Materials and Manufacturing Processes, 27: 304–308, 2012

ISSN: 1042-6914 print/1532-2475 online
DOI: 10.1080/10426914.2011.578005

Influence of Material Models on the Accuracy of the Sheet Forming Simulation

D. Banabic[1] and M. Sester[2]

[1]*Center of Research for Sheet Metal Forming Technology "CERTETA", Technical University of Cluj-Napoca, Cluj-Napoca, Romania*
[2]*AutoForm Engineering GmbH, Zurich, Switzerland*

This article is devoted to a comprehensive testing of the advanced materials models as implemented in the finite-element code. The influence of the numbers of the mechanical parameters on the accuracy of the sheet metal forming simulation has been studied for two materials (DC 04 steel grade and Ac121-T4 aluminum alloys). The results presented in the article prove the ability of the BBC2005 yield criterion to provide an accurate description of the anisotropic behavior for both steel and aluminium alloys. The performances of the model have been evaluated using the experimental data obtained from cross-die benchmark tests. The results demonstrate that for an accurate prediction of the sheet metal forming simulation it is crucial to take not only the uniaxial yield stresses and r-values into account but also the biaxial yield stress.

Keywords Advanced yield criteria; Forming simulation; Sheet metal.

Introduction

The accuracy of the simulation results is given mainly by the accuracy of the material model. In the recent years, the scientific research is oriented in developing new material models able to describe the material behavior (mainly the anisotropic one) as accurately as possible [1–3]. The computer simulation of the sheet metal forming processes needs a quantitative description of the plastic anisotropy by the yield locus [4, 5].

In order to take into account anisotropy, the classical yield criterion proposed by von Mises should be modified by introducing additional parameters. A simple approximation for the case of normal anisotropy is given by the quadratic criterion of Hill [6]. Although the "anomalous" behavior is captured with this function, the predicted yield surfaces are sometimes different from those either determined experimentally or predicted with polycrystalline models. Another important research direction in the field was initiated by Hosford [7] who introduced a non-quadratic yield function for isotropic materials, based on the results of polycrystalline calculations. Barlat and Lian [8] successfully extended Hosford's 1979 criterion to capture the influence of the shear stress. Experimental determination of the biaxial yield stress is very important for these new models [9, 10]. During recent years, new yield functions were introduced in order to improve the fitting of the experimental results, especially for aluminium and magnesium alloys. Barlat proposed in 2003 [11] a new model particularized for plane stress (2D). The linear transformation method is used to introduce the anisotropy. Aretz and Barlat [12] and Barlat et al. [13] extended the Barlat 2000 model for the 3D case using 18 mechanical parameters. The implementation of the Barlat 2004-18p model in finite-element codes allowed proving its capability to predict the occurrence of six and eight ears in the process of cup drawing. To introduce orthotropy in the expression of an isotropic criterion, Cazacu and Barlat [14] proposed an alternative method based of the theory of the representation of tensor functions. The method is applied for the extension of Drucker's isotropic yield criterion to transverse isotropy and cubic symmetries. The experimental researches have shown that for some hexagonal close packed (HCP) alloys (e.g., titanium-based alloys) the yield surface is better described by fourth-order functions. As a consequence, in order to describe such behavior, Cazacu et al. [15] proposed the model of an isotropic yield function for which the degree of homogeneity is not fixed. Different strategies, for example genetic algorithm, have been used in the latest years to identify the coefficients of the complex yield functions [16]. In the latest period, different researchers have focused their attention on the influence of yield criteria in the accuracy of the prediction of strain distribution in sheet metal forming processes [17, 18].

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. [19]. An improvement of this criterion was proposed recently by Banabic et al. [20], in order to account for an additional mechanical parameter, namely, the biaxial anisotropy coefficient. A modified

Received December 5, 2010; Accepted March 7, 2011
Address correspondence to Prof. D. Banabic, Center of Research for Sheet Metal Forming Technology "CERTETA", Technical University of Cluj-Napoca, Str. Memorandumului nr. 28, Cluj-Napoca, Romania; E-mail: banabic@tcm.utcluj.ro

version of the BBC2005 yield criterion has been implemented in the AutoForm V4.1 (AF 4.1) commercial finite element program. More detailed reviews of numerous anisotropic yield criteria are given in the references [2], [4], and [21].

