

Modelling of anisotropic behaviour and forming limits of sheet metals

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ABSTRACT

In the last decades, numerical simulation has gradually extended its applicability in the field of sheet metal forming. Constitutive modelling and formability are two domains closely related to the development of numerical simulation tools. This paper is focused, on the one hand, on the presentation of new phenomenological yield criteria developed in the last decade, which are able to describe the anisotropic response of sheet metals, and, on the other hand, on new models and experiments to predict/determine the forming limit curves.

Keywords: Anisotropy, Constitutive modelling, Formability, Sheet forming

ANISOTROPIC YIELD CRITERIA

The accuracy of the simulation results is given mainly by the accuracy of the material model. In the last years, scientific research has been oriented towards the development of new material models able to describe the material behaviour (mainly the anisotropic one) as accurately as possible [1-11]. The computer simulation of the sheet metal forming processes needs a quantitative description of the plastic anisotropy by the yield locus.

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For the case of an isotropic metallic material, the well-known von Mises yield criterion is often sufficient to describe yielding. This is, however, not true for anisotropic materials, especially aluminium sheet metals. In order to take into account anisotropy, the classical yield criterion proposed by von Mises has been modified by Hill [12] by introducing the anisotropy coefficients.

Woodthorpe and Pearce [13] have found that the yield stress in balanced biaxial tension, σ_b , for aluminium alloy sheets having a r -value lying between 0.5 and 0.6 is significantly higher than the uniaxial yield stress in the plane of the sheet. However, Hill's quadratic criterion [12] cannot describe this behaviour, i.e., materials with $r < 1$ and $\sigma_b > \sigma_u$. To capture this so-called "anomalous" behaviour, non-quadratic yield formulations were considered [13].

Later on, several scientists have proposed more and more sophisticated yield functions for anisotropic materials. Hill [14] himself improved his criterion and proposed a non-quadratic form. Although the "anomalous" behaviour is captured with this function, the predicted yield surfaces are sometimes different from those either determined experimentally or predicted with polycrystalline models. Hill [15] included the shear stress component in the expression of anisotropic yield function. Hill [16] stated that none of previous criteria are able to represent the behaviour of a material exhibiting a tensile yield stress almost equal in value in the rolling and transverse direction, while r -values vary strongly with the angle to the rolling direction. Another important research direction in the field was initiated by Hershey [17] who introduced a non-quadratic yield function for isotropic materials, based on the results of polycrystalline calculations. This criterion was later generalized to anisotropic materials by Hosford [18]. This criterion is a particular expression of Hill's 1979 yield criterion. Its main advantage is that it leads to a

good approximation of yield loci computed using the polycrystalline Bishop-Hill model by setting $a=6$ for BCC materials and $a=8$ for FCC materials [19]. An important drawback of this as well as of Hill's non-quadratic yield criteria is that they do not involve shear stresses. Barlat and Lian [20] successfully extended Hosford's 1979 criterion to capture the influence of the shear stress.

Different other non-quadratic formulations were developed: Gotoh [21] introduced a fourth degree polynomial yield function; Budiansky [22] prescribed a parametric expression in polar coordinates of the yield function (extended by Tourki et al.[23]). Barlat et al. [24] developed a six-component yield function, by using a linear transformation of the stress state (extended successively by Barlat et al. [25], denoted Yld94 and by Barlat et al. [26], denoted Yld96). Karafillis and Boyce [27] proposed a general yield criterion using a "weighted" linear transformation (extended by Bron and Besson [28]).

During the last years, new yield functions were introduced in order to improve the fitting of the experimental results, especially for aluminium and magnesium alloys. In order to remove the disadvantages of the Barlat 1994 and Barlat 1997 yield criteria, while still preserving their flexibility, Barlat proposed in 2003 [29] a new model particularized for plane stress (2D) (Yld 2000) using the linear transformation on stresses. The yield function is defined by eight coefficients, determined using as input the values of the stresses and anisotropy coefficients in tension along three directions, the balanced biaxial flow stress and biaxial anisotropy coefficient.

Barlat et al. [30] and Aretz and Barlat [32] proposed a generalization of Yld 2000 model for 3D case using 18 mechanical parameters. The implementation of the Barlat

2004-18p model in finite-element codes [32] 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 [33] 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 [34] yield criterion to transverse isotropy and cubic symmetries [35]. The experimental researches [36] have shown that for some HCP alloys (e.g., magnesium and titanium based alloys) the yield surface is better described by fourth order functions. As a consequence, in order to describe such behaviour, Cazacu et al. [37] proposed the model of an isotropic yield function for which the degree of homogeneity is not fixed.

Vegter [38, 39] proposed the representation of the yield function with the help of Bezier's interpolation using directly the test results (pure shear point, uniaxial point, plain strain point and equi-biaxial point).

Hill [40] proposed in 1950 a general formulation of a plane-stress anisotropic yield criterion having the polynomial expression. Gotoh [21] succeeded to apply that idea in the 1970's by developing a polynomial yield function of fourth degree. During the last years, a new family of polynomial yield criteria has been created on the basis of Hill's idea by Comsa [41]. Soare [42] proposed three yield criteria expressed by polynomial functions of 4th, 6th and 8th order, respectively (Poly4, Poly6 and Poly8).

Barlat 2003, Vegter 1995 and BBC 2005 models have been implemented in the last decade in the main FE commercial softwares (see Table 1).

	Hill 1948	Hill 1990	Barlat1989	Barlat 2003	Vegter1995	BBC2005
ABAQUS						
AUTOFORM						
LS-DYNA						
MARC						
PAM STAMP						

Table 1. The main FE commercial software and the anisotropic yield criteria implemented in them

Table 2 presents the main yield criteria developed for description of the anisotropic plastic behaviour. The mechanical parameters used for the identification of the models are also presented. The following notations have been used in the table: 3D- criterion can be extended to spatial stress states; A1 and A2- the criterion can describe the first and second order anomalous behaviour (see more details in [6]).

CERTETA is a Romanian research centre belong the Technical University of Cluj Napoca that supports metal forming companies in developing advanced and efficient technologies (see more details in the CERTETA webpage: <http://certeta.utcluj.ro/>). The CERTETA team has developed several anisotropic yield criteria. A description of these developments is presented in the next section.

