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Effect of the mechanical parameters used as input data in the yield criteria on the accuracy of the finite element simulation of sheet metal forming processes

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Abstract. The accuracy of the finite element simulation of sheet metal forming processes is mainly influenced by the shape of the yield surface used in the mechanical model and, in particular, by the number of input values used in the identification of the yield surface. This paper investigates the effect of the input values used for identifying the BBC 2005 yield criterion on the accuracy of the finite element predictions. The accuracy assessment of the simulation is based on the comparison of the numerical predictions obtained using the commercially available finite element (FE) code AutoForm and the experimental measurements obtained from the hydraulic bulging of sheet metals. Thickness and strain distributions, as well as the geometry of the bulged specimen were taken as comparison parameters. The accuracy of the finite element predictions obtained using the Hill-48 and Barlat-89 yield criteria is also studied and discussed in comparison with the results provided by the BBC 2005 yield criteria and the experimental data.

Introduction

In the last years, significant efforts have been made to improve the accuracy of the finite element simulation of sheet metal forming processes. The accuracy of the predictions is mainly influenced by the adequate modelling of the plastic deformation of sheet and therefore by the yield criteria and number of input data used to model the yield surface. Advanced constitutive models have been developed and implemented in various finite element codes, such as the Hill'48 [1], Barlat '89 [2] in ABAQUS, AutoForm and LS-Dyna, BBC 2005 [3] in AutoForm and the Vegter model [4] in Pam Stamp. These yield criteria need a certain number of input material parameters for determining the yield functions: Hill 48 model uses 2 or 4, Barlat 89 uses 4, BBC 2005 uses between 6 and 8, while BBC 2008 [5] uses between 8 and 24 material parameters. Of course, the use of a large number of mechanical parameters implies the increase of identification costs [6]. One of the widely used methods to asses the performance of the different yield criterion is the comparison of the strains provided by the finite element with the experimental data from different forming processes [7-10].

The aim of this paper is to investigate the effect of the input values used for identifying the BBC 2005 yield criterion on the accuracy of the finite element predictions. The accuracy of the finite element predictions obtained using the BBC 2005-6, the BBC 2005-7 and the BBC 2005-8 yield criteria is studied and discussed in comparison with the results provided by the Hill 48-2, the Hill 48-4 and Barlat-89 yield criteria and the experimental data. The performance of the six different yield criteria is done by comparison of the numerical predictions obtained using the commercially available FE-code AutoForm and experimental measurements obtained from the hydraulic bulge test. The polar thickness and strain distributions, as well as the geometry of the bulged specimen were taken as comparison parameters.

Material

An AA 6016-T4 aluminium alloy metallic sheet with 1 mm nominal thickness is considered in this paper for the experiment and finite element simulation. Table 1 shows the mechanical parameters of the AA6016 T4 aluminum alloy. This data was obtained from uniaxial tensile tests performed with specimens cut from the metal sheet in different orientations defined by 0˚, 45˚ and 45˚ angles measured from the rolling direction (RD) i.e. the yield stresses (σ_0, σ_{45} and σ_{90}) and the anisotropy coefficients (r_0, r_{45} and r_{90}). The hydraulic bulge test was used to determine the biaxial yield stress (σ_b) and the biaxial anisotropy coefficient (r_b). More details related to the method for the determination of σ_b and r_b from the hydraulic bulge test can be found in [11].

Table 1 Mechanical properties of the AA6016 T4 aluminium alloy (thickness: 1.0 mm)

Material	σ_0[MPa]	σ_{45}[MPa]	σ_{90}[MPa]	σ_b[MPa]	r_0	r_{45}	r_{90}	r_b
AA6016-T4	139	137	136	140.76	0.724	0.547	0.602	1.05

Hardening description. The true stress - true plastic strain curves from the tensile tests of five specimen oriented in the rolling direction were fitted using the Hockett-Sherby approximation, described by the equation (1), and the material parameters were determined as shown in Table 2. Figure 1 shows the representation of hardening curve of the AA6016 T4 aluminium alloy.

$$\sigma = \sigma_{Sat} - (\sigma_{Sat} - \sigma_i) \cdot \exp(-a \cdot \varepsilon_{pl}^{p}) \qquad (1)$$

