On Different Strategies for Micro-Macro Simulations of Metal Forming

A. Bertram[1], G. Risy[1], and T. Böhlke[2]

[1] Institut für Mechanik, Otto-von-Guericke-Universität Magdeburg
[2] Institut für Technische Mechanik, Universität Karlsruhe (TH)

Abstract. In metal forming processes, the accuracy of their simulations depends on the ability of the constitutive model to describe the relevant features of the material. For the inclusion of the texture-induced anisotropy, micro-macro models are favourable. However, the numerical effort must be drastically reduced for practical applications. A reduction of the number of crystallites on the macroscale will, unfortunately, result in an overestimation of the anisotropy. In this paper, three different methods are suggested which lead to a reduction of the numerical effort, for each of which this overestimation has been avoided by different means.

1 Introduction

During metal forming processes, large deformations occur which may lead to significant changes of the microstructure and, in particular, of the texture. In many cases, the initial material already possesses a texture, which will further evolve during additional deformations. In order to simulate such processes, the effects of both the initial and the evolving texture have to be taken into account. On the macro scale, this will cause a change of the elastic properties which is important for the springback behaviour, but also of the hardening and the anisotropy of the plastic flow. While the first is often negligible, the latter is of high technological importance since it results in typical effects like, e.g., the earing phenomenon.

Basically two different approaches to include these effects into the simulation can be found in the literature. Firstly, phenomenological models have been suggested to properly describe the anisotropy of the material. One of the oldest ones is perhaps that of von Mises [11] of an anisotropic yield criterion. In the sequel, many modifications and generalizations of this criterion have been suggested (see [13] for more references), but still a blossoming activity of inventing new yield criteria can be seen. Most of these approaches are capable to describe with more or less precision the typical forms of orthotropic or other yield loci, but hardly any of them takes into account that this anisotropy may change during the deformation, in particular under non-proportional processes. Accordingly, such approaches, although rather economical with respect to their computational costs, often turn out to be too limited in their capacities to describe the real material behaviour.

On the other hand, micro-macro simulations have recently become rather popular, since the mechanisms of the deformation on the microscopic level are much better understood than on the macro level. Crystal plasticity can be considered as a mature

branch of material modelling, where issues like anisotropy and plastic spin are clearly understood. Various methods of homogenisation such as the Taylor model [10] or the Sachs model [9], self-consistent schemes, and representative volume elements (RVE) or unit cell approaches can be found in numerous investigations. All of them take into account a certain number of orientations that give rise to a crystallite orientation distribution function (CODF), which should be as close as possible to the real one. These approaches have in common that a rather detailed and realistic picture of the evolving texture can be described if only a large number of orientations is used, however, at the cost of enormous computation times. So these approaches are either able to describe the material behaviour rather realistically but lead to prohibitive costs for industrial applications, or they are drastically reduced by restrictive assumptions, but then they become less realistic. In particular, if only a small number of different orientations is taken into account, such models tend to overestimate the anisotropy. The Taylor model, e.g., although rather economic with respect to computation times, is known to even amplify this spurious effect. As a consequence, one is interested in the development of new models which lead out of this dilemma between needed precision and acceptable computational afford.

In the sequel, three methods are presented, which approach this problem in different ways, but with the same intention, namely to reduce the computational costs but to still introduce the evolution of the anisotropy at a realistic level. In fact, each of them contains a parameter which directly controls the anisotropy of the models and, thus, can be used for calibrating it in an optimal way.

The first method combines a polycrystal model with an isotropic one. Here, the stress tensor is composed of two parts, one of which results from a Taylor model containing the most important components and fibres of the CODF, while the other one is determined by an isotropic plasticity law of von Mises type, called *isotropic background*, which corresponds to a grey texture. The weighting factor of the two parts is a control parameter for the anisotropy.

The second method does not use singular orientations at each grain or integration point, but instead orientation components, which are constituted by von Mises-Fischer distributions. In contrast to sets of singular orientations, only a small number of such components is needed to model smooth CODFs. Moreover, by using the bandwidths of these components, the smoothness of the resulting CODF can be directly controlled. Large values will bring it closer to an isotropic one, small values to a more contoured distribution.

The third method is a two-scale model. On the micro level a simple Taylor model with a rigid-viscoplastic behaviour is used to simulate the evolution of the texture. From this information, a fourth order tensorial texture coefficient is determined, which contains the main information of the anisotropy. This tensor is used within a macrosopic model constituted by an elastic law, a flow rule, and a hardening rule.