ADVANCED YIELD CRITERIA DEVELOPED IN THE CERTETA RESEARCH CENTRE

In 2000 the members of CERTETA started a research program having as principal objective the development of a model able to provide an accurate description of the yield surfaces predicted by texture computations. The new formulation [43], [44] was developed on the basis of the formulation proposed by Barlat in 1989 [20].

Author, Year	σ_0	σ_{30}	σ_{45}	σ_{75}	σ_{90}	σ_b	Γ_0	Γ_{30}	Γ_{45}	Γ_{75}	Γ_{90}	Γ_b	3D	A1	A2
Hill's Family															
Hill 1948	x						x		x		x		x		
Hill 1979	x					x	x						x	x	
Hill 1990	x		x			x	x		x					x	
Hill 1993	x					x	x	x			x			x	x
Lin, Ding 1996	x					x	x	x			x			x	x
Hu 2005	x		x			x	x	x			x		x	x	x
Leacock 2006	x		x			x	x	x			x			x	x
Hershey's Family															
Hosford 1979	x						x				x		x	x	
Barlat 1989	x						x				x			x	
Barlat 1991	x		x			x	x						x	x	
Karafillis, Boyce 1993	x		x			x		x			x		x	x	x
Barlat 1997	x		x			x	x	x			x		x	x	x
Banabic 2000	x		x			x	x	x			x		x	x	x
Barlat 2000	x		x			x	x	x			x			x	x
Bron, Besson 2003	x		x			x	x	x			x	x	x	x	x
Barlat 2004	x	x	x	x		x	x	x	x	x	x	x	x	x	x
Banabic 2005	x		x			x	x	x			x	x	x	x	x
Banabic 2008	x	x	x	x		x	x	x	x	x	x	x	x	x	x
Aretz, Barlat 2012	x	x	x	x		x	x	x	x	x	x	x	x	x	x
Drucker's Family															
Cazacu-Barlat 2001	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Cazacu-Barlat 2003	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Cazacu-Pluncket 2006	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Polynomial criteria															
Gotoh 1977	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Comsa, Banabic 2007	x		x			x	x	x			x	x	x	x	x
Soare 2007 (Poly 4, 6,8)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Other criteria															
Ferron 1994	x		x			x			x		x			x	
Vegter 1995	x	x	x	x	x	x	x	x	x	x	x			x	x

Table 2. The main yield criteria and experimental data to be evaluated for their material parameters identification [6]

The version published in 2005 [45] incorporates a number of 8 coefficients and, consequently, its identification procedure uses 8 mechanical parameters (3 uniaxial yield stresses, 3 uniaxial coefficients of anisotropy, the biaxial yield stress and the biaxial coefficient of plastic anisotropy). An improvement of this criterion has been implemented in the finite element commercial code AUTOFORM version 4.1 [46]. The equivalent stress is defined by the following formula:

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

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

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

Nine material parameters are involved in the expression of the BBC equivalent stress: k , a , b , L , M , N , P , Q and R (see Eqns (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; $k=4$ 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) (see more details in [6]).

The BBC 2005 model can be reduced to Hill 1948 or Barlat 1989 yield criteria if are choose appropriate values of the material parameters (see more details in [6]).

The yield criterion proposed by Barlat and Lian in 1989 can be obtained by enforcing the following constraints on the material parameters:

$$Y = Y_0, \quad k = 3 \text{ or } 4, \quad L = N = Q, \quad M = P = R \tag{3}$$

The identification procedure needs only r_0 , r_{45} and r_{90} as input data.

Another situation of practical interest is the so-called normal anisotropy ($r_0=r_{45}=r_{90}=r$, $Y_0=Y_{45}=Y_{90}=Y$). In this case, BBC 2005 also reduces to the Hill 1948 or Barlat 1989 yield criteria (depending on the value of the exponent k):

$$k = 1 \text{ (Hill 1948)}, \quad k = 3 \text{ or } 4 \text{ (Barlat 1989)},$$

$$a = \frac{1}{1+r}, \quad b = \frac{r}{1+r}, \quad L = N = Q = M = P = R = \frac{1}{2} \quad (4)$$

Figure 1 shows a comparison of the yield loci predicted by different formulations of BBC2005 for AA6016-T4 aluminium alloy [47]. The mechanical parameters of the tested alloy are the following: $\sigma_0=139$ MPa, $\sigma_{45}=137$ MPa, $\sigma_{90}=136$ MPa, $\sigma_b=140.76$ MPa, $r_0=0.724$, $r_{45}=0.547$, $r_{90}=0.602$, $r_b=1.05$. 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. The presented results show the ability of the BBC2005 yield criterion to provide an accurate description of the anisotropic behaviour for AA6016-T4 aluminium alloy.

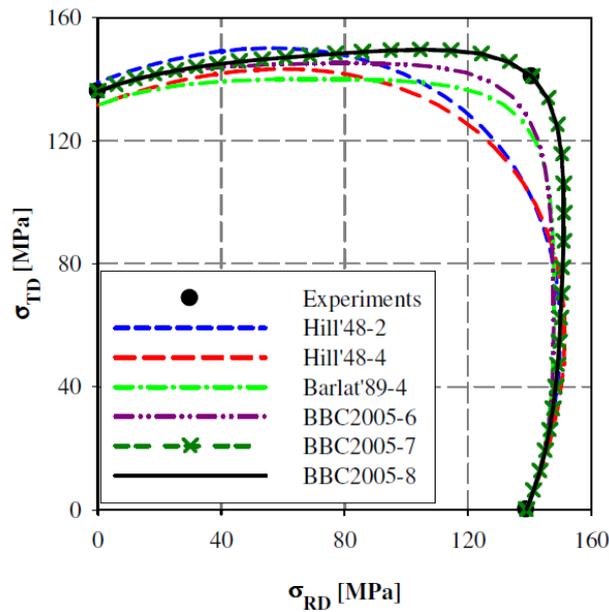


Figure 1 Yield loci predicted by using different versions of the BBC2005 model for AA6016-T4 aluminium alloy

Figure 2 shows the distribution of the thickness strain versus the distance measured from the bulge axis [47]. 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 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.