The BBC2005 yield criterion

The BBC2005 yield criterion version [18] implemented in the AutoForm 4.1 is presented in this section. The equivalent stress is defined by the following formula:

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

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:

$$\Gamma = L\sigma_{11} + M\sigma_{22}$$
$$\Lambda = \sqrt{(N\sigma_{11}-P\sigma_{22})^2+\sigma_{12}\sigma_{21}}$$
$$\Psi = \sqrt{(Q\sigma_{11}-R\sigma_{22})^2+\sigma_{12}\sigma_{21}}. \quad (2)$$

Nine material parameters are involved in the expression of the BBC equivalent stress: k, a, b, L, M, N, P, Q, and R (see Eqs. (1) and (2)). The integer exponent k has a special status, due to the fact that its value is fixed from the very beginning in accordance with the crystallographic structure of the material: $k=3$ for BCC materials and $k=4$ for FCC materials.

The identification procedure calculates the other parameters (a, b, L, M, N, P, Q, and R) by forcing the constitutive equations associated to the BBC yield criterion to reproduce the following experimental data: the uniaxial yield stresses associated to the directions defined by 0°, 45°, and 90° angles measured from RD (denoted as Y_0, Y_{45}, and Y_{90}); the coefficients of uniaxial plastic anisotropy associated to the directions defined by 0°, 45°, and 90° angles measured from RD (denoted as r_0, r_{45}, and r_{90}); the biaxial yield stress associated to RD and TD (denoted as Y_b); the coefficient of biaxial plastic anisotropy associated to RD and TD (denoted as r_b).

Table 1.—Different strategies to identify the coefficients in the BBC2005 yield function.

Mechanical parameter	BBC 2005-8	BBC 2005-7	BBC 2005-6	BBC 2005-5	BBC 2005-4	BBC 2005-2
σ_0	X	X	X	X	X	X
σ_{45}	X	X	X			
σ_{90}	X	X	X			
σ_b	X	X		X		
r_0	X	X	X	X	X	X
r_{45}	X	X	X	X	X	
r_{90}	X					
r_b						

There are eight constraints acting on eight material parameters. The identification procedure has enough data to generate a set of equations having a, b, L, M, N, P, Q, and R as unknowns. The identification procedure uses Newton's method to obtain its numerical solution. A detailed presentation of the identification procedure is presented in the paper [20]. The identification procedure can also use a reduced number of mechanical parameters (2, 4, 5, 6, or 7), as shown in Table 1.

Material tested

Two materials have been tested: DC04 steel sheet material (0.79 mm) and Ac121-T4 aluminium sheet material (1.01 mm), respectively.

Hardening Description

The parameters of a combined Swift–Hockett/Sherby approach are approximated from hardening curves measured in the 0^0 tensile tests:

$$\sigma = (1-\alpha)\left\{C\left(\varepsilon_{pl}+\varepsilon_0\right)^m\right\} + \alpha\left\{\sigma_{Sat} - (\sigma_{Sat}-\sigma_i)e^{-a\varepsilon_{pl}^p}\right\}. \quad (3)$$

The approximated hardening parameters are presented in Table 2. The yield stress σ_0 computed from these parameters is identical with the value used in the yield surface description.

Yield Surface Description

From the tensile tests, the three yield stresses σ_0, σ_{45}, σ_{90} and the three r-values r_0, r_{45}, r_{90} are known (see Table 3). From the load-deflection curves measured in the bulge tests, the biaxial yield stress σ_b can be derived. In the bulge tests, no strain measurement was performed. Therefore, the r_b-values of the materials are not known. The plane strain test data is not used. The yield surfaces of the yield functions presented in the Table 1 are displayed in the principal stress plane. The BBC2005-8 formulation is missing because a measured r_b value is not available.

For the DC04 material, the yield surface of the Hill48 model is plotted in addition to the various forms of the

Table 2.—Hardening parameters of DC04 and Ac121-T4.

Material	α	ε_0	m	C [MPa]	σ_i [MPa]	σ_{Sat} [MPa]	a	P
DC04	0.50	0.0061	0.26	561	153	415	6.13	0.8
Ac121-T4	0.50	0.0070	0.29	492	130	330	9.08	0.96

Table 3.—Yield stresses and r-values of DC04 and Ac121-T4.

Material	σ_0 [MPa]	σ_{45} [MPa]	σ_{90} [MPa]	σ_b [MPa]	r_0	r_{45}	r_{90}	r_b
DC04	151	166	163	192	1.83	1.39	2.11	–
Ac121-T4	126	122	121	137	0.65	0.40	0.77	–

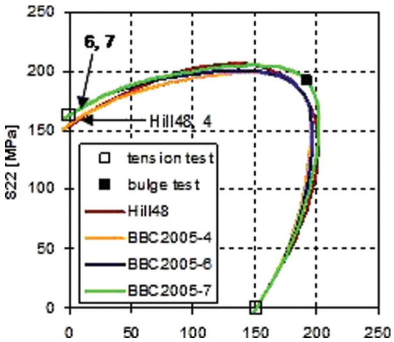

FIGURE 1.—Yield surfaces of the DC04 material (color figure available online).