Table 2 Hockett-Sherby hardening law parameters of the tested material

Material	σ_{Sat}[MPa]	σ_i[MPa]	a	p
AA6016-T4	370.43	134.5	6.7	0.878

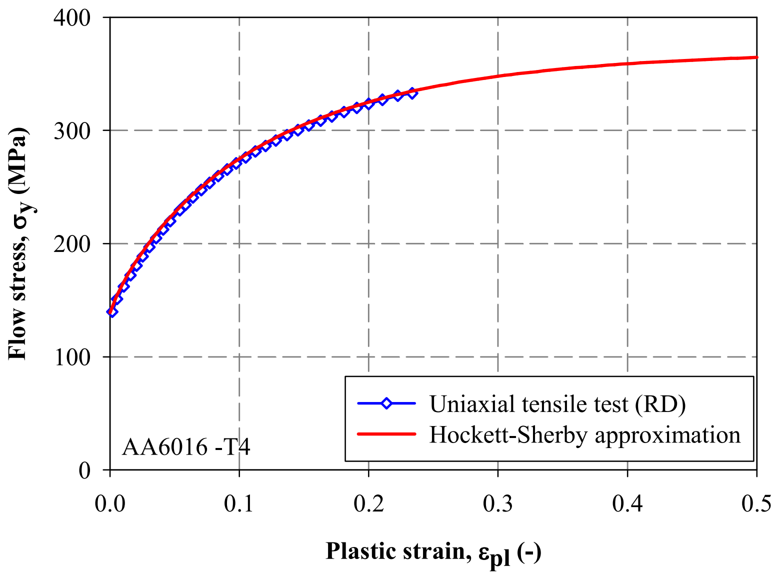


Fig. 1. Stress-strain curves of AA6016 T4 aluminium alloy sheet

Yield surface description. The yield models provided by the Hill 48-2, Hill 48-4, Barlat-89, BBC 2005-6, BBC 2005-7 and BBC 2005-8 are used to obtain the yield surfaces for the AA6016 T4 aluminium alloy. The experimental mechanical parameters given in Table 1 are used as input data in the identification procedure to obtain the coefficients of each yield criterion. The strategies used in the "Material generator" module of AutoForm program to generate the yield surfaces are presented in Table 3.

Table 3 The mechanical parameters used as input data in the yield criteria

Mechanical parameters	Hill'48-2	Hill'48-4	Barlat'89-4	BBC2005-6	BBC2005-7	BBC2005-8
σ_0	●	●	●	●	●	●
σ_{45}				●	●	●
σ_{90}				●	●	●
σ_b					●	●
r_0	●	●	●	●	●	●
r_{45}		●	●	●	●	●
r_{90}		●	●	●	●	●
r_b						●
M	2	2	8	8	8	8

Figure 2 shows the yield surface obtained using the above mentioned yield criteria and the identification strategies given in table 3 in comparison with the experimental points. In this paper, the bulge test with a biaxial stress state at the pole is used to compare the performance of the yield models, in relation to their ability to accurately predict the experimental data. As a consequence, it is significant to evaluate the yield surface provided by each model in the region of the biaxial stress state. One may notice in Figure 2 that all models in which the biaxial stress is missing, underestimate the experimental biaxial yield point. Only the yield surfaces provided by the BBC 2005-7 and the BBC 2005-8 yield criteria, which use the biaxial yield stress in the identification procedure, pass through the biaxial yield point.

