SCALE BRIDGING IN SHEET FORMING SIMULATIONS: FROM CRYSTAL PLASTICITY VIRTUAL EXPERIMENTS TO EVOLVING BBC2008 YIELD LOCUS

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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 is closely related to the development of numerical simulation tools. The accuracy of the simulation results is given mainly by the accuracy of the material model. The accuracy of the phenomenological yield criteria is considerably influenced by the completeness and reliability of calibration data. In principle, the data should be representative for the stress state expected during the exploitation of the yield locus. Unfortunately, many of these stress states can be hardly investigated in mechanical testing setups. The Virtual Experimental Framework (VEF), which is based on the crystal plasticity ALAMEL model, is able to provide data points for virtually any stress or strain mode, thus the yield criterion can be calibrated in a much more comprehensive way. In this paper we present a new identification procedure of the plane stress BBC2008 yield criterion. We demonstrate that the new identification method is more robust and less sensitive to local minima of the objective function than the method based only on uniaxial and equibiaxial tension testing. This generic feature is particularly useful in case of any yield criteria that contain a large number of adjustable parameters. The BBC2008 yield criterion and its new identification procedure have been incorporated into the hierarchical multi-scale framework (HMS) that allows one to take into account evolution of the plastic anisotropy during sheet forming processes.

KEYWORDS: Sheet forming, Hierarchical multi-scale modeling, Texture evolution, Plastic anisotropy, Yield criterion

1 INTRODUCTION

In many cases, the plastic anisotropy of sheet metals is attributed to the crystallographic texture of the material. This factor is typically taken into account by macroscopic constitutive laws for such materials, expressed as yield loci models, e.g. [1-3]. However, these phenomenological macroscopic descriptions do not account for phenomena that occur in the material at the crystal level, thus are inherently incapable of predicting the evolution of texture. At the other end of the spectrum, crystal plasticity (CP) models are able to derive an accurate description of the plastic behaviour of sheet metals from texture information. One can consider at least three viable ways to include texture or crystal plasticity data into Finite Element (FE) simulations of sheet forming processes: (1) initial calibration of some phenomenological plasticity model using CP virtual experiments, (2) systematic update of texture by applying macroscopic deformation rates and subsequent recalibration of the phenomenological plasticity model for each Gauss point of the FE mesh, and (3) direct embedding of a CP model in the FE formulation. The first and at the same time the simplest option presents a clear interest for the sheet forming industry, as it could in principle replace some (or all) of the costly and time-consuming mechanical tests used today to calibrate the plasticity models used in FE simulations of forming processes. The strength of the phenomenological yield functions combined with crystal plasticity models has been already recognized by the metal forming community. In the papers [4-8] virtual experiments were performed using crystal plasticity models to provide data points needed for calibration of advanced yield functions. The second option, called Hierarchical Multi-Scale (HMS) modelling, was successfully tested in [8-11] with the Facet plastic potential, a relatively complex but very accurate phenomenological plasticity model. The third option, while theoretically the most precise, is still considered to have a prohibitive computational cost. In order to be adopted by the sheet forming industry, these last two options must provide a clear benefit in terms of improved and more complete predictions, especial-

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ly for those forming simulations where the modelling error is mainly due to limitations of the material model and not to other factors (such as friction model, process details, etc.).

2 HIERARCHICAL MULTI-SCALE FRAMEWORK FOR EVOLVING PLASTIC ANISOTROPY

The model presented in this work adapts the notion of hierarchical modelling. Accordingly, the interacting models of different length scales exchange information: upscaling defines the flow of information from the finer-scale to the coarser-scale, while the flow in the opposite direction is called downscaling. The crucial assumption in the presented approach is that the upscaling and downscaling may involve yet another intermediate model acting as a proxy. On one hand, the proxy provides an expedient approximation of certain quantities that can be predicted by the finer-scale model. On the other hand, the proxy may define criteria that decide whether and when the downscaling should be carried out to update the state of the finer-scale model. Thus, the scheme introduces a certain level of indirection in the interactions between the models operating at different length scales. Obviously, the state variables of the coarser– and finer–scale models are treated separately and non-concurrently. The details of the Hierarchical Multi-Scale (HMS) model of the evolving plastic anisotropy are presented in detail in [8] and [11]. Here we briefly present the methodology. Firstly, we will elaborate on the crystal plasticity framework that delivers essential data for recalibration of the phenomenological plasticity model. The phenomenological yield locus and its identification algorithms will be presented next. The HMS model by Gawad et al. [8] originally used the Facet method, which is a general three–dimensional dual plastic potential [7]. In this work we explore a less complicated description of the macroscopic yield locus, namely the BBC2008 plane stress yield criterion proposed by Comsa and Banabic [3]. The combined model will be referred to as HMS-BBC2008.