All the three methods have in common that a scalar parameter controls the amount of the anisotropy. These three methods can be further combined if wanted. In the sequel we will describe each of them in more detail and give some results to demonstrate their effect on the anisotropy.

2 The Isotropic Background Model (IB)

The first model is an elastic-viscoplastic model based on discrete crystal orientations [3]. The macroscopic Kirchhoff stress is given by a superposition of the single crystal stresses. The model is enhanced by an isotropic constitutive equation modeling the isotropic part of the texture (IB - discrete Taylor model with isotropic background texture). More precisely, the IB model is modified by decomposing the stress tensor into two parts

$$\mathbf{T} = \nu \mathbf{T}_{\text{iso}} + (1-\nu)\, \mathbf{T}_{\text{cryst}}. \tag{1}$$

One part $\mathbf{T}_{\text{iso}}$ describes the isotropic effective viscoplastic behaviour due to a random texture. The other part $\mathbf{T}_{\text{cryst}}$ results from a the superposition of the crystal stresses. Consequently, we have two types of volume fractions. One type corresponds to the texture components, the other one describes how isotropic the microstructure is. The overestimation of anisotropy can be avoided by adapting the isotropic volume fraction ν.

3 The Continuous Taylor Model (CT)

The second model is an (elastic-)rigid-viscoplastic model based on a continuous CODF on the orientation space [2, 3] constituted by von Mises-Fischer distributions [5, 6] which permit an explicit modelling of the scattering around texture components. The von Mises-Fischer distribution is a central distribution. The scattering of a texture component can be described by a half-width value. If one amplifies the half-width values for all components by a joint factor β, then this value can be used as a parameter which controls the contour of the CODF and can, thus, be used to reduce its anisotropy. In contrast to the model of Raabe and Roters [7], the CT model directly incorporates this parameter for the calculation of the macroscopic stresses.

Both material models have been implemented into the finite element code ABAQUS [1] using the interface UMAT, and are applied to the simulation of deep drawing processes. Fig. 1 shows the experimental and the simulated earing profiles for the CT model. The starting texture for the model has been calculated from the experimental CODF section given in [4] for fcc aluminium. It can be seen that the CT model overestimates the earing height if the half-widths of the texture components are chosen in order to approximate the CODF in an optimal way (β=1). However, if the half-widths of the texture components are enlarged by a factor β=2 then the continuous model rather accurately predicts the earing profile. Thus, the modification of the half-widths allows to correct the predictions of the Taylor model which inherently overestimates the sharpness of the texture.

The predictions of the IB model is analysed in the case of a pure cube texture. In Fig. 2 the predicted earing profiles are shown for the IB model and the CT model. In the case of the discrete model, the volume fraction of the isotropic part has been varied in the range of 30% - 90%. In the case of the continuous model, the half-width has been varied in the range of 15° - 60°. It can be seen that the isotropic volume fraction of 30% corresponds approximately to a half-width of 15°. A volume fraction of 50%