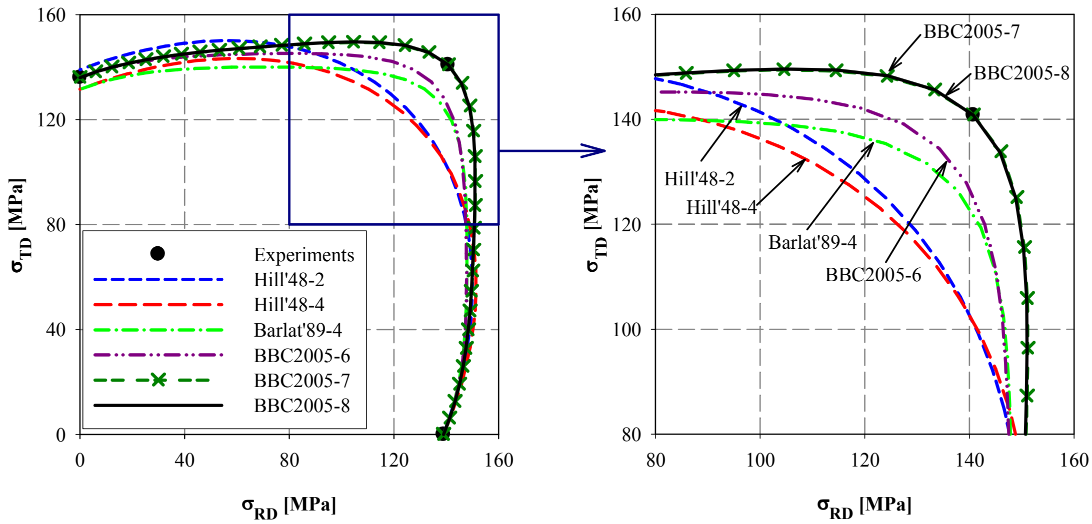
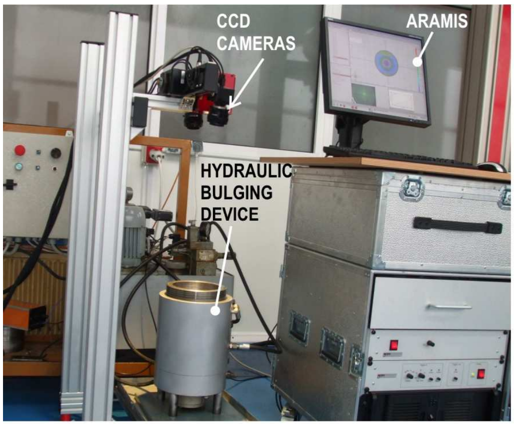
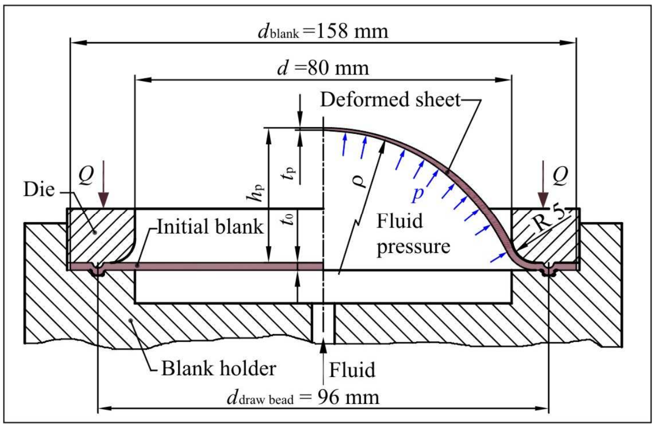


Fig. 2. Yield surfaces for the AA6016 T4 aluminum alloy

Experiments

The hydraulic bulge test is carried out using the experimental set-up presented in Figure 3. This consists in a bulging device which is connected to a hydraulic pump to create the required pressure for the testing process as well as to ensure the clamping force during the experiment. The laboratory stand is equipped with a measurement system which enables to measure the fluid pressure during the experiment. The blank is firmly clamped on its contour between a blank holder and a die, Figure 3.b (left side). When the fluid gets into the hydraulic chamber, the blank is deformed through a die heaving a circular aperture Figure 3.b (right side). A die with an aperture diameter (d) of 80 mm and a fillet radius (R) of 5 mm was used to perform the bulge experiments. A 3D optical measurement system ARAMIS with two CCD cameras was used to measure the strain and geometry of specimen during the bulge test.



