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Effect of the constitutive laws on the accuracy of sheet metal simulation

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Abstract. During the last three decades, numerical simulation has gradually extended its applicability in the field of sheet metal forming. Constitutive modeling is one of the domains closely related to the development of numerical simulation tools. The paper is devoted to a comprehensive testing of the advanced materials models as implemented in the finite-element code. The test proves the capability of the advanced materials models response of DC04 steel sheet to describe the effects of the plastic anisotropy of the sheet metals subjected to industrial forming processes.

Introduction

The accuracy of the simulation results is given mainly by the accuracy of the material model. In the last years, the scientific research is oriented in developing of new material models able to describe the material behavior (mainly the anisotropic one) as accurate as possible [1]. The computer simulation of the sheet metal forming processes needs a quantitative description of the plastic anisotropy by the yield locus [2]. During last decade, the CERTETA team has developed several anisotropic yield criteria (so-called BBC yield criteria). The first formulation of the yield criterion was proposed by Banabic et al. [3] and improved later [4], [5]. An improvement of this criterion was proposed recently by Banabic et al. [6], in order to account for an additional mechanical parameter, namely, the biaxial anisotropy coefficient. A modified version of the BBC2005 [7] yield criterion has been implemented in the AutoForm V4.1 (AF 4.1) commercial Finite Element program.

Comparison of the yield loci obtained using different identification strategies of the BBC2005 criterion

The BBC2005 yield criterion version implemented in the AutoForm 4.1 is presented in paper [7]. The particular cases of the BBC 2005 criterion using 4, 6, 7, or 8 mechanical parameters are presented in the book [2]. The material used in this study is DC04 steel sheet with 0.85 mm nominal thickness. 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 determined on samples cut at 0^o, 45^o and 90^o from the rolling direction (n and K represent the coefficients in the Hollomon's hardening law). The values of yield stresses are normalized (divided by the yield stress associated to the 0^o direction). Table 2 lists the biaxial material characteristics. These are the yield stress and the anisotropy coefficient corresponding to the equbiaxial loading along the rolling and transverse directions.Table 3 contains the values of the yield criterion coefficients corresponding to each of these identification cases.

Tabel 1 Uniaxial mechanical parameters of the DC04 steel (0.85 mm thickness)

Angle	r^{exp} [-]	$\sigma_\theta^{exp} / \sigma_0^{exp}$	n[-]	K[MPa]
0^o	1.95	1.00	0.21	526.75
45^o	1.29	1.06	0.20	541.323
90^o	2.19	1.04	0.20	513.559

Table 2 Biaxial mechanical parameters of the DC04 steel (0.85 mm thickness)

$\sigma_b^{exp} / \sigma_0^{exp}$	r_b^{exp} [-]
1.28	0.84

Table 3 Coefficients of the BBC2005 yield criterion (DC04 steel; 0.85 mm thickness)

Yield criterion/Mechanical parameters	a	b	L	M	N	P	Q	R
BBC2005 with 4 coefficients	0.1506	0.3109	0.5687	0.5580	0.5687	0.5580	0.5687	0.5580
BBC2005 with 6 coefficients	0.3323	0.3930	0.5005	0.4767	0.4886	0.4886	0.6092	0.5594
BBC2005 with 7 coefficients	1.0123	0.3291	0.3590	0.3355	0.4903	0.4903	0.6209	0.5705
BBC2005 with 8 coefficients	1.0139	0.3290	0.3519	0.3422	0.4936	0.4864	0.6205	0.5717

Fig. 1 shows a comparison of the yield loci predicted by different formulations of BBC2005. Three experimental points are also plotted on the same diagram. Due to the fact that both BBC2005 with 7 and 8 coefficients use in identification procedure the experimental value of σ_b^{exp}, the predictions of these formulations are more accurate.

Simulation of the deep drawing processes

The forming simulation results of a cross geometry are very sensitive to the chosen material model. This is demonstrated for a cross geometry made of a DC04 sheet material. Measured draw in values and thickness measurements are compared with AutoForm 4.1 simulations using the Hill48 [8] (using 4 mechanical parameters as BBC2005-4), the BBC2005-4, the BBC2005-6 and the BBC2005-7 models.