3 MACROSCOPIC PLASTICITY MODEL: THE BBC 2008 YIELD CRITERION

In order to distinguish between the elastic and the plastic state of deformation, a scalar-valued yield function is usually defined:

$$F(\boldsymbol{\sigma}) = \bar{\sigma}(\boldsymbol{\sigma}) - Y \leq 0 \tag{1}$$

where $\sigma \geq 0$ is the equivalent yield stress and $Y > 0$ is an arbitrary reference yield stress. The yield surface holds the property that $F(\boldsymbol{\sigma}) = 0$, thus the deformation occurs elasto-plastically, whereas purely elastic stress state satisfies the strict inequality $F(\boldsymbol{\sigma}) < 0$.

The formalism of equation (1) does not account for the influence of the material state on plastic anisotropy. An extension to the yield criterion can be introduced by adding parameters that depend on the instantaneous material state:

$$F(\boldsymbol{\sigma}, \mathbf{z}) = \bar{\sigma}(\boldsymbol{\sigma}) - Y \leq 0 \tag{2}$$

where the vector of parameters $\mathbf{z} = \mathbf{z}(\varepsilon_{pl})$ is derived from the current microscopic state of the material. Therefore, the extended form (2) also discards the assumption that the plastic anisotropy does not change during the plastic deformation.

This study extends the BBC2008 yield criterion, which was originally proposed by Comsa and Banabic [3]. The formulas presented below use the formalism provided by equation (2).

The macroscopic plasticity model makes a constitutive assumption that the material is a plastically orthotropic membrane under plane-stress conditions. Given the plane-stress constraint, the only non-zero components of the Cauchy stress tensor $\boldsymbol{\sigma}$ are σ_{11}, σ_{22} and $\sigma_{12} = \sigma_{21}$. The BBC2008 yield criterion defines the equivalent stress as:

$$\bar{\sigma}(\boldsymbol{\sigma}, \mathbf{z}) = \left[(w-1)\sum_{i=1}^{s}\left\{w^{i-1}P(\boldsymbol{\sigma}, \mathbf{z}) + w^{s-1}Q(\boldsymbol{\sigma}, \mathbf{z})\right\}\right]^{\frac{1}{2k}} \tag{3}$$

$$P(\boldsymbol{\sigma}, \mathbf{z}) = \left[L^{(i)}(\boldsymbol{\sigma}, \mathbf{z}) + M^{(i)}(\boldsymbol{\sigma}, \mathbf{z})\right]^{2k} + \left[L^{(i)}(\boldsymbol{\sigma}, \mathbf{z}) - M^{(i)}(\boldsymbol{\sigma}, \mathbf{z})\right]^{2k} \tag{4}$$

$$Q(\boldsymbol{\sigma}, \mathbf{z}) = \left[M^{(i)}(\boldsymbol{\sigma}, \mathbf{z}) + N^{(i)}(\boldsymbol{\sigma}, \mathbf{z})\right]^{2k} + \left[M^{(i)}(\boldsymbol{\sigma}, \mathbf{z}) - N^{(i)}(\boldsymbol{\sigma}, \mathbf{z})\right]^{2k} \tag{5}$$

The coefficient w is defined as $w = (3/2)^{1/s} > 1$, where $s \in N$. The choice of the exponent k must satisfy the condition that $s \in N$ to ensure convexity of the yield surface [3]. Furthermore, Comsa and

Banabic [3] recommend to use k = 4 and k = 3 for fcc and bcc materials, respectively. The scalar functions L, M and N are given by:

$$L^{(i)}(\boldsymbol{\sigma},\mathbf{z}) = L^{(i)}(\sigma_{11},\sigma_{22},\mathbf{z}) = l_1^{(i)}(\mathbf{z})\sigma_{11} + l_2^{(i)}(\mathbf{z})\sigma_{22} \tag{6}$$

$$M^{(i)}(\boldsymbol{\sigma},\mathbf{z}) = M^{(i)}(\sigma_{11},\sigma_{22},\sigma_{12},\mathbf{z}) = \sqrt{\left[m_1^{(i)}(\mathbf{z})\sigma_{11} - m_2^{(i)}(\mathbf{z})\sigma_{22}\right]^2 + \left[m_3^{(i)}(\mathbf{z})\left(\sigma_{12}+\sigma_{21}\right)\right]^2} \tag{7}$$

