N\sigma_{12}^2 \qquad (1)$$

where F, G, H and N are material coefficients. Four mechanical parameters are needed to evaluate these coefficients. The experimental data used in the identification procedure are: r_0, r_{45}, r_{90} (anisotropic coefficients determined along 0°, 45° and 90° from the RD) and σ_0 (yield stress determined along RD).

2.2 Barlat89

The Barlat89 (Barlat and Lian 1989) yield criterion has the following expression of the equivalent stress:

$$\bar{\sigma}^M = a\left|k_1 + k_2\right|^M + a\left|k_1 - k_2\right|^M + c\left|2k_2\right|^M \qquad (2)$$

where

$$k_1 = \frac{\sigma_{11} + h\sigma_{22}}{2}$$
$$k_2 = \sqrt{\left(\frac{\sigma_{11} - h\sigma_{22}}{2}\right)^2 + p^2\sigma_{12}^2} \qquad (3)$$

are functions depending on the planar components of the stress tensor, while a, h, c and p are material coefficients. The parameter M is set according to the crystallographic structure of the material: $M = 6$ for BCC metals, and $M = 8$ for FCC metals. In the particular case $M = 2$ this model reduces to the Hill48 formulation. Four mechanical parameters are needed for calculating the independent coefficients a, h, c and p. Those are: r_0, r_{45}, r_{90} and σ_0.

2.3 BBC2005

The complex yield criterion incorporating more mechanical parameters then Hill48 and Barlat89 is BBC2005 (Banabic et al., 2008). Hill48 and Barlat89 yield criteria are special cases of the BBC2005 yield criterion. Therefore, the equivalent stress of BBC2005 yield criterion is defined as follows:

$$\bar{\sigma}=[a\left(\Lambda+\Gamma\right)^{2k}+a\left(\Lambda-\Gamma\right)^{2k}+ \\ +b\left(\Lambda+\Psi\right)^{2k}+b\left(\Lambda-\Psi\right)^{2k}]^{\frac{1}{2k}} \tag{4}$$

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

$$\Gamma=L\sigma_{11}+M\sigma_{22} \\ \Lambda=\sqrt{\left(N\sigma_{11}\text{-}P\sigma_{22}\right)^2+\sigma_{12}\sigma_{21}} \\ \Psi=\sqrt{\left(Q\sigma_{11}\text{-}R\sigma_{22}\right)^2+\sigma_{12}\sigma_{21}} \tag{5}$$

The yield criterion contains nine coefficients: k, a, b, L, M, N, P, Q and R. As in Barlat89's case, the exponent k depends on the crystallographic structure of the material: $k = 3$ for BCC metals and $k = 4$ for FCC metals. The remaining coefficients are calculated using the experimental values of eight mechanical parameters. The identification procedure implemented in AutoForm FE program can run if only uniaxial mechanical parameters are available. In this case, the following constraints are enforced:

$$L + M = 2N, \quad N = P \tag{6}$$

Thus, only six coefficients are computed by the identification strategy.

3. COMPARISON OF THE PREDICTED YIELD SURFACES

The aluminium alloy with 1mm thickness used in this study is widely exploited in the automotive industry. Its mechanical parameters are listed in Tables 1 and 2. Table 1 shows the values of the uniaxial mechanical parameters: yield stresses and anisotropy coefficients as well as coefficients of Swift hardening law determined on samples cut at 0°, 45° and 90° from the rolling direction. Table 2 lists the equibiaxial material characteristics. These are the yield stress and the anisotropy coefficient corresponding to the equal traction along the rolling and transverse directions (TD).

Table 1. Uniaxial mechanical parameters of the AA6016-T4 aluminium alloy (1 mm thickness)

Angle	r^{exp} [-]	σ^{exp} [MPa]	n[-]	K [MPa]
0°	0.553	158.0	0.239	479.7
45°	0.409	152.2	0.239	468.5
90°	0.550	154.8	0.242	480.2

Table 2. Biaxial mechanical parameters of the AA6016-T4 aluminium alloy (1 mm thickness)

σ_b^{exp}[MPa]	r_b^{exp}[-]
160.1	1.05

Table 3. Biaxial mechanical parameters of the AA6016-T4 aluminium alloy (1 mm thickness)