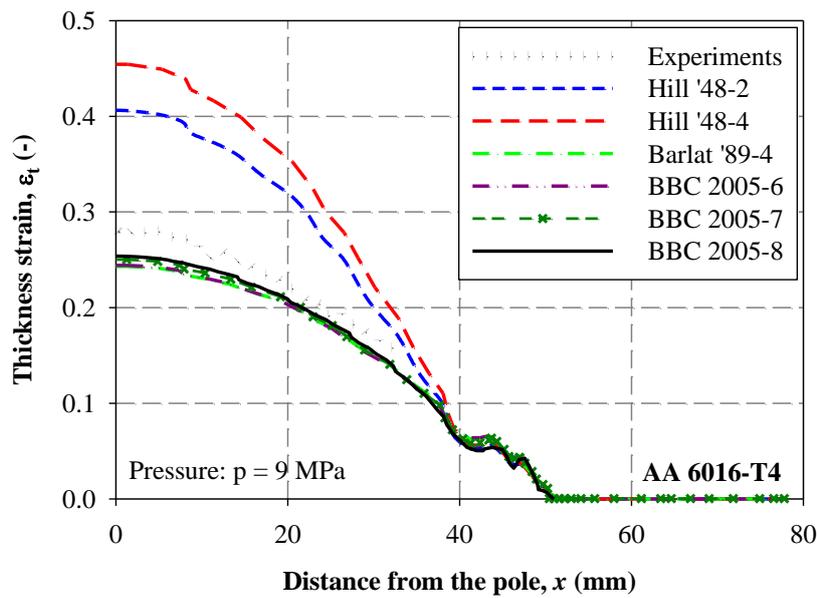


Figure 2. Comparison between FE simulation and experiment for thickness-strain distribution

In order to enhance the flexibility of the BBC2005 yield criterion, a new version (BBC2008) of this model has been developed [48]. The model is expressed as a finite series that can be expanded to retain more or fewer terms, depending on the amount of experimental data. Different identification strategies (using 8, 16, 24, etc. input values) could be used in order to determine the coefficients of the yield function.

The BBC2008 equivalent stress is defined as follows:

$$\frac{\bar{\sigma}^{2k}}{w-1} = \sum_{i=1}^s \left\{ w^{i-1} \left\{ [L^{(i)} + M^{(i)}]^{2k} + [L^{(i)} - M^{(i)}]^{2k} \right\} + \right. \\ \left. w^{s-i} \left\{ [M^{(i)} + N^{(i)}]^{2k} + [M^{(i)} - N^{(i)}]^{2k} \right\} \right\}$$

$$k, s \in \mathbf{N}^* \quad w = (3/2)^{1/s} > 1$$

$$L^{(i)} = \ell_1^{(i)} \sigma_{11} + \ell_2^{(i)} \sigma_{22}$$

$$M^{(i)} = \sqrt{\left[m_1^{(i)} \sigma_{11} - m_2^{(i)} \sigma_{22} \right]^2 + \left[m_3^{(i)} (\sigma_{12} + \sigma_{21}) \right]^2} \quad (5)$$

$$N^{(i)} = \sqrt{\left[n_1^{(i)} \sigma_{11} - n_2^{(i)} \sigma_{22} \right]^2 + \left[n_3^{(i)} (\sigma_{12} + \sigma_{21}) \right]^2}$$

$$\ell_1^{(i)}, \ell_2^{(i)}, m_1^{(i)}, m_2^{(i)}, m_3^{(i)}, n_1^{(i)}, n_2^{(i)}, n_3^{(i)} \in \mathbf{R}.$$

The quantities denoted $k, \ell_1^{(i)}, \ell_2^{(i)}, m_1^{(i)}, m_2^{(i)}, m_3^{(i)}, n_1^{(i)}, n_2^{(i)}, n_3^{(i)}$ ($i=1, \dots, s$) are material parameters. One may prove that $k \in \mathbf{N}^*$ is a sufficient condition for the convexity of the yield surface defined by Eqn (5). The identification procedure to identify the coefficients is described in details in [6] and [48].

It is easily noticeable that Eqs. (5) reduce to the isotropic formulation proposed by Barlat and Richmond [49] if

$$\ell_1^{(i)} = \ell_2^{(i)} = m_1^{(i)} = m_2^{(i)} = m_3^{(i)} = n_1^{(i)} = n_2^{(i)} = n_3^{(i)} = 1/2, \quad i = 1, \dots, s \quad (6)$$

Under these circumstances, the exponent k may be chosen as in Barlat and Richmond's model, i.e. according to the crystallographic structure of the sheet metal: $k = 3$ for BCC materials ($2k = 6$), and $k = 4$ for FCC materials ($2k = 8$).

Due to the expandable structure of the yield criterion, many identification strategies can be devised. In the papers [6] and [48] is presented a procedure that uses only normalized yield stresses and r-coefficients obtained from uniaxial and biaxial tensile tests. An identification procedure that strictly enforces a large number of experimental constraints on the yield criterion would be inefficient in practical applications. The failure probability of such a strategy increases when the external restrictions become stronger. Taking into account this aspect, the authors have developed an identification procedure based on the minimization of the error-function [48].

Two versions of the BBC2008 yield criterion have been evaluated from the point of view of their performance [48]. They include 8 and 16 material coefficients, respectively, and correspond to the smallest values of the summation limit ($s=1$ and $s=2$). The identification of the BBC2008 (16 parameters) model has been performed using the following mechanical parameters: $y_{0^\circ}^{(\text{exp})}$, $y_{15^\circ}^{(\text{exp})}$, $y_{30^\circ}^{(\text{exp})}$, $y_{45^\circ}^{(\text{exp})}$, $y_{60^\circ}^{(\text{exp})}$, $y_{75^\circ}^{(\text{exp})}$, $y_{90^\circ}^{(\text{exp})}$, $y_b^{(\text{exp})}$, $r_{0^\circ}^{(\text{exp})}$, $r_{15^\circ}^{(\text{exp})}$, $r_{30^\circ}^{(\text{exp})}$, $r_{45^\circ}^{(\text{exp})}$, $r_{60^\circ}^{(\text{exp})}$, $r_{75^\circ}^{(\text{exp})}$, $r_{90^\circ}^{(\text{exp})}$ and $r_b^{(\text{exp})}$. In the case of BBC2008 (8 parameters), the input data has been restricted to the values $y_{0^\circ}^{(\text{exp})}$, $y_{45^\circ}^{(\text{exp})}$, $y_{90^\circ}^{(\text{exp})}$, $y_b^{(\text{exp})}$, $r_{0^\circ}^{(\text{exp})}$, $r_{45^\circ}^{(\text{exp})}$, $r_{90^\circ}^{(\text{exp})}$ and $r_b^{(\text{exp})}$.

