Finite element simulation of sheet metal forming and springback using a crystal plasticity approach

A. Bertram*, T. Böhlke†, A. Krawietz** and V. Schulze‡

*Otto-von-Guericke-Universität Magdeburg, Institut für Mechanik, PSF 4120, 39016 Magdeburg, Germany, email: bertram@mb.uni-magdeburg.de

†Universität Karlsruhe (TH), Institut für Technische Mechanik, PSF 6980, 76128 Karlsruhe, Germany, email: boehlke@itm.uni-karlsruhe.de

**Technische Fachhochschule Berlin, Fachbereich VIII, Luxemburger Str. 10, 13353 Berlin, Germany, email: krawietz@t-online.de

‡Volkswagen AG, E2KB Berechnung Aufbau E2, Brieffach 1537/2, Germany, email: volker.schulze@volkswagen.de

Abstract. In this paper the application of a crystal plasticity model for body-centered cubic crystals in the simulation of a sheet metal forming process is discussed. The material model parameters are identified by a combination of a texture approximation procedure and a conventional parameter identification scheme. In the application of a cup drawing process the model shows an improvement of the strain and earing prediction as well as the qualitative springback results in comparison with a conventional phenomenological model.

Keywords: Crystal plasticity, bcc crystals, deep drawing simulation, springback simulation, rate-independent model

INTRODUCTION

The simulation of sheet metal forming has become an important tool for the evaluation of forming processes. One aspect to increase the accuracy of the results is the improvement of the material modelling. At present the material behavior is typically modeled by phenomenological material laws. These laws are based on specific assumptions on the way a multiaxial straining is influencing the development of the hardening and the yield locus. Due to these assumptions the computational effort is fairly low. However, the possible development of the material behavior is determined by these a priori assumptions in a very restrictive way. This reduces the prediction of the development of the anisotropy.

Conventional ferritic steels consist of an agglomerate of body-centered cubic crystals. While the deformation of these crystals can be described fairly easily, the complex macroscopic behavior is the result of the interaction of the grains. Consequently, a material model that is based on the description of the deformation of the crystallites has the advantage that the development of the material behavior is much less restricted compared to phenomenological models. However, the price for the improvement in the material description is an increased computational effort, which depends on the material modeling of the crystals, the type of the micro-macro-transition and the number of crystals taken into account. In an effort to improve the simulation results, a reduced crystal plasticity model for bcc crystals has been implemented in the finite element code LS-Dyna. The rate-independent crystal plasticity model uses the pencil glide assumption to reduce the calculation effort on the micro scale. The homogenization is based on the Taylor assumption and the number of crystals is minimized by a special approximation procedure in combination with the use of an isotropic background model.

MATERIAL MODEL

The used material model is based on the usual evolution equation for the plastic internal variable $\mathbf{F}_p$ as a shear deformation in the active glide systems

$$\dot{\mathbf{F}}_p\mathbf{F}_p^{-1} = \sum_{j\in J} \dot{\gamma}_j \mathbf{m}_j \otimes \mathbf{n}_j \tag{1}$$

with the shear rate $\dot{\gamma}_j$, the glide direction $\mathbf{m}_j$ and the glide plane normal $\mathbf{n}_j$ in a glide system j belonging to the active set of systems J.

The effective shear stress $\bar{\tau}_j$ in the glide system, which is a modified resolved shear stress, is determined by

$$\bar{\tau}_j = \mathbf{C}_e\mathbf{Z}_e : \mathbf{m}_j \otimes \mathbf{n}_j \tag{2}$$

with $\mathbf{C}_e$ as the elastic part of the right Cauchy-Green-tensor $\mathbf{C}$ and $\mathbf{Z}_e$ as the lattice stress defined by

$$\mathbf{C}_e = \mathbf{F}_p^{-T}\mathbf{C}\mathbf{F}_p^{-1} \tag{3}$$

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$$\mathbf{E}_e = \frac{1}{2}(\mathbf{C}_e - \mathbf{1}) \quad (4)$$

$$\mathbf{Z}_e = \mathscr{C} : \mathbf{E}_e \quad (5)$$

$$\mathbf{T} = \frac{1}{\rho}\mathbf{F}_p\mathbf{F}^{-1}\mathbf{Z}_e\mathbf{F}^{-T}\mathbf{F}_p^T \quad (6)$$

with $\mathscr{C}$ the fourth-order anisotropic stiffness tensor, $\mathbf{E}_e$ Green's elastic strain tensor, $\mathbf{T}$ the Cauchy stress tensor and ρ the mass density in the current configuration [9, 10].