$$N^{(i)}(\boldsymbol{\sigma},\mathbf{z}) = N^{(i)}(\sigma_{11},\sigma_{22},\sigma_{12},\mathbf{z}) = \sqrt{\left[n_1^{(i)}(\mathbf{z})\sigma_{11} - n_2^{(i)}(\mathbf{z})\sigma_{22}\right]^2 + \left[n_3^{(i)}(\mathbf{z})\left(\sigma_{12}+\sigma_{21}\right)\right]^2} \tag{8}$$

Equations (6), (7) and (8) contain several material-dependent parameters, which can be conveniently gathered into the vector:

$$\mathbf{p} = \left\{ l_1^{(i)}(\mathbf{z}),\, l_2^{(i)}(\mathbf{z}),\, m_1^{(i)}(\mathbf{z}),\, m_2^{(i)}(\mathbf{z}),\, m_3^{(i)}(\mathbf{z}),\, n_1^{(i)}(\mathbf{z}),\, n_2^{(i)}(\mathbf{z}),\, n_3^{(i)}(\mathbf{z})\ (i = 1,\ldots,s) \right\} \tag{9}$$

Depending on the parameter s, the BBC2008 yield criterion may include 8 components in **p** for s = 1, 16 components if s = 2, 24 components for s = 3 and so forth. A simple naming convention will be followed: BBC2008pN stands for the BBC2008 yield criterion comprising N parameters. Throughout this paper we shall exclusively use the BBC2008p16, therefore to find the required 16 parameters, at least the same number of data points has to be found by means of either the virtual or mechanical testing. In the subsequent paragraphs the quantities of experimental nature (even though the experiment might be virtual) are denoted with the superscript '(exp)'. To identify the parameters in **p**, Comsa and Banabic proposed an identification procedure that involves minimization of an error function (see more details in [3]).

Note that the identification procedure proposed in [3] uses data points that can be obtained by means of relatively uncomplicated mechanical tests. These tests are typically standardized, which is of a clear advantage to reliability and reproducibility of the results, but they do not explore all relevant deformation modes. Owing to a recent progress in mechanical testing, several more advanced techniques become technically feasible [12].

4 ENHANCED IDENTIFICATION PROCEDURE

Another alternative is to use crystal plasticity models [11], which can provide an almost unlimited number of data points that the calibration procedure could exploit. In many cases there is more experimental data available than would be needed to calibrate a flexible and generously parameterised yield locus model. This abundance of data can only be utilized if some extensions to the calibration method are introduced. The identification procedure outlined in [3] can then be further extended and generalized with the aim to consider a broader group of data points. The generalization may also take into account inputs of various nature that can be provided for the calibration of the yield criteria.

Let us consider the BBC2008 plane stress yield criterion as an example of a yield locus model. Suppose that the criterion contains 16 parameters assembled in the vector **p**, hence it can be calibrated by supplying at least 16 data points. Following the formalism introduced in [11], let us define the error-function

$$\mathbf{E}(\mathbf{p}) = \begin{Bmatrix} w_y \Delta\mathbf{y}(\mathbf{p}) \\ w_r \Delta\mathbf{r}(\mathbf{p}) \\ w_{yb} \Delta\mathbf{y}_b(\mathbf{p}) \\ w_{rb} \Delta\mathbf{r}_b(\mathbf{p}) \\ w_S \Delta\mathbf{S}(\mathbf{p}) \\ w_\beta \Delta\boldsymbol{\beta}(\mathbf{p}) \end{Bmatrix} \tag{10}$$

that takes into account the residual error with respect to the uniaxial yield stresses $\Delta\mathbf{y}$, Lankford coefficient (uniaxial *r*-values) $\Delta\mathbf{r}$, balanced biaxial tensile yield stress $\Delta\mathbf{y}_b$, and the corresponding r_b – value, respectively, as well as yield stresses for arbitrary plane stress ratios $\Delta\mathbf{S}$ and the corresponding normals to the yield locus $\Delta\boldsymbol{\beta}$. The weighing factors w_y, w_r, w_{yb}, w_{rb}, w_S, and w_β allow one to control the relative importance of the individual components.