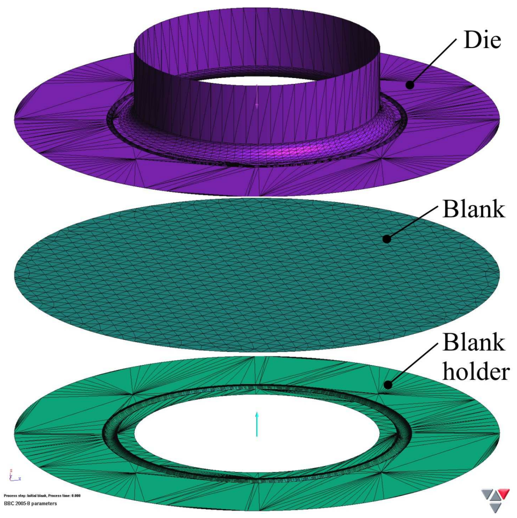


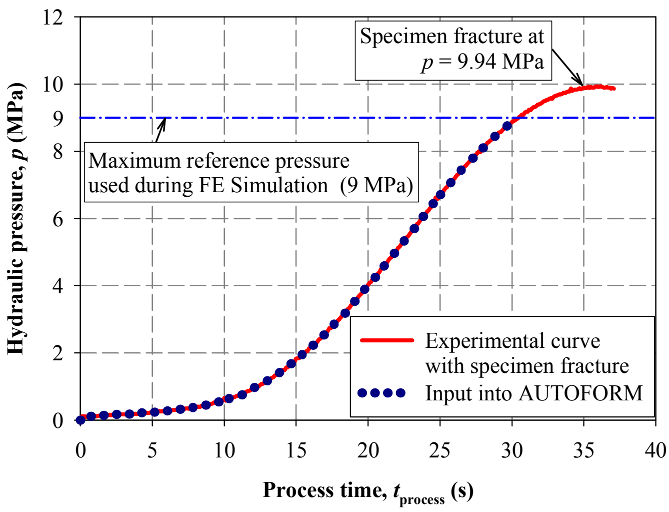
a) b)

Fig. 3. Hydraulic bulge test: a)-experimental devices; b)-geometry of the bulge test

Simulation of the hydraulic bulge test

The finite-elements model of the bulge test was developed using the commercially available finite element code AutoForm^{plus} R2 4.4 [12]. The geometry of the FE model was similar to the experiment shown in Figure 3.b. The finite element model of the bulge test includes the die, the blank holder and the blank (Fig. 4.a). Shell elements with the initial size of 3 mm without adaptive refinement during the simulation were used. The Hockett Sherby approximation, described in the Table 2, was used to model the hardening curve in all simulations. The simulations were repeated with six different yield surface models: Hill'48-2, Hill'48-4, Barlat'89-4, BBC2005-6, BBC2005-7 and BBC2005-8, as described in Table 3. The Hydro Mech process step and "active pressure" option were used for the simulation of the bulging processes, which made possible to indicate the hydraulic pressure as a function of process time, as shown Figure 4.b. The final hydraulic pressure was set on 9 MPa. In the simulation, a constant friction coefficient of 0.08 was set between the blank and tools. The bulge height and the strain distribution during the bulging steps and at the final stage were computed for each case of yield surface model.





a) b)

Fig. 4. Finite element model of the bulge test (a) and the applied hydraulic pressure (b)

Results and discussion

In order to asses the ability of the Hill'48-2, Hill'48-4, Barlat'89-4, BBC2005-6, BBC2005-7 and the BBC2005-8 yield criteria, the results provided by finite element simulation were compared with the experimental data from the hydraulic bulge test.

Figure 5.a shows the distribution of dome height versus fluid pressure provided by the finite element simulation in comparison with the experimental data. From this diagram one may notice that the experimental curve is fitted sufficiently accurate by all yield criteria except the Hill'48-2 and Hill'48-4 yield models, which overestimate the experimental data especially at the final stages of the deformation. A similar trend is observed when the distribution of the polar thickness versus hydraulic pressure is considered, as shown in Figure 5.a.