BBC2005 model (Fig. 1). Uniaxial yield stresses σ_0 and σ_{90} from the tensile tests and biaxial yield stress from the bulge test are plotted as data points. All yield functions use the given r-values as input. This is why the slopes of the yield surfaces in the uniaxial points are the same for all models. The BBC2005-7 model describes all measured yield stresses exactly because all of them are used as input parameters for the model. The BBC2005-6 model matches only the measured σ_{90} value but not the σ_b value. Finally, the BBC2005-4 curve and the Hill48 curve do not pass σ_{90} and σ_b but only σ_0.

The Hill48 model is a special case of the BBC2005-4 model with $M = 2$ instead of $M = 6$. Therefore, these models have the same uniaxial and biaxial yield stresses. The biggest differences between the Hil48 curve and the BBC2005-4 curve is in the plane strain region (see Fig. 1).

For the yield surfaces of the Ac121-T4 material shown in Fig. 2, the previous discussion of the data in Fig. 1 holds as well. The only difference is that only the BBC2005 models are displayed, which is because the Barlat89 model is identical with the BBC2005-4 model.

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

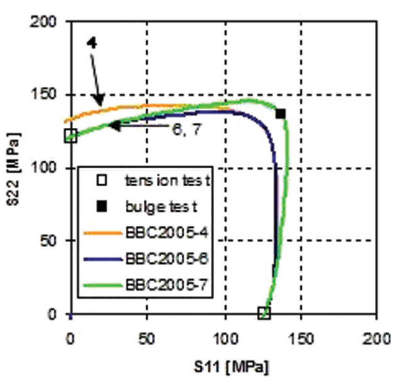

FIGURE 2.—Yield surfaces of the Ac121-T4 material (color figure available online).

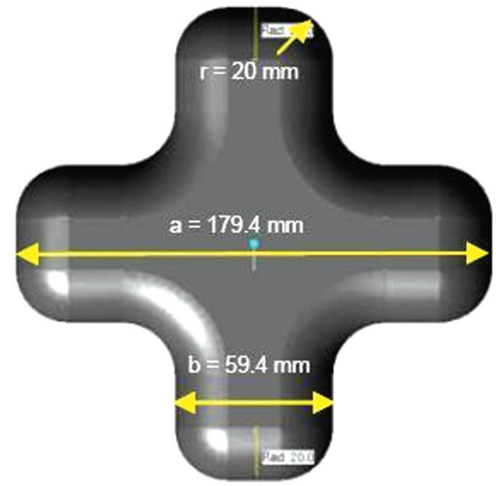

FIGURE 3.—Punch geometry (color figure available online).

and a Ac121-T4 sheet material, respectively. Measured draw in values and thickness measurements are compared with AutoForm 4.1 simulations using the Hill48 (using four 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. 3.

The clearance between punch and die is 2.3 mm. In the experiments, the sheet dimensions and the blank holder force 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. 4. The blank holder forces are 350 kN for steel sheet and 116 kN for aluminium sheet. The simulations of the cross-die forming experiments were run with the Auto-Form Version 4.1 solver, employing three node shell elements with five integration points through the thickness. The initial element size was set

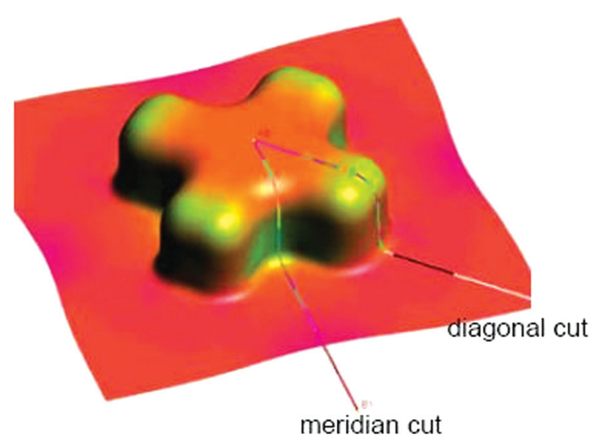

FIGURE 4.—Sheet at punch stroke 60 mm, with sections for draw in and thickness measurements (color figure available online).