The components of vectors $\Delta\mathbf{y}(\mathbf{p})$ and $\Delta\mathbf{r}(\mathbf{p})$ include the residuals pertaining to the series of *n* uniaxial tensile tests performed at the angles α_i with respect to RD:

$$\Delta\mathbf{y}(\mathbf{p}) = \left\{ 1 - \frac{y(\mathbf{p},\alpha_1)}{y^{(\exp)}(\alpha_1)}, \ldots, 1 - \frac{y(\mathbf{p},\alpha_n)}{y^{(\exp)}(\alpha_n)} \right\}^T \tag{11}$$

$$\Delta\mathbf{r}(\mathbf{p}) = \left\{ 1 - \frac{r(\mathbf{p},\alpha_1)}{r^{(\exp)}(\alpha_1)}, \ldots, 1 - \frac{r(\mathbf{p},\alpha_n)}{r^{(\exp)}(\alpha_n)} \right\}^T \tag{12}$$

where $y^{(\exp)}(\alpha)$ and $y(\mathbf{p},\alpha)$ denote the yield stress in the direction α and its counterpart derived from the yield criterion (3), respectively, while $r^{(\exp)}(\alpha)$ and $r(\mathbf{p},\alpha)$ are the *r*-values obtained in analogous way. The residual errors regarding the balanced equibiaxial tension point are calculated likewise:

$$\Delta\mathbf{y}_b(\mathbf{p}) = \left\{1 - \frac{y_b(\mathbf{p})}{y_b^{(\exp)}}\right\}^T \quad (13)$$

$$\Delta\mathbf{r}_b(\mathbf{p}) = \left\{1 - \frac{r_b(\mathbf{p})}{r_b^{(\exp)}}\right\}^T \quad (14)$$

Eq. (10) introduces the terms $\Delta\mathbf{S}(\mathbf{p})$ and $\Delta\boldsymbol{\beta}(\mathbf{p})$ that provide additional constraints on the solution in the regions of the yield locus that can be specified by a ratio between σ_{11} and σ_{22}, combined with a given value of the shear stress $\tau = \sigma_{12}$:

$$\Delta\mathbf{S}(\mathbf{p}) = \left\{1 - \frac{S(\mathbf{p},\theta_1,\tau_1)}{S^{(\exp)}(\theta_1,\tau_1)},\ldots,1 - \frac{S(\mathbf{p},\theta_m,\tau_n)}{S^{(\exp)}(\theta_m,\tau_n)}\right\}^T \quad (15)$$

$$\Delta\boldsymbol{\beta}(\mathbf{p}) = \left\{\cos\left(\beta^{(\exp)}(\theta_1,\tau_1) - \beta_1(\mathbf{p},\theta_1,\tau_1)\right),\ldots, \cos\left(\beta^{(\exp)}(\theta_m,\tau_n) - \beta_m(\mathbf{p},\theta_m,\tau_n)\right)\right\}^T \quad (16)$$

As a matter of convenience, the angle θ is used to express the relation between the σ_{11} and σ_{22} components: $\tan\theta = \sigma_{22}/\sigma_{11}$. The magnitude of the yield stress in the direction given by the angle θ is denoted as $S(\mathbf{p},\theta,\tau)$. The normal to the yield contour and the σ_{11} direction form the angle $\beta(\theta)$. Figure 1 presents the relations between these quantities in a normalized yield section. From the normality rule, $\beta(\theta)$ corresponds to the direction of the plastic strain rate. In principle, both quantities can be measured experimentally, e.g. [12]. Therefore, the amount of information acquired from the data points can be maximized by capturing the size of the yield locus and its curvature at the same time. Furthermore, two special cases can be considered: $\beta(\theta) = 0^\circ$ and $\beta(\theta) = 90^\circ$, which correspond to the plane strain conditions, provided that $\tau = 0$.

It can be expected that some local minima of the error function used in [3] would not be necessarily the extreme values of $\|\mathbf{E}(\mathbf{p})\|$, since the latter uses also other terms to quantify the quality of the solution. Figure 2 exemplifies such a case. The figure compares two solutions of the BBC2008p16 identification problem.