The yield condition in each glide system is given by the critical resolved shear stress criterion in the glide systems

$$f_j = \left|\bar{\tau}_j\right| - \bar{\tau}_j^{\text{crit}}\left(\zeta_j\right) = 0 \quad (7)$$

in which $\bar{\tau}_j^{\text{crit}}$ is the critical shear shear stress depending on a hardening parameter ζ_j. If the yield condition is equally fulfilled, the consistency condition has to be satisfied

$$\dot{f}_j = \left|\dot{\bar{\tau}}_j\right| - \dot{\bar{\tau}}_j^{\text{crit}} \leq 0 \quad (8)$$

The evolution of the critical stress is governed by

$$\dot{\zeta}_j = \left((1-q)\dot{\gamma}_j + q\sum_i \dot{\gamma}_i\right) \quad (9)$$

$$\bar{\tau}_j^{\text{crit}} = A_1\left[1 + A_2\left(\sqrt{A_3^2 + \zeta_j^2} - A_3\right)\right]^n \quad (10)$$

where q is the ratio of self and latent hardening, and A_i and n are fitting parameters for the yield curve.

The body-centered cubic crystals (bcc) have 48 possible glide systems. For a rate-independent material law, an admissible combination of the glide systems is to be found that satisfies the yield condition (Eq. 7) and the consistency condition (Eq. 8). This systematic testing sequence is very time consuming. For the case of bcc crystals, this cumbersome procedure can be reduced by using the pencil glide model. Since the possible glide planes are very close to each other, in this model all planes are possible glide planes that have a normal that is orthogonal to the glide direction. This reduces the number of glide systems to four. Due to this additional assumption, the glide plane normals $\mathbf{n}_j$ have to be determined. This can be achieved by defining an effective shear vector $\bar{\mathbf{s}}_j$ for each glide system

$$\bar{\mathbf{s}}_j = \mathbf{m}_j\mathbf{C}_e\mathbf{Z}_e\left(\mathbf{1} - \mathbf{m}_j \otimes \mathbf{m}_j\right) \quad (11)$$

The vector $\bar{\mathbf{s}}_j$ is orthogonal to the glide direction $\mathbf{m}_j$. The effective shear stress $\bar{\tau}_j$ results from

$$\bar{\tau}_j = \bar{\mathbf{s}}_j \cdot \mathbf{n}_j \quad (12)$$

This stress has its maximum if the glide direction $\mathbf{n}_j$ is parallel to the effective shear stress vector $\bar{\mathbf{s}}_j$. Consequently the direction of the glide plane normal is given by

$$\mathbf{n}_j = \frac{\bar{\mathbf{s}}_j}{\left|\bar{\mathbf{s}}_j\right|} \quad (13)$$

Since the modeling of a polycrystalline material with a low number of crystals causes a material anisotropy that is usually to sharp, the anisotropic crystals are accompanied by an isotropic part modeled by a conventional von Mises model. This part of the material model represents the isotropic background of the crystallographic texture of the material under consideration.

The micro macro transition is performed by using the Taylor model. Therefore the deformation gradient $\mathbf{F}$ is identical for each crystal at a given integration point and equal to the macroscopic one. The resulting stress is calculated as the volume average of the crystal stresses.

PARAMETER IDENTIFICATION

For the model identification, a set of crystal orientations has to be determined that approximates the crystallite orientation distribution function (codf) [4, 5]. This can be achieved by using different methods. Techniques based on statistical methods lead to a rather large number of crystals for the approximation [12]. The approach by Helming [8] to use components with different scatters to approximate the initial texture is strongly depending on the knowledge of the operator. In addition the secondary approximation of the different scatter of the components increases the number of crystals. Other techniques in literature [6, 7] are are specificly designed for certain texture classes.

In this work a mixed integer quadratic programming method has been used to determine a small number of very sharp components representing single crystals to the measured textures [3]. This procedure enables the systematic identification of an optimal set of orientations and their respective volume fractions for a predefined number of components. An example of a typical texture of a deep drawing steel and the approximation of this texture with 24 components with a 6° scatter and an isotropic background are shown in Fig. 1 and Fig. 2.

Having a fixed initial orientation, the remaining material parameters are identified using macroscopic tension tests. These tests are performed in three directions 0°, 45° and 90° with respect to the rolling direction. In a first step the elastic constants for the stiffness tensor are identified from the measured Young's modulus in the repective directions. Secondly the parameters of the hardening law (Eq. 10) are determined using a quadratic optimiza-

tion scheme. The resulting macroscopic yield curves parallel to the rolling direction for several crystal groups are given in Fig. 3.

DEEP DRAWING SIMULATION

As an example for a deep drawing process, a cylindrical cup has been drawn. The initial diameter of the blank is 280 mm, the thickness 1 mm. The cup has a diameter of 150 mm with a drawing height of 92 mm. The applied blankholder force during the deep drawing process is 500 kN. For the verification, the strain distribution and the earing have been measured by optical means.