Hill48	H	G	F	N
	0.356	0.644	0.647	1.168
Barlat89	a	c	h	p
	0.6445	0.3554	1.0017	0.8505
BBC2005 – 6param	a	b	L	M
	1.4097	0.3475	0.4487	0.4674
	N	P	Q	R
	0.4580	0.4580	0.5446	0.5654
BBC2005 – 8param	a	b	L	M
	2.3229	0.2824	0.3983	0.4161
	N	P	Q	R
	0.4601	0.4604	0.5533	0.5731

As mentioned above, the yield criteria used in this study are Hill48, Barlat89 and BBC2005. Table 3 contains the values of the yield criteria coefficients.

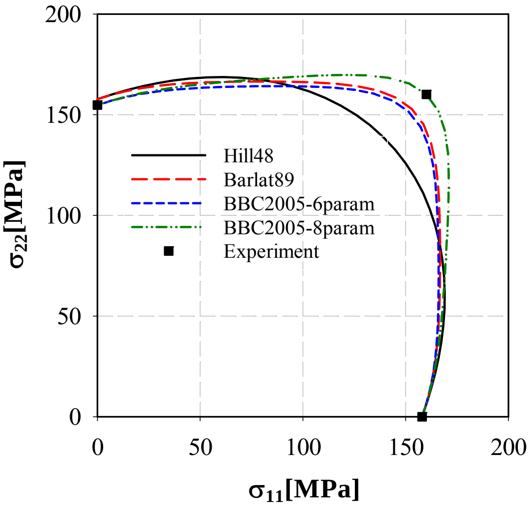

Fig.1. Yield surfaces predicted by different yield criteria for AA6016-T4 aluminium alloy

Figure 1 shows a comparison of the yield loci predicted by different anisotropic criteria. Three experimental points are also plotted on the same diagram. Due to the fact that BBC2005 with 8 coefficients uses in identification procedure the experimental value of σ_b, the predictions of these formulation are more accurate.

4. EXPERIMENTS AND NUMERICAL MODELLING OF A SQUARE CUP DRAWING

The experimental equipment used for performing square deep-drawing is an Erichsen Universal Sheet Metal Testing Machine, Model 142-20. The tooling setup is provided in Fig. 2.

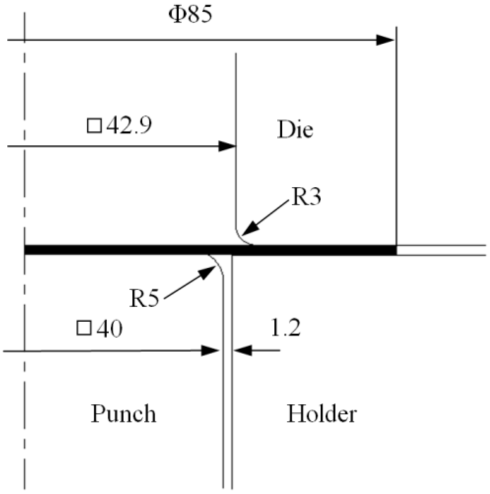

Fig.2. Schematic view of the tooling setup

A detailed presentation of the tools dimensions and lubrication conditions is available in Table 4.

Table 4. Tool dimensions and lubrication conditions

Blank	Diameter	85 mm
	Thickness	1.0 mm
Die	Corner radius	10.2 mm
	Profile radius	3 mm
	Square side	42.9 mm
Punch	Height	70 mm
	Corner radius	9 mm
	Profile radius	4 mm
	Square side	40 mm
Blank holder	Corner radius	10.2 mm
	Square side	42.9 mm
	Binding force	10 kN
Lubrication	Punch/Blank	None
	Die/Blank	MoS_2 based lubricant

The wall thickness variation of the deformed square cup along 0°, 45° and 90° from the RD is analyzed. The drawn specimens sectioned along these directions are presented in Fig. 3.