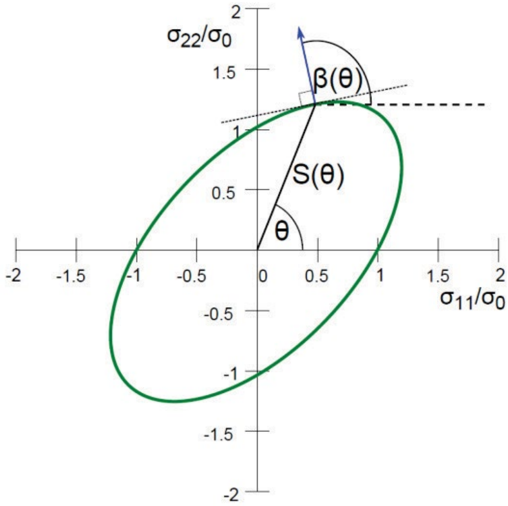

Fig.1. *Schematic illustration of $S(\theta)$ and $\beta(\theta)$ in a normalized yield locus section. The direction of σ_{11} coincides with RD, while σ_{22} is parallel to TD. $S(\theta)$ denotes the distance from the origin to the yield locus, while $\beta(\theta)$ is the angle between the normal to the yield locus and the σ_{11} direction.*

The method that makes use of classical error function [3] is referred to as the *basic identification*, while the *enhanced identification* exploits the function (10). The calibration data (marked with symbols) comprises all the data points needed by both methods. Although the yield locus section shown in Figure 2.d includes the calibration points that correspond to the uniaxial and balanced biaxial tension, the contributions from these points were not used in (15) and (16), since they are already tackled by the terms (11)-(14). For the sake of simplicity, only the yield locus section with no shear component is considered, thus $\tau = 0$ in (15)-(16).

To localize the minima of the respective error functions, the Levenberg-Marquardt algorithm was used. For each function the identification procedure started from an identical initial guess and it was carried out until good numerical convergence was reached. As seen in Figures 2.a and 2.b, both runs result in a very accurate prediction of the *r*-values and uniaxial yield stresses over a broad range of directions. In this respect, it is hard to discriminate between the calibration data and the BBC2008p16 approximation, even though the minimization of the classical error function used in [3] appears to perform slightly better in terms of the normalized uniaxial yield stresses. The balanced biaxial tension is ideally reproduced in both cases, as can be seen in Figure2.c.

However, from the normalized yield locus sections shown in Figure 2.d it emerges that the enhanced identification method provides much higher fidelity of the yield locus approximation. The figure reveals considerable discrepancies if the basic identification algorithm is used. The divergence is particularly striking in the regions that are distant from the uniaxial or balanced biaxial stress states, which are the only points in that section that the basic method considers.

The enhanced identification method can benefit from both the size of the yield surface and its curvature. It is worth mentioning that these two contributions (from the components (15) and (16), respectively) are in many cases complementary. For instance, in Figure 2.d the points at $\theta = 135^{\circ}$ on the green and red curves are clearly different in terms of the distance $S(\theta)$, yet there is hardly any difference with respect to the angle $\beta(\theta)$. If the point at $\theta = 15^{\circ}$ is considered, the deviation with regard to the contour curvature noticeably prevails.