The simulation is performed by the finite element code LS-Dyna, using an underintegrated Belytschko-Lin-Tsay-shell [2]. For the approximation of the bending processes this model is used with seven integration points in the thickness direction. In order to speed up the solution, an adaptive mesh refinement is applied. For the description of the tools, rigid elements are used. The contact between the tooling surfaces and the blank is modeled with a penalty contact and a Coulomb friction model.

The simulation is performed for the crystal plasticity model using 16 to 96 crystals plus an isotropic background which is fitted to the initial material behavior as decribed above.

As a comparison for the performance of the crystal plasticity model, the standard macroscopic model, a three-parameter Barlat model [1] is also used to simulate the process.

A comparison of the measured and simulated major principle strain at a cut through the cup from the centre parallel to the rolling direction is shown in Fig. 4. While the conventional model tends to overestimate the strains in the highly strained regions, the crystal plasticity model is in good agreement with the measured strain distribution.

The second example for the verification is the earing (Fig. 5). One can clearly see that the standard Barlat-models overestimate the height of the ears. Also the position of the maximal feed is not correctly predicted. The crystal plasticity model with 16 crystals also shows an earing that is not corresponding to the measurements. The performance of the crystal plasticity model improves if a higher number of crystals used. With only 32 crystals the results of the model is already satisfying with respect to the earing height and the position of the maximal feed.

SPRINGBACK SIMULATION

An important information for the design of the tools is the correct prediction of the springback. In order to improve this behavior, the influence of the numerical parameters of several simulation programs have been subject to an earlier study by Rohleder [11]. Using the same concept of slicing a cup into rings and measuring the radii of these rings before and after the opening of the rings (Fig. 6), the springback has been evaluated. The geometry has been measured by optical means and the radii have been determined by a least square approximation procedure.

In Fig. 7 the results of the springback analysis are compared to the measured values. The lowest ring closes a little bit, while the other rings are opened and have finally nearly the same radius. The simulation by the Barlat-model with $m = 2$ is not able to predict the closing of the lowest ring correctly. Also the opening of the other rings is overestimated. While the prediction of the first three rings by the Barlat-model with the exponent $m = 6$ shows a good agreement with the measurement, it fails to give a good qualitative prediction for the upper ring, which has received the maximal deformation. The predictions of the crystal plasticity model are in good qualitative agreement with the measured values of the ring radii after the opening, however the opening values are overestimated. The mean error of the crystal plasticity model is smaller than the one of each of the Barlat-models.

SUMMARY

A crystal plasticity model using a small set of crystals which are approximating the initial texture of a deep drawing steel has been used to simulate a deep drawing process. The predicted strain distribution as well as of the earing are in good agreement with the measurements. After performing a cutting and a springback simulation, the predicted values of the springback are in a good qualitative agreement with the experimental data.

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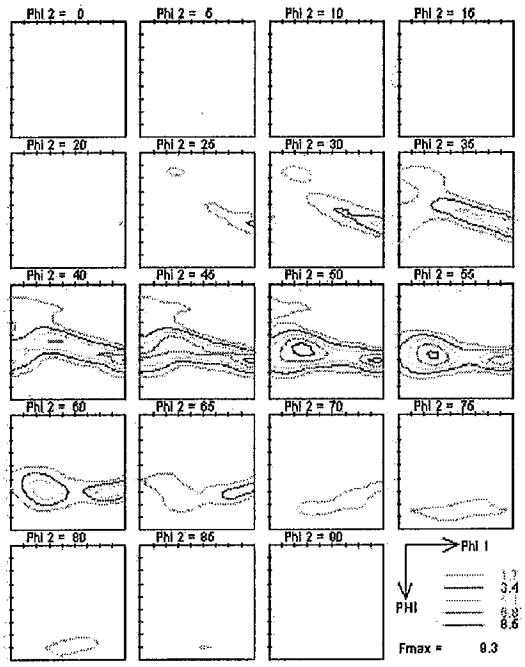