The geometry of the cross die example is shown in Fig. 2. The clearance between punch and die is 2.3 mm. In the experiments the sheet dimensions and the blank holder force (350 kN) were chosen such that a punch stroke of 60 mm could be reached without fracture. After stopping the forming after 60 mm punch stroke, the draw in and the thickness were measured along the two sections displayed in Fig. 3. The simulations of the cross die forming experiments were run with the Auto-Form Version 4.1 solver, employing three node shell elements with 5 integration points through the thickness.

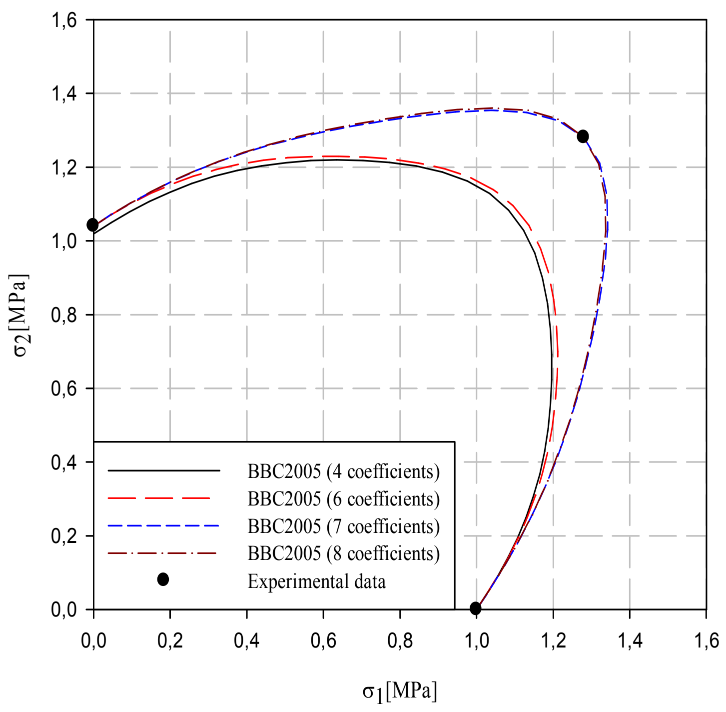

Figure 1. Yield loci predicted by using different BBC2005 models for DC04 steel

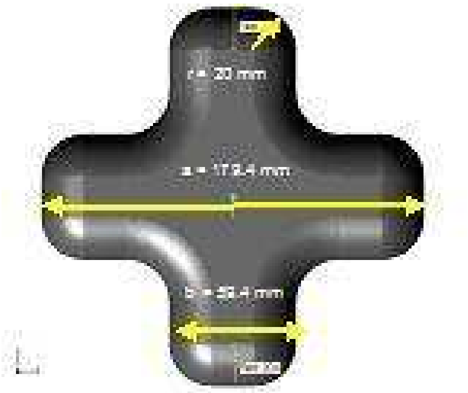

Figure 2. Punch geometry

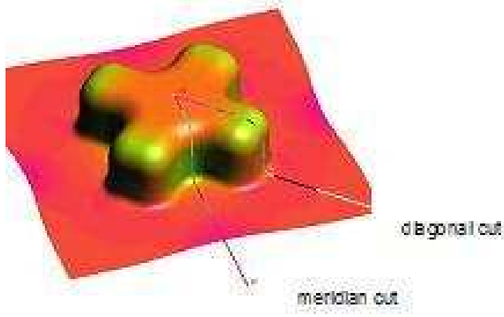

Figure 3. Thickness distribution at 60 mm punch stroke

The initial element size was set to 8 mm in all simulations, and adaptive refinement with "accuracy fine" was turned on. Typically, this resulted in 35 solution increments with 4000 elements at the beginning and 20000 elements at the end of the simulation. First of all, in simulations using the BBC2005-7 yield surface model the coefficient of Coulomb's friction law and the elastic stiffness of the tools were adjusted to measured draw in values along the diagonal and the meridian cut. A value of 0.05 for Coulomb's friction coefficient was found to give a satisfactory agreement between measured and computed. The following simulations with different yield surface models were run with these settings fixed. In Fig. 4 thickness measurements are compared with computed thickness distributions for the yield surfaces displayed in Fig. 1. The distances runs from the centre of the cross specimen outwards along the diagonal cut and the meridian cut as displayed in Fig. 3.