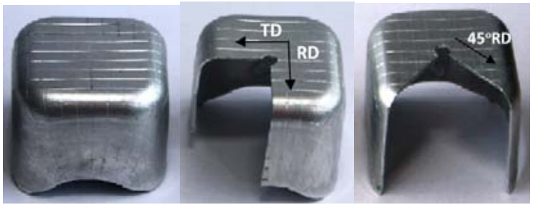

Fig.3. Photos of the deformed parts cut along 0°, 45° and 90° from the RD

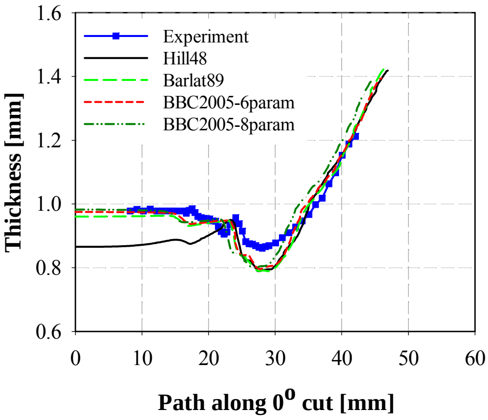

Fig.4. Comparison of the numerical results and experimental data referring to the wall thickness of the square cup cut along the RD

The measurements of the wall thickness along the specified paths were carried out using a DEA GLOBAL SILVER, Coordinate Measuring Machine. The measurement methodology consisted in getting points on the interior and exterior wall relative to a coordinate system. The local values of the thickness were obtained by numerical processing of the point coordinates.

The AutoForm FE software package has been used for simulating the square cup deep-drawing process. Four simulations with different yield criteria have been performed in order to study the accuracy of the thickness predictions.

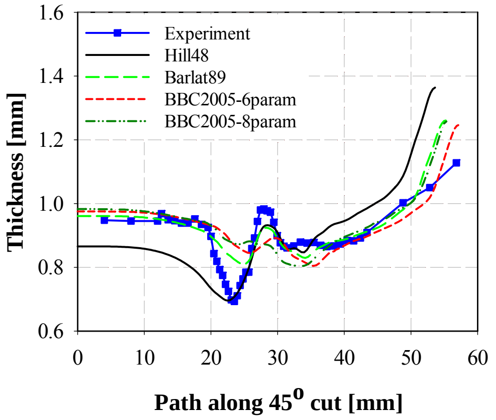

Fig.5. Comparison of the numerical results and experimental data referring to the wall thickness of the square cup cut at 45° from the RD

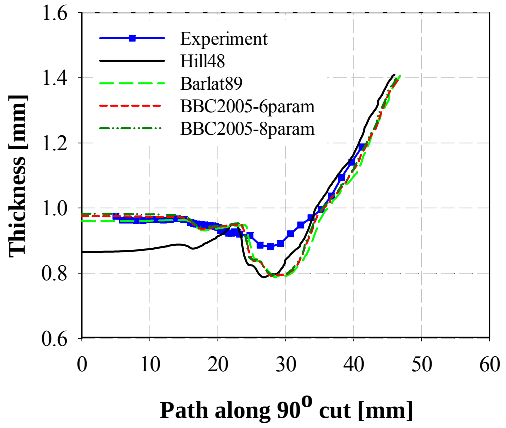

Fig.6. Comparison of the numerical results and experimental data referring to the wall thickness of the square cup cut along the TD

The diagrams in Figures 4-6 show the thickness distribution along the 0°, 45° and 90° cutting planes, as predicted by the FE program for the final stage of the deep-drawing process. The experimental data obtained from optical measurements is also presented on the graphs. One may notice that the least accurate thickness predictions along all three directions on the bottom of the cup are given by Hill48 yield model. The predictions provided by the other yield criteria along rolling and transverse directions are grouped together and almost follows the experimental data. A slightly discrepancy is observed after the radius fillet, on the vertical wall of the part. On the section cut at 45° from the rolling direction all the yield criteria capture with enough accuracy two thinner portions experimentally detected in the neighbourhood of the fillet radius.

5. CONCLUSION

The aim of this paper consists in evaluating the influence of the yield criteria on the quality of the thickness predictions of square deep-drawing cup. The analysis performed by the authors in the case of AA6016-T4 aluminium alloy reveals a close relationship between the number of mechanical parameters used in the identification procedure of the yield criterion and predictions of the thickness distribution. As a conclusion, using a larger number of mechanical characteristics lead to a better numerical results.

6. REFERENCES

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7. ACKNOWLEDGMENTS

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