The predictions of the BBC2008 model with 16 parameters are superior to those given by the 8-parameters version (see Figures 3, 4 and 5).

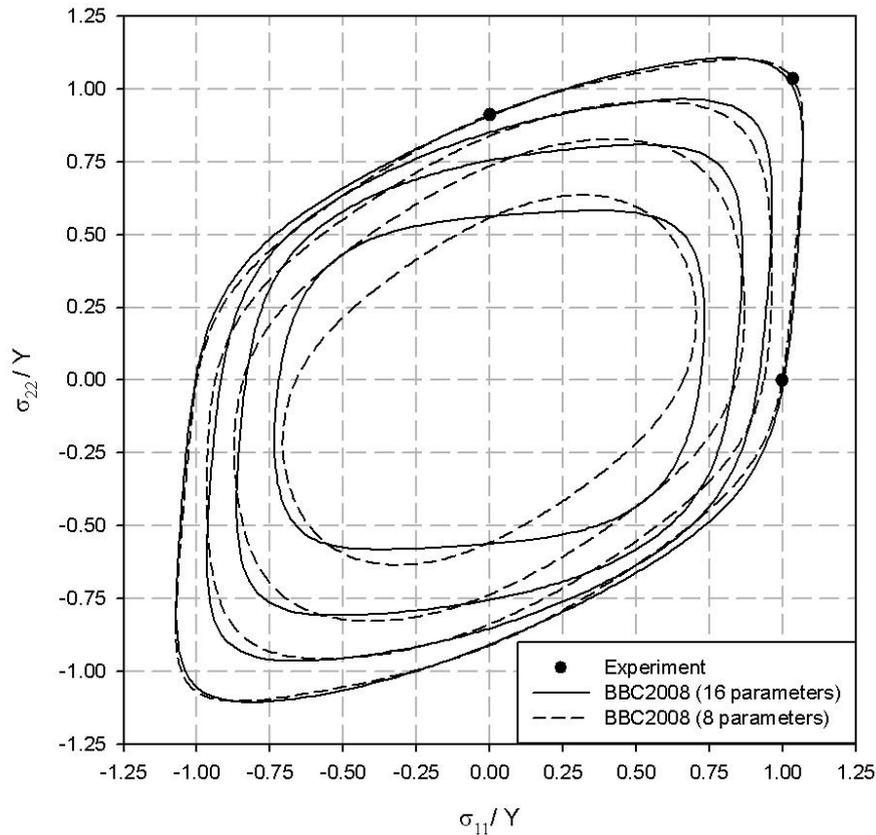


Figure 3. Normalized yield surface predicted by BBC2008 model for AA2090-T3 aluminium alloy

The improvement is noticeable especially in the case of the r -coefficients. This capability of the 16-parameter version is relevant for the accurate prediction of thickness when simulating sheet metal forming processes. For the materials exhibiting a distribution of the anisotropy characteristics that would lead to the occurrence of 8 ears in a cylindrical deep-drawing process [50], the planar distribution of the r -coefficient predicted by the BBC2008 yield criterion with 8 parameters is very inaccurate (see [48]). This model would not be able to predict the occurrence of more than 4 ears at the top edge of a cup deep-drawn from a circular blank. In contrast, the variation of the r -coefficient described by BBC2008 with 16 parameters closely follows the reference data. In conclusion, this model would predict the occurrence of 6 or 8 ears as reported by Yoon et al. [32]. As compared with other formulations described in the literature, the new model does not use

linear transformations of the stress tensor. Due to this fact, its computational efficiency should be superior in the simulation of sheet metal forming processes.

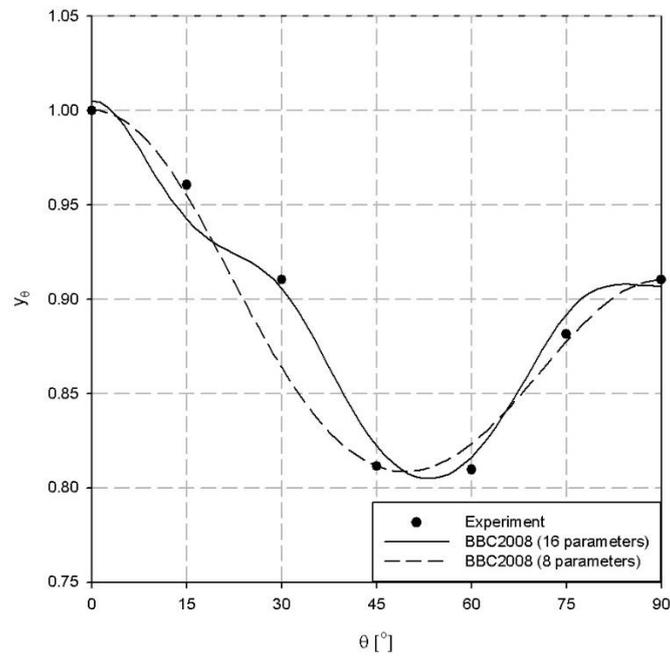


Figure 4. Planar distribution of the uniaxial yield stress predicted by BBC2008 model for AA2090-T3 aluminium alloy

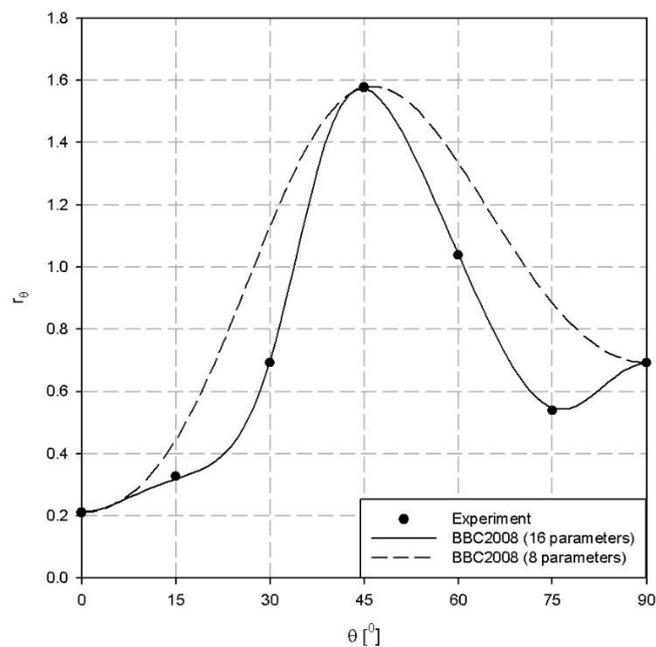


Figure 5. Planar distribution of the r-coefficient predicted by BBC2008 model for AA2090-T3 aluminium alloy

Figure 6a displays the simulated final geometry of deep drawn cup (for 16 parameters model) and the corresponding equivalent plastic strain distribution, whereas in Figure 6b a comparison between predicted and experimental ears is given [50]. Also, for the sake of comparison, the ears profile calculated with the Yld2004 model [32] is included.