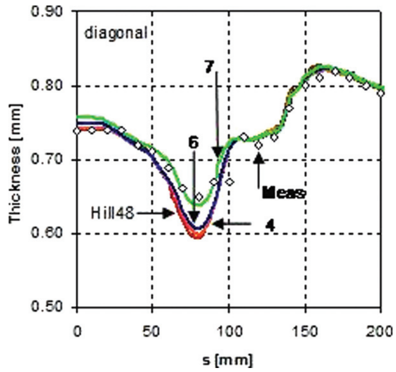

FIGURE 5.—Measured and computed thickness for DC04 (color figure available online).

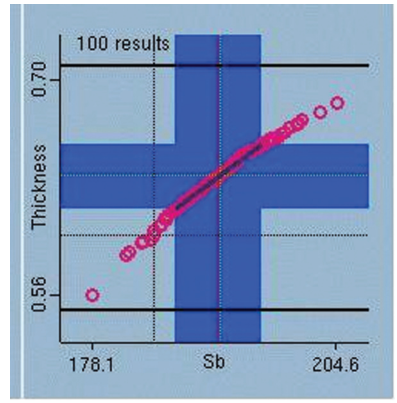

FIGURE 7.—Variation of the equi-biaxial yield stress, σ_b (color figure available online).

to 8 mm in all simulations, and adaptive refinement with "accuracy fine" was turned on. Typically, this resulted in 35 solution increments with 4,000 elements at the beginning and 20,000 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 draw in both for DC04 and Ac121-T4. The elastic stiffness of the blankholder was increased by a factor of 20 compared to the AutoForm default value. This was necessary in order to take the effect of thickening under the blankholder into account. The following simulations with different yield surface models were run with these settings fixed.

In Figs. 5 and 6, thickness measurements are compared with computed thickness distributions for the yield surfaces displayed in Figs. 1 and 2. The distance runs from the centre of the cross-specimen outwards along the diagonal cut and the meridian cut as displayed in Fig. 4.

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. For the Ac121-T4 material, the BBC2005-7 simulation matches the thickness measurements rather well, especially in the meridian cut. 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). 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. 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. 7 and 8.

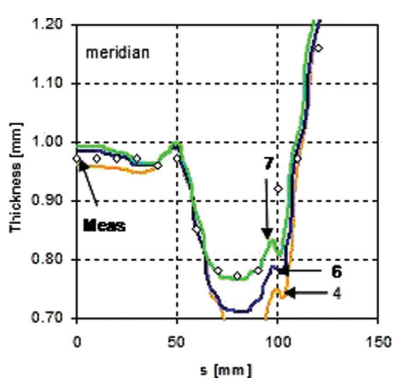

FIGURE 6.—Measured and computed thickness for Ac121-T4 (color figure available online).

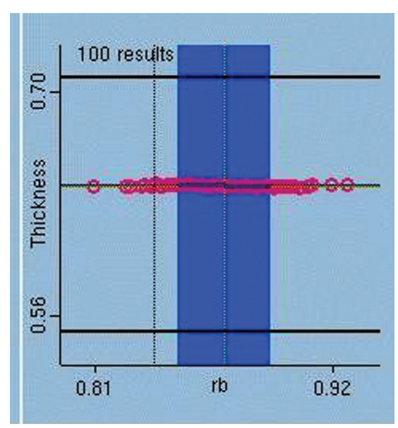

FIGURE 8.—Variation of the equi-biaxial anisotropy coefficient, r_b (color figure available online).

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 (Fig. 7). 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 0.87). This means that even if r_b had 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.

Conclusions

The results presented in the article prove the ability of the BBC2005 yield criterion to provide an accurate description of the anisotropic behavior both for steel and aluminium alloys. The performances of the model have been evaluated using the experimental data obtained from a cross-die benchmark tests. The results demonstrate that, for an accurate prediction of the sheet metal forming simulation it is crucial to take not only the uniaxial yield stresses and r-values into account, but also the biaxial yield stress. The main conclusions of the results presented in this article are the following ones: first, the yield criterion has a crucial influence on the accuracy of the predicted results; secondly, it is not enough to use an advanced constitutive model, but one also needs a sufficient number of mechanical parameters to obtain an accurate prediction.

Acknowledgments

DB's work was supported by the Romanian National University Research Council (CNCSIS), Program PCCE, Grant No. 6/2010.