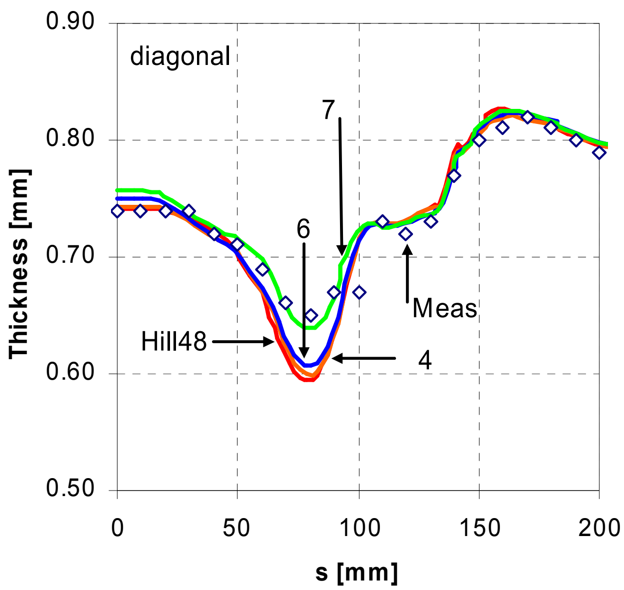

Figure 4. Measured and computed thickness for DC04

For the DC04 material, the simulation with the BBC2005-7 model matches the thickness measurements very well. Especially, the minimum thickness is predicted accurately. All the other yield surface descriptions yield higher deformations and, thus, overestimate the risk of failure for that part. The data is described much better by the BBC2005-7 model than by BBC2005-6 and BBC2005-4 (which is identical with the Barlat89 model [9]). The widely used Barlat89 model largely overestimates the risk of failure for that part. The question remains if the prediction could be further improved by taking also the r_b value into account with help of the BBC2005-8 model.

Since no measured r_b value is available, this question was tackled with a purely numerical sensitivity analysis using the SIGMA module of AF 4.1 [2]. Two series of simulations were performed for the DC04 material. In the first series, only the σ_b value was varied while keeping the other material parameters fixed. In the second series, the same procedure was applied to the r_b value. The computed thickness is evaluated in the diagonal cut at the position of minimum thickness ($s \approx 80$ mm). The results are compared in Figs. 5 and 6. The dependency between the computed thickness and the biaxial yield stress σ_b is nearly linear, especially in the range 192 MPa ± 4.8 MPa (Figure 5). The value of 4.8 MPa was input as standard deviation for the SIGMA analysis. Since no statistical information was available for the DC04 material, the value was arbitrarily chosen to be 2.5 % of the value 192 MPa. The assumed standard deviation for the biaxial anisotropy parameter r_b is 0.02175 (2.5 % of the value 0.84). This means that even if r_b would have been measured and used in the simulation, it had no significant impact on the computed minimum thickness. In this light, for the cross die simulation the usage of the BBC2005-7 model is proven to be sufficiently accurate.