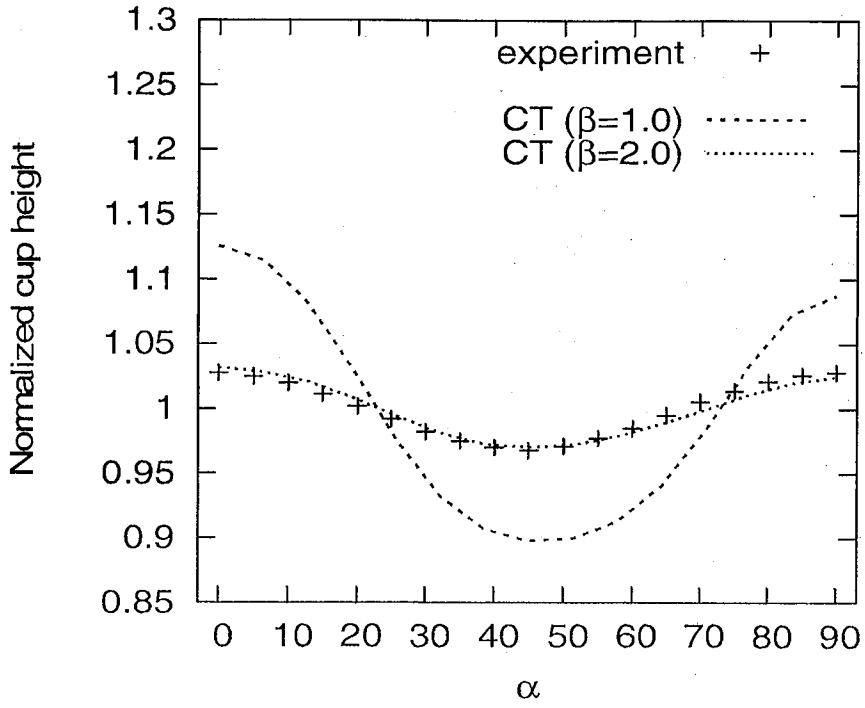

Fig. 1. Comparison of the earing profile calculated by the CT model with experimental data [4]

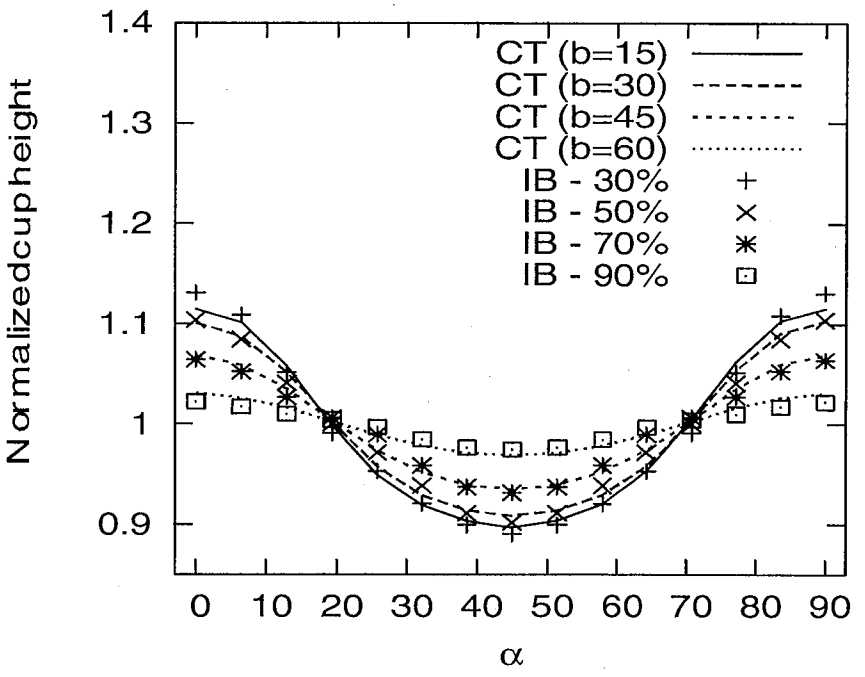

Fig. 2. Earing profile for a cube texture corresponding to different isotropic volume fractions in the IB model and different half-widths b [°] in the CT model

corresponds to a half-width of 30°. As a thumb rule, for half-width values larger than 10% one can use the fact that the isotropic volume fraction in the IB model is approximately given by $(10 + 240b/\pi)\%$ (b in rad). If one takes into consideration that even b should be increased by a factor of 2...3, then one has a rough estimate of the isotropic volume fraction in the IB model directly based on the CODF.

However, this estimate depends on the number of crystals involved in the IB model. The estimate given here can be considered as an upper bound. If more discrete orientations are used, the isotropic volume fraction should be smaller. Since for a small number of crystal orientations the discrete model is computational less expensive, this modification of the discrete Taylor model seems to be versatile.

4 The Two Scale Model (TS)

The third approach which we want to suggest combines the advantages of both a macroscopic and a microscopic approach [8, 14]. While the elastic law, the flow rule, and the hardening rule are formulated with respect to the macroscale, a 4th-order texture coefficient

$$V = \frac{1}{\sqrt{30}}\left(5 \sum_{\alpha=1}^{N} \nu_\alpha \sum_{i=1}^{3} \mathbf{Q}_\alpha \mathbf{e}_i \otimes \mathbf{Q}_\alpha \mathbf{e}_i \otimes \mathbf{Q}_\alpha \mathbf{e}_i \otimes \mathbf{Q}_\alpha \mathbf{e}_i - \overset{2}{\mathbf{I}} \otimes \overset{2}{\mathbf{I}} - 2 \overset{4}{\mathbf{I}} \right)$$