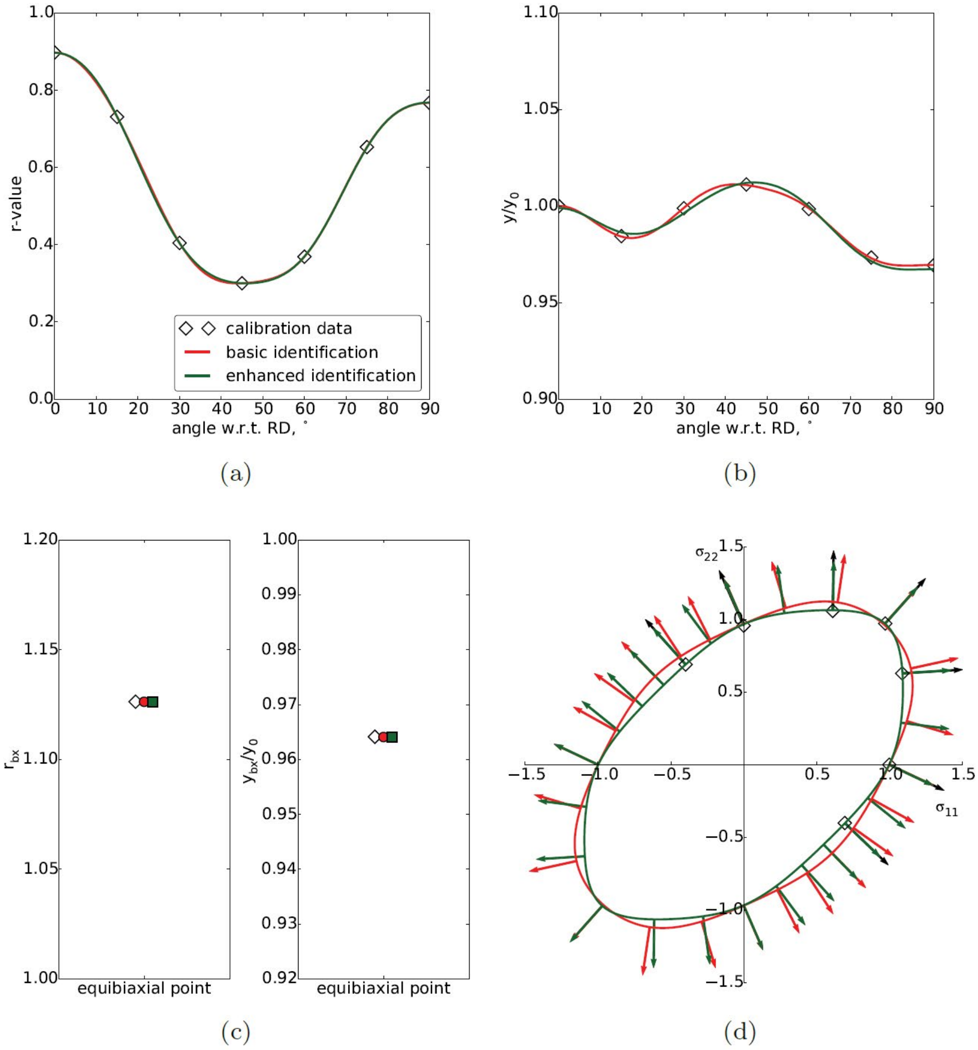

Fig. 2. *Comparison of BBC2008p16 calibrated by means of the basic identification procedure [3] and the enhanced procedure. a) r-value, b) the scaled uniaxial yield stress, c) balanced biaxial r-value and scaled balanced biaxial yield stress, d) contour of the yield locus in the* σ_{11} *-* σ_{22} *section. The calibration data points are marked with black symbols. The arrows denote the normal directions to the yield locus sections. The arrows related to the calibration points are drawn longer merely for a clearer visual appearance.*

5 EFFECT OF ANISOTROPY EVOLUTION UNDER UNIAXIAL LOADING

To investigate the effect of anisotropy evolution under uniaxial loading, a series of virtual experiments have been conducted by means of the Virtual Experimentation Framework (VEF) [11], which employs the crystal plasticity ALAMEL model to provide data points for virtually any stress or strain mode. The virtual samples were subjected to tensile deformation of total ε_{vM}=0.5, split over 10 uniformly distributed sub-increments. The texture was updated after every sub-increment and the calibration data needed for the BBC2008p16 were calculated.

Figure 3 presents the initial and predicted final deformation textures that were obtained in the virtual tension along the RD, TD and 45 w.r.t. RD. The corresponding contours of the final yield loci are shown in Figure 4. For the purpose of comparison, the initial yield locus is shown as well. The corresponding r-values and the uniaxial yield stresses are shown in Figure 5.