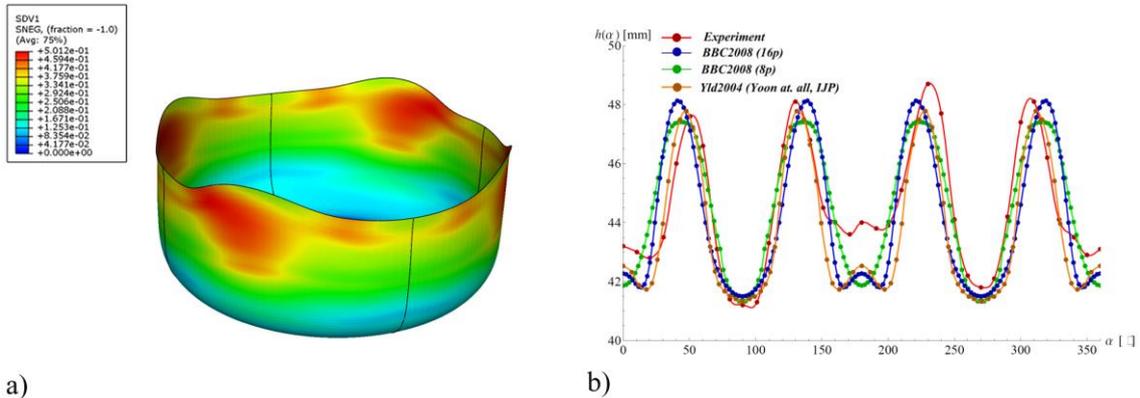


Figure 6. Earing prediction for aluminium AA2090-T3, a) simulation b) ears profile

Predictions of the BBC2008 model are in good agreement with the prediction of the Yld2004 model and also with the experiment [32]. As expected, the 8 parameters version was unable to predict 6 ears, which were experimentally observed. On the contrary, the 16 parameters version predicts 6 ears and their location, and at least qualitatively, the results are in good agreement with the experiment.

An extension of the BBC 2008 yield criterion has been proposed [51], [52], which provides adaptive updates of the local anisotropy in the integration points of the macroscopic FE model. The BBC 2008 model is systematically recalibrated to the data provided by the crystal plasticity virtual experiment framework (VEF) using the ALAMEL crystal plasticity model developed at the Catholic University Leuven [53]. An enhanced identification algorithm has been proposed [52]. The new algorithm exploits comprehensive material characterization delivered by the VEF. In Figure 7 is presented the comparison of BBC2008p16 calibrated by means of the basic identification procedure

and an enhanced procedure. Input data points (open symbols) were calculated by the stress-driven VEF according to the ALAMEL homogenization scheme. The normal directions to the yield locus sections are marked with arrows every $\Delta\theta = 15^\circ$. The arrows denoting the normals to the VEF/ALAMEL yield locus section are drawn longer merely for a clearer visual appearance [52]

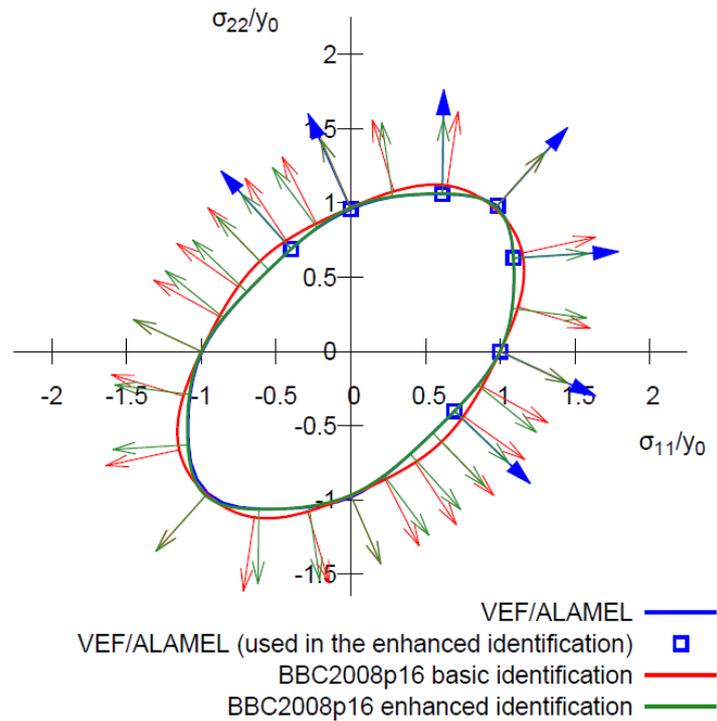


Figure 7. Comparison of BBC2008p16 calibrated by means of the basic identification procedure and the enhanced procedure [52]

A new hierarchical multi-scale (HMS) framework that allows taking into account evolution of the plastic anisotropy during sheet forming processes has also been proposed (see Figure 8 [52]). The earing number and height profile was measured experimentally drawn cups for an AA6016 T4 aluminium alloy and compared to simulations with the continuously calibrated HMS-BBC2008 model (Figure 9). The texture A, B, C and D denote texture at 0%, 25%, 50% depths and the average of the three, respectively.