FIGURE 1. Texture of DX53

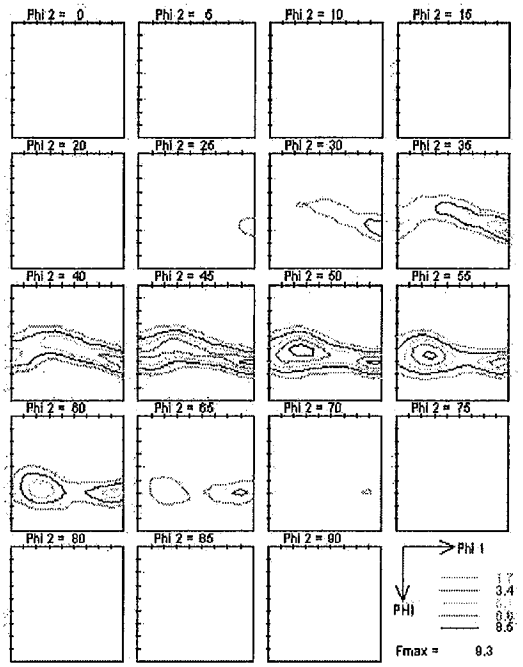

FIGURE 2. Texture approximation with 24 components

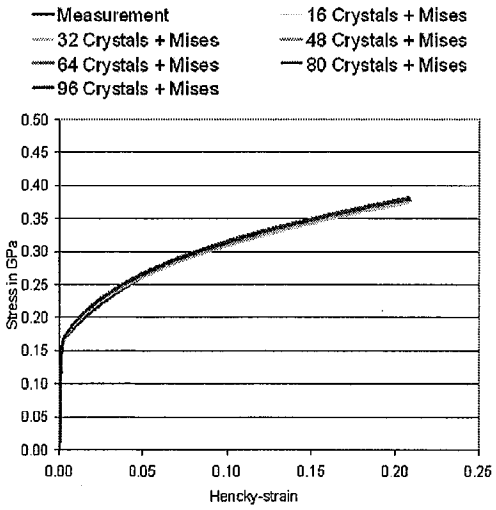

FIGURE 3. Yield curve approximation parallel to the rolling direction

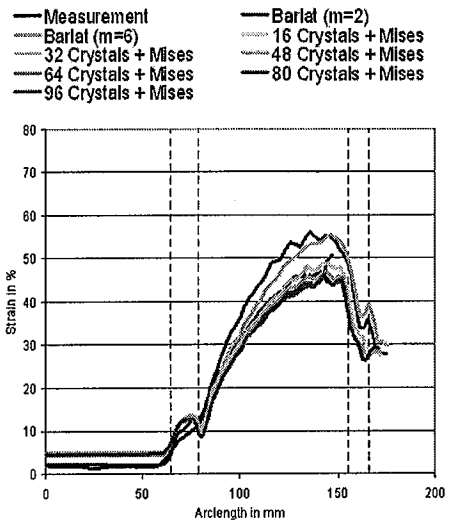

FIGURE 4. Major strain parallel to the rolling direction

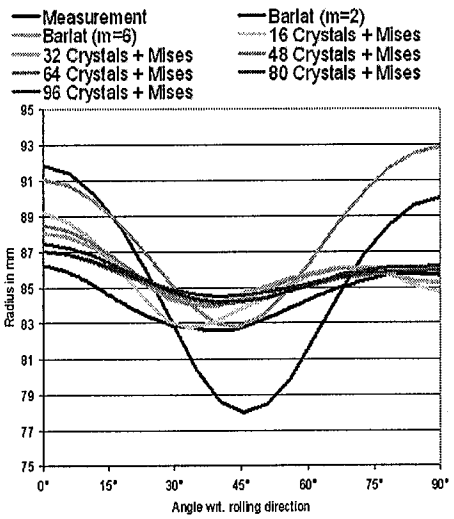

FIGURE 5. Earing of the cup

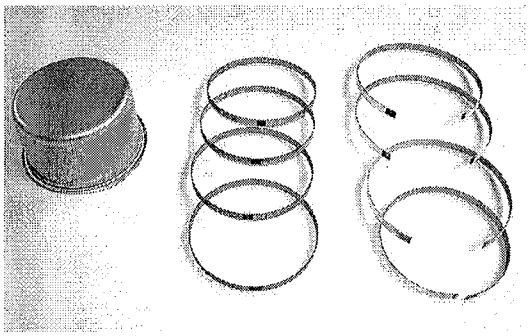

FIGURE 6. Springback experiment: cup,rings, open rings

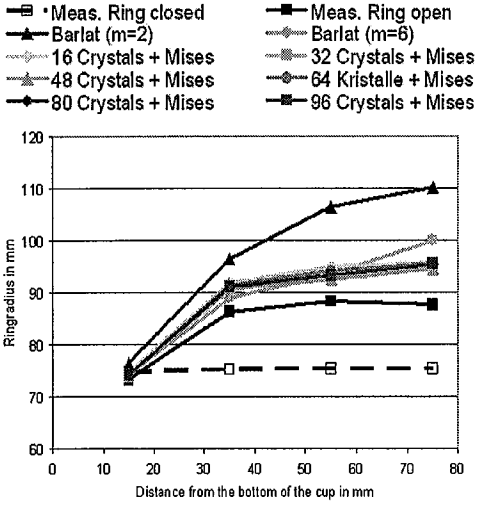

FIGURE 7. Springback results: Distribution of the radii