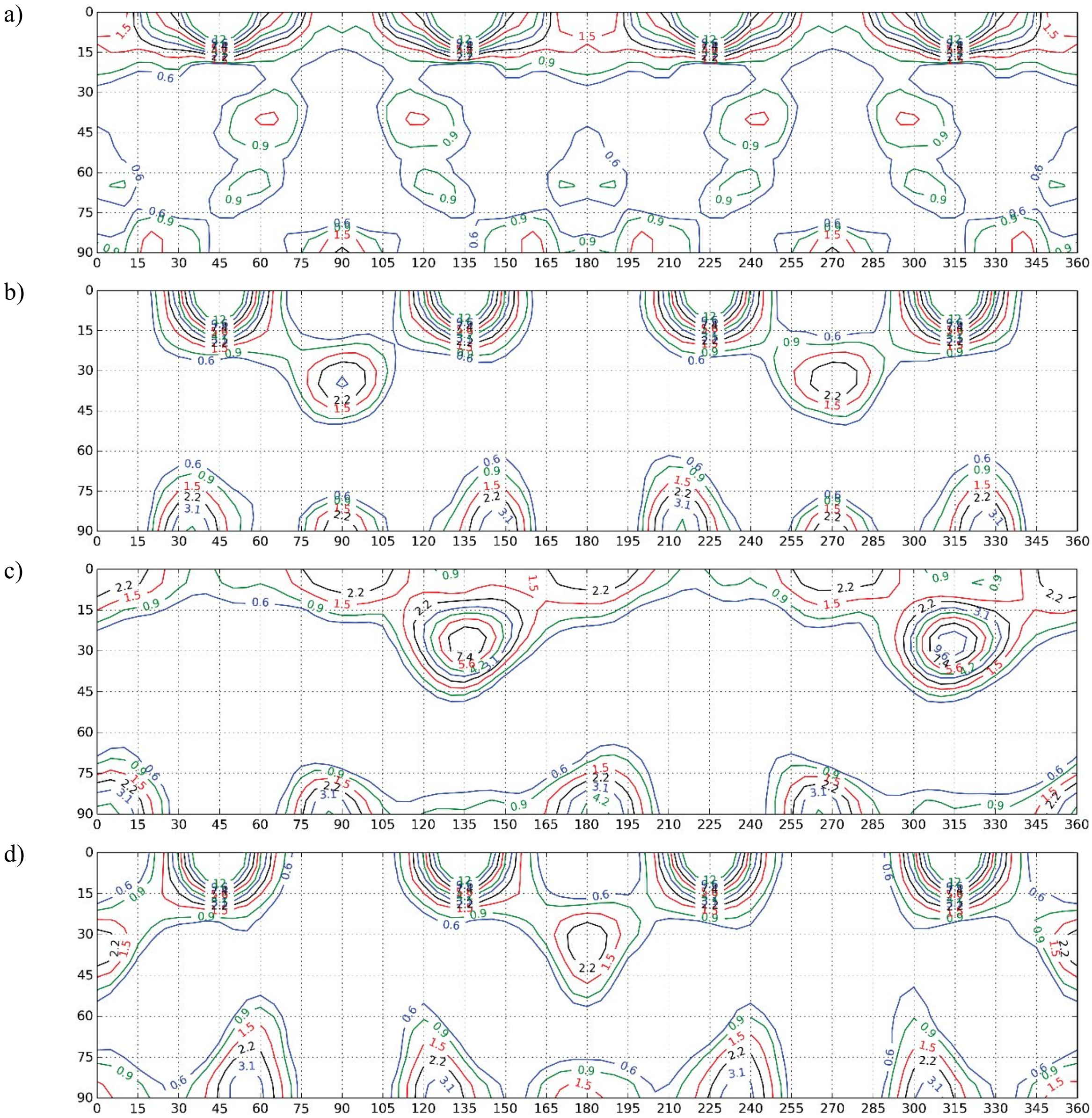

Fig. 3. *$\phi_2 = 45°$ ODF section of the textures that evolved from the initial mid-plane texture (a) under uniaxial loading along the RD (b), 45 w.r.t. RD (c) and TD (d).*

6 CONCLUSIONS

The HMS-BBC2008 model allows capturing evolution of plastic anisotropy that occurs in a sheet metal subjected to plastic deformation. To achieve this, the macroscopic FE model includes a local yield criterion in each integration point. The coefficients of the BBC2008 yield criterion co-evolve with the local crystallographic texture. The changes in the local plastic anisotropy are implemented by systematic reconstruction of the BBC2008, where the calibration data are gathered by virtual experiments.

An enhanced identification procedure is proposed for the BBC2008 yield criterion. The main improvement is attributed to an in-depth exploitation of data points on the yield locus contour. The identification procedure uses not only the size of the yield locus, but also its local curvature. As a result, the identification algorithm is more robust and less sensitive to local minima of the objective function. This generic feature is particularly useful in case of yield criteria that contain a large number of adjustable parameters.

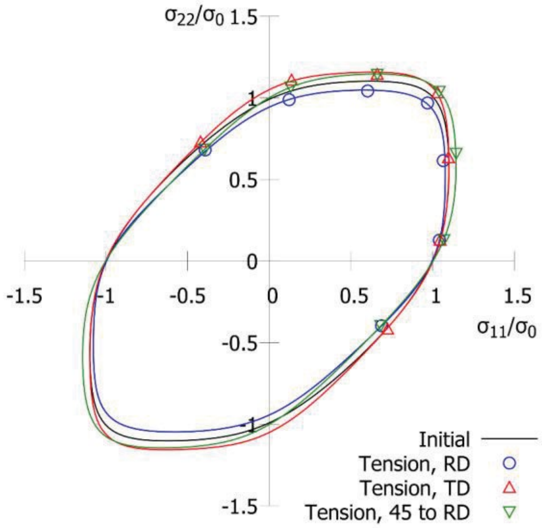

Fig. 4. *The evolved yield locus predicted under different uniaxial loadings. The open points present the result of the VEF used in calibration of the BBC2008p16 (lines).*