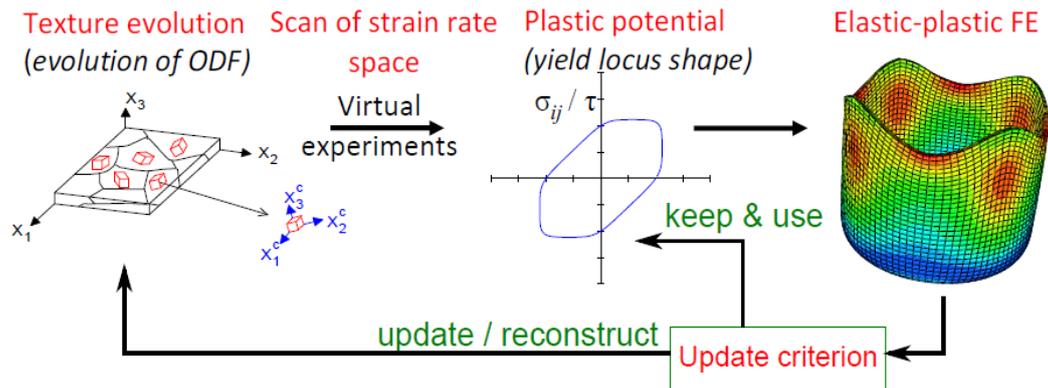


Figure 8. Hierarchical Multi-Scale (HMS) computational plasticity framework

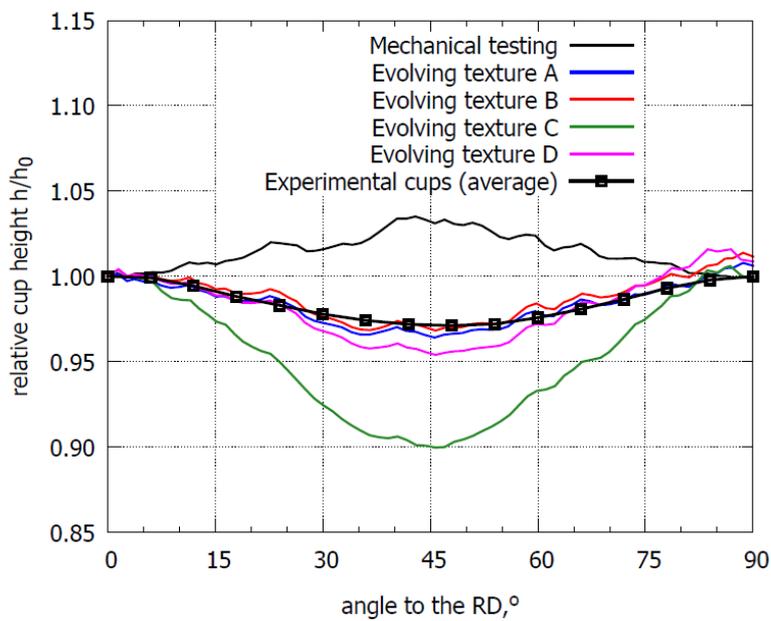


Figure 9. Comparison of experimental and predicted cup profiles using BBC 2008 model identified by mechanical testing and using the evolving anisotropy HMS-BBC 2008 [52]

As it can be seen in Figure 9, the HMS-BBC2008 simulations started from different textures tend towards decreasing ear height. With the only exception for the simulation initialized with the mid-thickness texture, the calculated cup profiles nearly coincide. Moreover, in terms of the ear height the predictions started from textures A, B and D are accurate. This indicates that the selection of the initial texture is important, but not

necessarily predetermines the deformation process and can be spontaneously corrected by the local deformation informed crystal plasticity code.

THEORETICAL AND EXPERIMENTAL DETERMINATION OF THE FORMING LIMIT CURVES

Several theoretical models and a new experimental method to determine the limit strains have been developed in the CERTETA research centre (presented below).

It is well known that the position and shape of the FLD is influenced by the shape of the yield surface adopted in the computational model [54], [55]. A sensitivity analysis regarding laws upon the limit strains is needed in the pre-processing stage.

Such an analysis is also useful for the sheet metal producers, when trying to obtain materials having desired formability characteristics. Aiming to meet these requirements, a software package named FORM-CERT able to calculate FLD's [56] has been developed in the CERTETA centre. The program is based on the Marciniak-Kuczynski (M-K) model of the necking process. A useful facility offered by the program is the possibility to perform the sensitivity analysis both for the yield surface and the forming limit curves. The numerical results can be compared with experimental data, using the import/export facilities included in the program. The program may be incorporated in finite element codes.

Recently, the CERTETA team used the Gurson's model with some recent extensions to model the porous material, following both the evolution of a homogeneous sheet and the evolution of the distribution of voids [57]. At each moment, the material is tested for a potential change of plastic mechanism, by comparing the stresses in the uniform region to those in a virtual band with a larger porosity. The main difference with the coalescence of voids in a bulk solid is that the plastic mechanism for a sheet admits a supplementary degree of freedom, namely the change in the thickness of the virtual band.

For strain ratios close to the plane-strain case, the limit-analysis (LA) model predicts almost instantaneous necking, but in the next step the virtual band hardens enough to deactivate the localization condition. In this case, a supplementary condition for incipient necking has been applied, similar to the one used in Hill's model for the second quadrant. It has been showed that this condition is precisely the one for incipient bifurcation inside the virtual (and weaker) band. Figure 10 compares again the results of the new LA necking model and M-K models. The following notations have been used: f -porosity in the LA model; f_a and f_b are the porosities in zones "a" and "b" in the MK model.

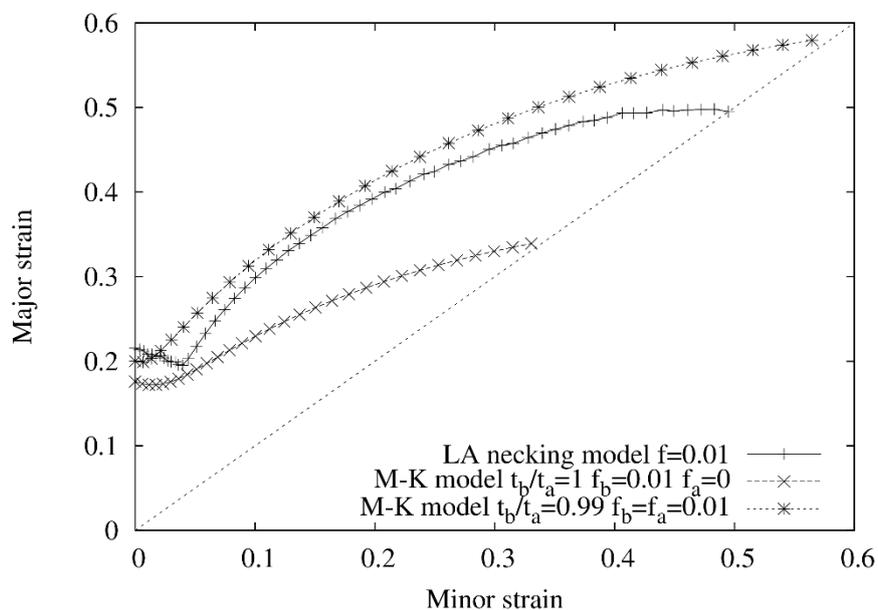


Figure 10. Numerical FLD predictions for Gologanu model: LA necking model versus M-K model.