References

1. Banabic, D.; Bunge, H.J.; Pöhlandt, K.; Tekkaya, A.E. *Formability of Metallic Materials*; Springer: Heidelberg-Berlin, 2000.
2. Banabic, D.; Barlat, F.; Cazacu, O.; Kuwabara, T. Anisotropy and formability. In *Advances in Material Forming*; Chinesta, F., Cueto, E., Eds.; Springer: Heidelberg-Berlin, 2007; 143–173.
3. Banabic, D.; Tekkaya, E.A. Forming simulation. In *Virtual Fabrication of Aluminum Alloys: Microstructural Modeling in Industrial Aluminum Production*; Hirsch, J., Ed.; Wiley-VCH: Weinheim, 2007; 275–302.
4. Banabic, D. *Sheet Metal Forming Processes*; Springer: Heidelberg-Berlin, **2010**.
5. Natal Jorge, R.M.; Valente, R.A.F.; Roque, A.P.; Parente, M.P.L.; Fernandes, A.A. Numerical simulation of hydroforming process involving a tubular blank with dissimilar thickness. *Materials and Manufacturing Processes* **2007**, *22*, 286–291.
6. Hill, R. A theory of the yielding and plastic flow of anisotropic metals. *Proc. Royal Soc.* **1948**, *A193*, 281–297.
7. Hosford, W.F. On yield loci of anisotropic cubic materials. In *Proc. 7th North American Metalworking Conf.*, Dearborn, MI, May 13–16, 1979; 191–197.
8. Barlat, F.; Lian, J. Plastic behaviour and stretchability of sheet metals (Part 1). *A yield function for orthotropic sheet under plane stress conditions. Int. J. Plasticity* **1997**, *5*, 51–56.
9. Vallellano, C.; Morales, D.; García-Lomas, G.F. A study to predict failure in biaxially stretched sheets of aluminum alloy 2024-T3. *Materials and Manufacturing Processes* **2008**, *23*, 303–310.
10. Karthikeyan, L.; Senthilkumar, V.S.; Padmanabhan, K.A. Biaxial stressing of sheets of friction stir processed aluminum alloy A319. *Materials and Manufacturing Processes* **2010**, *25*, 1297–1303.
11. Barlat, F. et al. Plane stress yield function for aluminium alloy sheets. *Part I: Formulation. Int. J. Plasticity* **2003**, *19*, 1297–1319.
12. Aretz, H.; Barlat, F. General orthotropic yield function based on linear stress deviator transformations. In *Materials Processing and Design: Modelling, Simulation and Applications*; Ghosh, S., Castro, G.C., Lee, J.K., Eds.; Proc. of the NUMIFORM 2004 Conference: Columbus, OH, 2004; 147–151.
13. Barlat, F.; Aretz, H.; Yoon, J. W.; Karabin, M. E.; Brem, J. C.; Dick, R. C. Linear transformation-based anisotropic yield functions. *Int. J. Plasticity* **2005**, *21*, 1009–1039.
14. Cazacu, O.; Barlat, F. Generalization of Drucker's yield criterion to orthotropy. *Mathematics and Mechanics of Solids* **2001**, *6*, 613–630.
15. Cazacu, O.; Plunkett, B.; Barlat, F. Orthotropic yield criterion for hexagonal close packed metals. *Int. J. Plasticity* **2006**, *22*, 1171–1194.
16. Jackiewicz, J. Assessing coefficients of the Barlat yield criterion for anisotropic aluminum alloy sheets by means of the evolutionary strategy. *Materials and Manufacturing Processes* **2009**, *14*, 375–383.
17. Hariharan, K.; Raghu, V.; Prakash, M.; Sathya, P. Influence of yield criteria in the prediction of strain distribution and residual stress distribution in sheet metal formability analysis for a commercial steel. *Materials and Manufacturing Processes* **2010**, *25*, 828–836.
18. Banabic, D. et al. Influence of constitutive equations on the accuracy of prediction in sheet metal forming simulation. In *Numisheet 2008 Conference*, Interlaken, September 1–5, 2008; 37–42.
19. Banabic, D. Kuwabasa, T.; Balan, T.; Comsa, D. S.; Julean, D. Non -quadratic yield criterion for orthotropic sheet metals under plane-stress conditions. *Int. J. Mechanical Sciences* **2003**, *45*, 797–811.
20. Banabic, D.; Aretz, H.; Comsa, D. S.; Paraianu, L. An improved analytical description of orthotropy in metallic sheets. *Int. J. Plasticity* **2005**, *21*, 493–512.
21. Banabic, D.; Barlat, F.; Cazacu, O.; Kuwabara, T. Advances in anisotropy and formability. *Int. J. Mater. Form.* **2010**, *3*, 165–189.