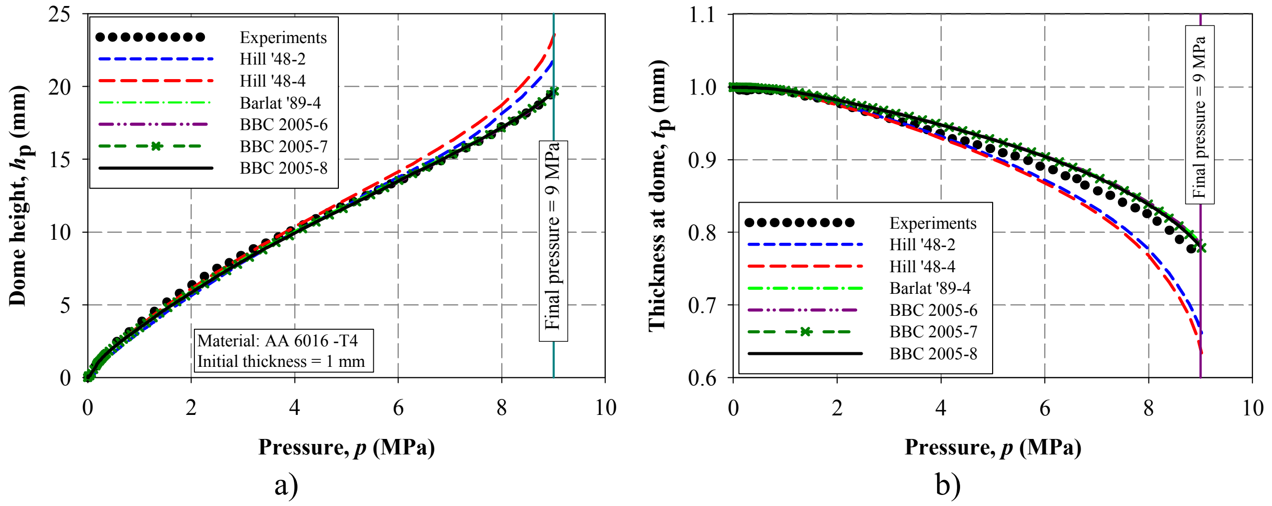


Fig. 5. Comparison between FE simulation and experimental results for a)-dome height versus pressure and b)-thickness at dome apex versus pressure

Figure 6 shows the distribution of the thickness strain versus the distance measured from the bulge axis. From this diagram one may notice that the results provided by the BBC 2005-7 and BBC 2005-8 show the best agreement with the experimental data. The reason for this behavior is that the above mentioned models use the biaxial yield stress as input data in the identification. Furthermore, the diagram also shows that Barlat'89 and BBC 500-6 models provide good results, which means that the FE-code AutoForm is able to predict the biaxial yield stress sufficiently precise.

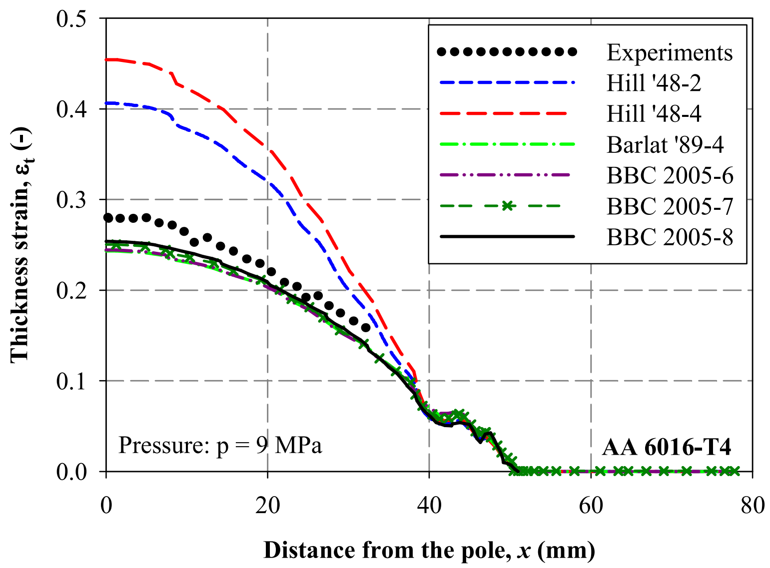


Fig. 6. Comparison between FE simulation and experiment for thickness-strain distribution

Conclusion

In this paper the performance of the Hill'48-2, Hill'48-4, Barlat'89-4, BBC2005-6, BBC2005-7 and BBC2005-8 yield criteria has been evaluated by comparing the finite element predictions with the experimental data provided by the ARAMIS system from the hydraulic bulge test. The results obtained in the paper show that the BBC 2005 yield criteria are in very good agreement with the experimental data. The predictions of the yield criteria are very sensible to the number of input data. The results of the finite element simulation are in the best agreement with the experimental data, when the whole set of eight input parameters is used.

Acknowledgements

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