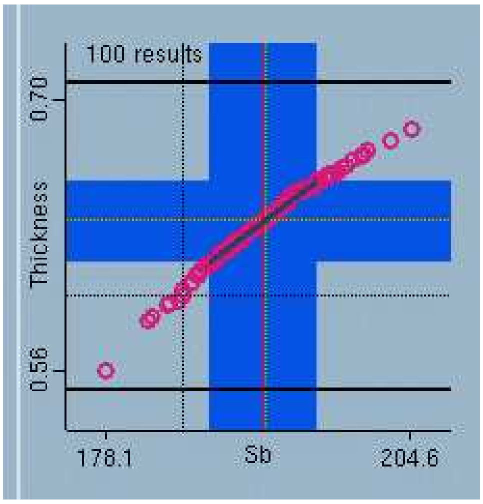

Figure 5. Variation of the equi-biaxial yield stress σ_b

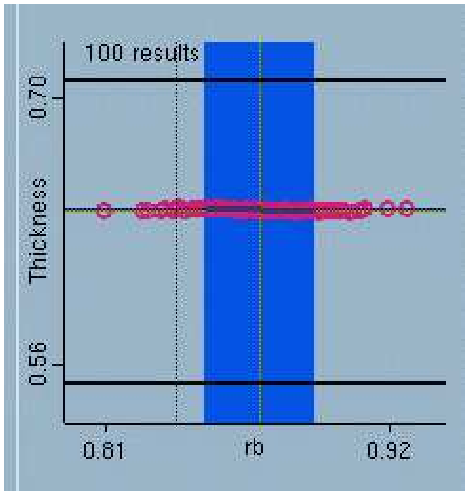

Figure 6. Variation of the equi-biaxial anisotropy r_b

Prediction of the Forming Limit Curves

The forming limit curves have calculated using the Marciniak-Kuczynski (M-K) model. The implicit scheme allows the reduction of the M-K model to the numerical solution of a single non-linear equation [2]. In order to avoid any divergence, the authors have used the bisection method coupled with a bracketing strategy.

Fig. 7 shows the forming limit curves predicted by the M-K model for different identification cases of the BBC2005 yield criterion (with 4, 6, 7 and 8 mechanical parameters). Some experimental points are also placed on the diagram. One may notice that the best predictions of the M-K model correspond to the cases when the BBC2005 yield criterion has been identified with 7 and 8 parameters. In both situations, the calculated curves are in the vicinity of the experimental points. If only 4 or 6 mechanical parameters are used in the identification procedure, the predictions of the M-K model overestimate the formability along the right branch of the FLD (tension-tension). The differences between the calculated limit curves can be easily explained by making reference to the shape of the yield loci shown in Fig. 1. In the cases when the identification procedure is based on 7 or 8 mechanical parameters, the distance between the plane strain and the equibiaxial point is shorter. As a consequence, the strain localization process will be accelerated and the right branch of the FLD will be lowered. Fig. 1 also shows that the equibiaxial yield stress has a considerably stronger influence on the shape of the yield locus than the equibiaxial coefficient of plastic anisotropy. Due to this fact, the forming limit curves predicted by the BBC2005 identified with 7 and 8 mechanical parameters are almost coincident.

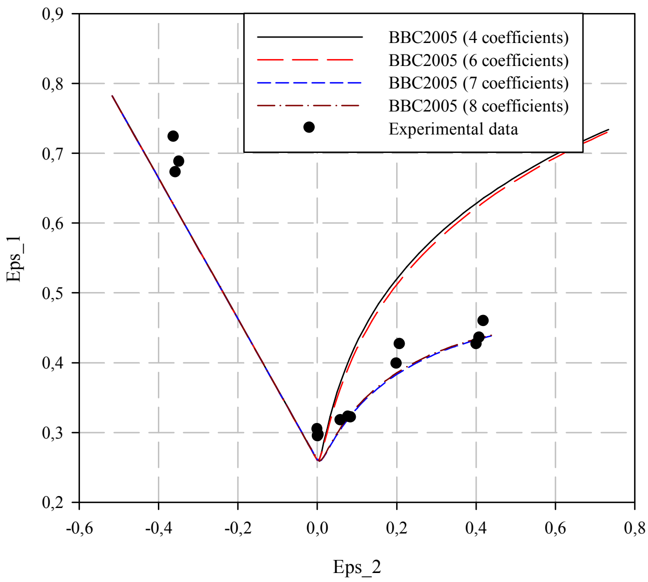

Figure 7. FLC predicted with MK model

Conclusions

The results presented in the paper prove the ability of the BBC2005 yield criterion to provide an accurate description of the anisotropic behaviour for steel. The performances of the model have been evaluated using the experimental data obtained from a cross-die benchmark tests and Forming Limit Diagram. The results demonstrate that for an accurate prediction of the sheet metal forming simulation it is crucial to take not only the uniaxial mechanical parameters into account but also the biaxial yield stress. The main conclusions of the results presented in this paper are the follows: first, the yield criterion has a crucial influence on the accuracy of the predicted results; second, it is not enough to use an advanced constitutive model, you also need a sufficient number of mechanical parameters to obtain an accurate prediction. From these parameters, the equibiaxial yield stress seems to have the most important influence both on the shape of the yield locus and the limit strains corresponding to the tension-tension branch of the FLD.

Acknowledgments

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