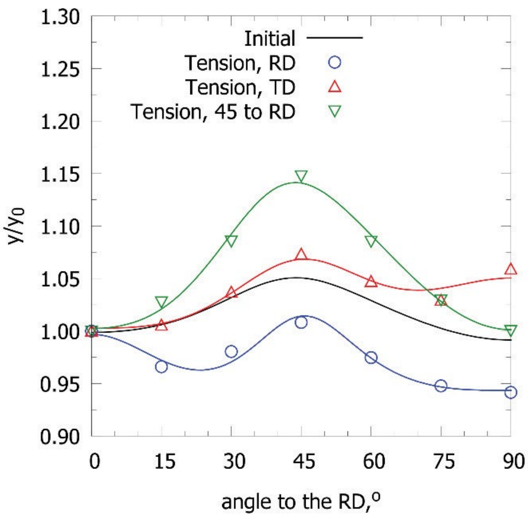

Fig. 5. *The evolved profiles of the r-values (a) and uniaxial stresses scaled by the uniaxial yield stress along the RD (b). The open points present the result of the VEF used in calibration of the BBC2008p16 (lines).*

7 ACKNOWLEDGEMENT

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REFERENCES

[1] Banabic, D., Aretz, H., Comsa, D. S., Paraianu, L.: *An improved analytical description of orthotropy in metallic sheets*. Int. J. Plast. 21 (3), 493–512, 2005.

[2] Barlat, F., Yoon, J., Cazacu, O.: *On linear transformations of stress tensors for the description of plastic anisotropy*. Int. J. Plast. 23, 876–896, 2007.

[3] Comsa, D., Banabic, D.: *Plane-stress yield criterion for highly-anisotropic sheet metals*. In: Numisheet 2008, Interlaken. pp. 43–48, 2008.

[4] Barlat, F., Aretz, H., Yoon, J., Karabin, M., Brem, J., Dick, R.: *Linear transfomation-based anisotropic yield functions*. Int. J. Plast. 21 (5), 1009–1039, 2005.

[5] Grytten, F., Holmedal, B., Hopperstad, O., Børvik, T.: *Evaluation of identification methods for YLD2004-18p*. Int. J. Plast. 24 (12), 2248–2277, 2008.

[6] Kraska, M., Doig, M., Tikhorimov, D., Raabe, D., Roters, F.: *Virtual material testing for stamping simulations based on polycrystal plasticity*. Comp. Mat. Sci. 46, 383–392, 2009.

[7] Van Houtte, P., Yerra, S. K., Van Bael, A.: *The Facet method: A hierarchical multilevel modelling scheme for anisotropic convex plastic potentials*. Int. J. Plast. 25 (2), 332–360, 2009.

[8] Gawad, J., Van Bael, A., Eyckens, P., Samaey, G., Van Houtte, P., Roose, D.: *Hierarchical multi-scale modeling of texture induced plastic anisotropy in sheet forming*. Comp. Mater. Sci. 66, 65–83, 2013.

[9] Van Houtte, P., Gawad, J., Eyckens, P., Van Bael, A., Samaey, G., Roose, D.: *A full-field strategy to take texture induced anisotropy into account during FE simulations of metal forming processes*. JOM 63, 37–43, 2011.

[10] Gawad, J., Banabic, D., Van Bael, A., Comsa, D.S., Gologanu, M., Eyckens, P., Van Houtte, P., Roose, D.: *Evolving texture-informed anisotropic yield criterion for sheet forming*, The 9th International Conference on Numerical Simulation of 3D Sheet Metal Forming Processes NUMISHEET 2014, Melbourne, AIP Proc. 1567, 350-355, (2013).

[11] Gawad, J., Banabic, D., Van Bael, A., Comsa, D.S., Gologanu, M., Eyckens, P., Van Houtte, P., Roose, D.: *An evolving plane stress yield criterion based on crystal plasticity virtual experiments,* Int. J. Plasticity, (2015), (DOI: 10.1016/j.ijplas.2015.02.011)

[12] Kuwabara, T.: *Advances in experiments on metal sheets and tubes in support of constitutive modeling and forming simulations.* Int. J. Plasticity, 23, 385-419, 2007.