The Gurson-Tvergaard-Needleman (GTN) damage model has been used to determine the FLC of AA6016-T4 aluminium alloy [58]. Figure 11 indicates that the results obtained by numerical simulation using the GTN damage model are in good agreement with the experimental data. The comparison becomes even more favourable when confronted with the predictions of the Marciniak-Kuczynski (M-K) model and the Modified Maximum

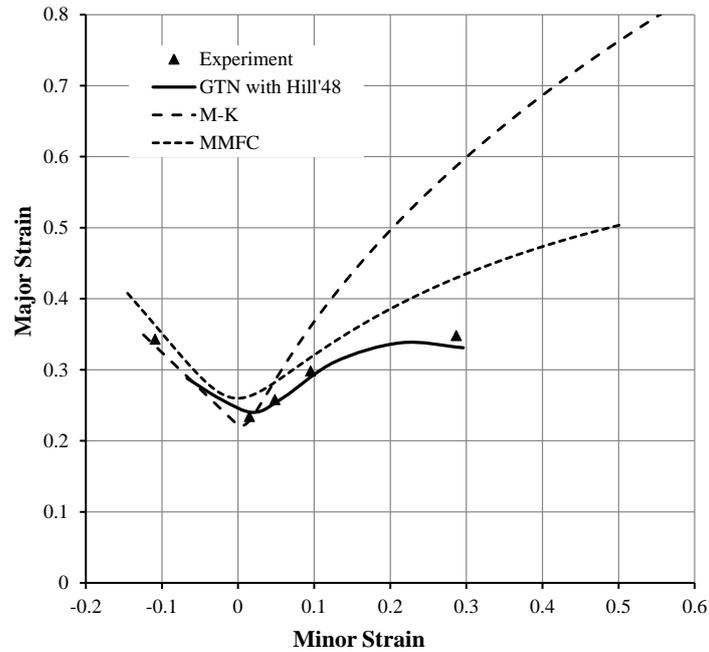


Figure 11. Comparison between the FLC obtained by different methods

Force Criterion (MMFC) [59] – see Fig. 11. The Hill'48 yield criterion has been used in the FLC predictions.

One may notice from the diagram that the quality of the GTN predictions is far better, especially along the right branch of the forming limit curve, where both M-K and MMFC models overestimate the formability of the metallic sheet. Fixing this deficiency can be achieved by implementing in the MK and MMFC plasticity models of non-quadratic criteria.

A drawback of the MMFC models is the fact that it contains a singularity that emerges if the yield locus contains straight line segments, like Barlat 2003 [29] or BBC 2005 [45]. Comsa and Banabic [60] removed this limitation of the MMFC criterion by modifying the initial formulation (Enhanced Maximum Force Criterion-EMFC). Comparison of the FLCs predicted by using different models (Marciniak-Kuczynski, Modified Maximum Force Criterion (Hora) and Enhanced Maximum Force Criteria +

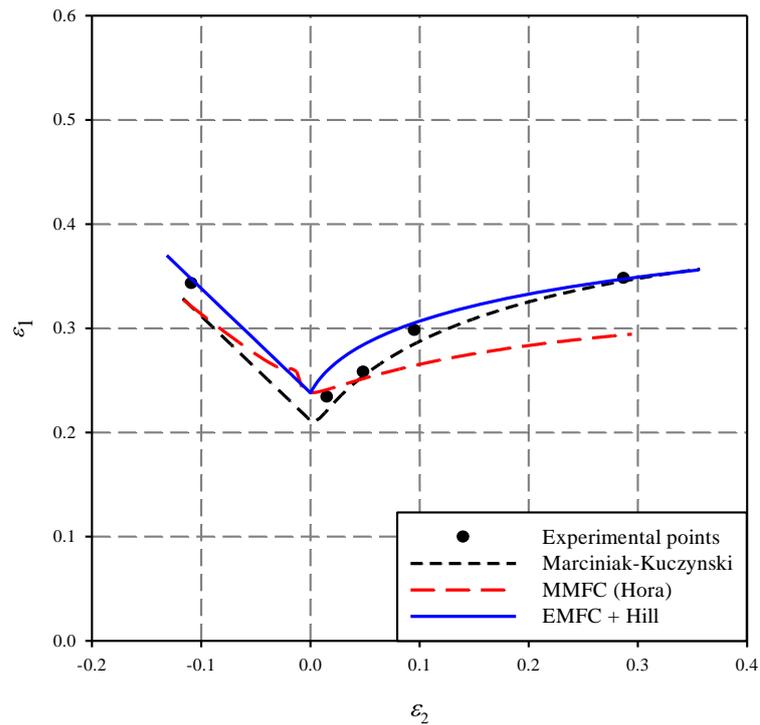


Figure 12. Comparison of the FLCs predicted by using different models with the experiments for AA6016-T4 aluminium alloy

Hill Criteria) models with the experiments for AA6016-T4 aluminium alloy is presented in the Figure 12.

Banabic and Soare [61], have analysed the influence of the normal pressure on the Forming Limit Curve using an enhanced Marciniak model. The Figure 13 show a significant increasing of the limit strains for any strain path (more significant in the equi-biaxial region) with the increasing of the superimposed hydrostatic pressure.

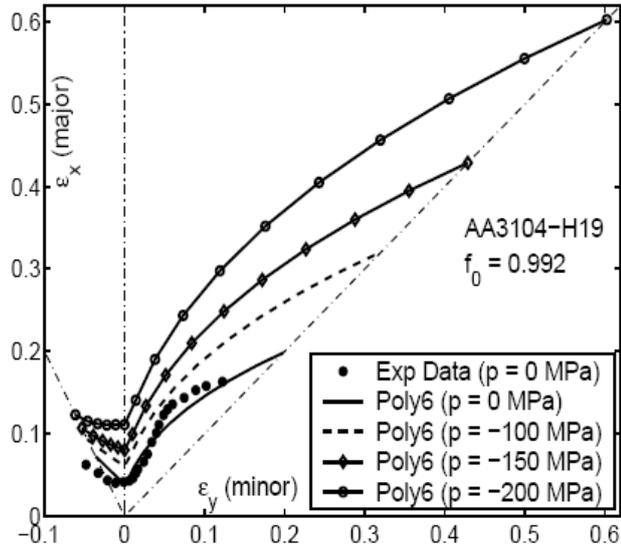


Figure 13. Forming Limit Curves for several values of the normal pressure for AA3104-H19 aluminium alloy [61]

The CERTETA team developed a new procedure for the experimental determination of the FLCs [62]. The methodology is based on the hydraulic bulging of a double specimen (Figure 14).

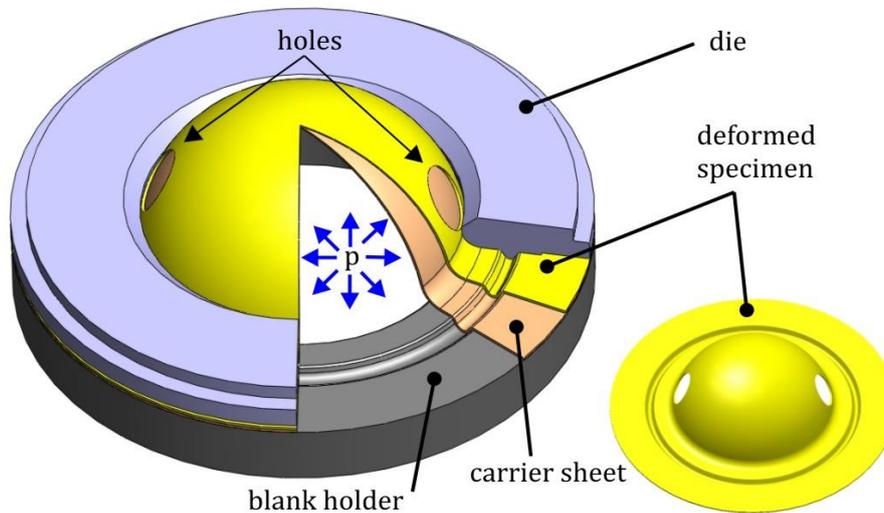


Figure 14. Schematic view of the new formability test

The upper blank has a pair of holes pierced in symmetric positions with respect to the centre, while the lower blank acts both as a carrier and a deformable punch. By modifying

the dimensions and reciprocal position of the holes, it is possible to investigate the entire deformation range of the FLC. The most important advantages of the method proposed by the authors are the following: capability of investigating the whole strain range specific to the sheet metal forming processes; simplicity of the equipment; simplicity of the specimen configuration; reduction of the parasitic effects induced by the frictional interactions between the specimen and the other elements of the experimental device; occurrence of the necking and fracture in the polar region of the specimen. The comparison between the FLCs determined using the new procedure and the Nakazima test shows minor differences.

Figure 15 compares the FLCs obtained using the methodology proposed by the authors and the Nakazima test (according to the specifications of the international standard ISO 12004-2). In both cases, the limit strains have been measured using the ARAMIS system.

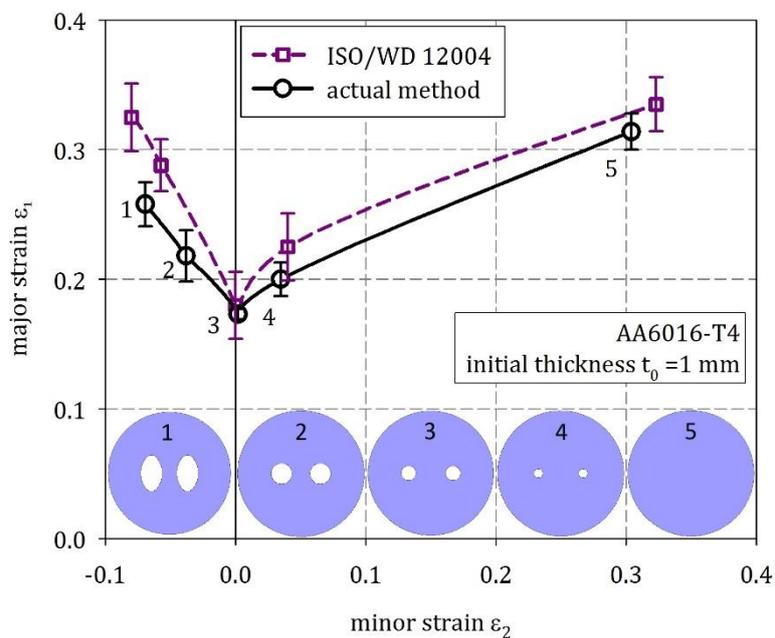


Figure 15. Forming Limit Diagram of the AA6016-T4 alloy

CONCLUSION

The accuracy of the simulation results is given mainly by the accuracy of the material models. As it has been shown in the previous chapters, advanced yield criteria allow accurate prediction of the anisotropic behaviour of materials. On the one hand, it is possible to simultaneously describe both the uniaxial yield stress variation and the anisotropic coefficient in the sheet. On the other hand, it is also possible to model both „first and second order anisotropic behaviour anomalies“. Furthermore, the yield criteria have also been extended to 3D. The asymmetry of the yield loci can be accurately predicted.

The new yield criteria developed in the last years in the CERTETA research centre show a very good prediction of the plastic anisotropy of sheet metals, especially for aluminium alloys. Comparison with data show that the new criteria presented can successfully describe anisotropic behaviour in both aluminium and steel sheets. In general, these models lead to yield surface shapes consistent with those predicted using polycrystal models. The biaxial yield stress and the biaxial anisotropy coefficient of the sheet metal are the parameters used in the identification procedure in the above-mentioned criteria. As shown by the results presented in this paper, the BBC2005 and BBC2008 yield criteria offer more accurate predictions than the classical yield criteria. The new models for FLC developed by the CERTETA team show a very good prediction of the experiments. The experimental procedure proposed to determine the limit strains demonstrates several advantages comparison with the classical procedures.

In the future, the research in this field of study will be oriented towards developing new models that include special properties (superplastic materials, shape memory materials etc.). By including the evolution of the coefficients in yield functions, it will be possible

to predict the yield loci for nonlinear loading [63], [64]. Stochastic modelling will be used for a more robust prediction of the yield loci and forming limit curves (taking into account the variability of the mechanical parameters). Coupling of the phenomenological models with the ones based on crystal plasticity will allow better simulation of the parameters evolution in technological processes (temperature, strain rate, strain path, structural evolution).

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