is used to capture the anisotropies on the macroscale. Here, N is the number of orientations with index α, ν_α is its volume fraction, $\mathbf{Q}_\alpha$ its orientation in terms of an orthogonal tensor, $\mathbf{e}_i$ the crystallographic direction, $\overset{2}{\mathbf{I}}$ the second order identity tensor, and $\overset{4}{\mathbf{I}}$ the fourth order identity on the symmetric tensors after [12]. This texture coefficient is incorporated in the macroscopic elastic law, in the macroscopic yield criterion after [11], and in the associated macroscopic flow rule. Its evolution is determined by the use of a rigid-viscoplastic Taylor model. As a consequence, there is no need for an explicit modelling of the plastic spin on the macroscale. The rotation

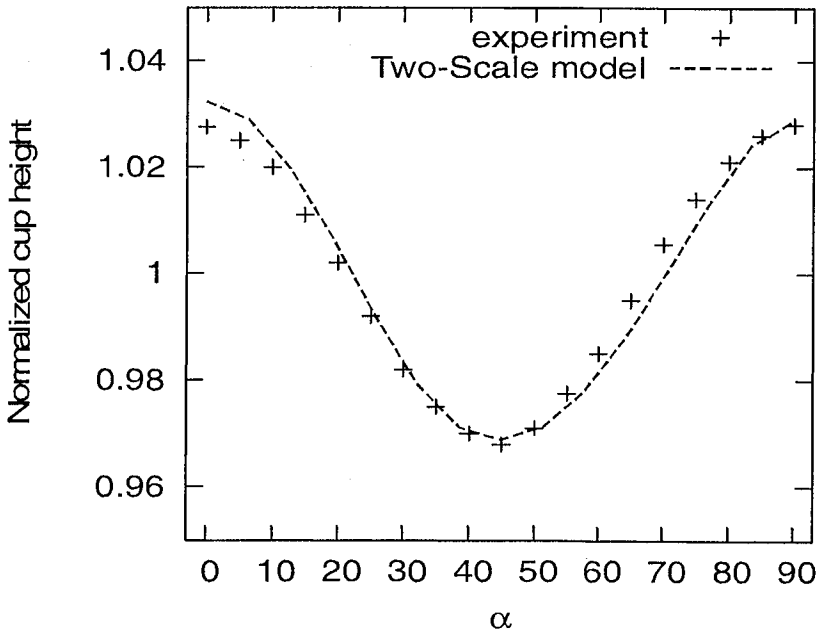

Fig. 3. Comparison of the earing profile calculated by the TS model with experimental data [4]

of the crystal lattice vectors in relation to the material is taken into account by the micro-mechanical model. The macroscopic anisotropy results from a specific orientation distribution on the microscale which changes with large inelastic deformations.

The predictions of the Two Scale model for the earing profile is shown in Fig. 3 together with the experimental data [4]. The starting texture for both models has been again calculated from the experimental CODF section given in [4]. The influence of the 4th-order anisotropy tensor in the macroscopic flow rule is controlled by the scalar factor η [8]. When choosing $\eta = 0.02$, there is a good agreement between the two scale approach and the experimental results.

Compared to classical micro-macro models, the computation of the macroscopic stress is much simpler and faster. Since the texture evolves slowly compared to the yield stress, an update of the texture coefficient is not required in each time step. Furthermore, even if only a small number of crystal orientations is used, the anisotropy is not necessarily overestimated since the discrete orientations enter the model through the 4th-order texture coefficient specifying the quadratic flow rule.

5 Conclusions

We presented three approaches for micro-macro simulations of metal forming processes. In each of them a different method is applied to reduce the spurious overestimation of the anisotropy of the Taylor model and other micro-macro models with a reduced number of orientations. By comparing these three methods from their results, some conclusions can be drawn. As expected, both the CT model and the IB model over-predict the earing behaviour drastically, in particular if only a small number of grains is taken into account. For the CT model, a larger half width parameter of the von Mises-Fischer distributions leads to a clear reduction of the earing anisotropy. The result is a reduction of the contour of the texture, which also helps to compensate the over-prediction due to the Taylor assumption. By an appropriate calibration of this parameter, the results show a good agreement with the experimental findings.

The same effect has been accomplished in the DT model by appropriately calibrating the weight of the isotropic background. Some coarse rules for estimating the values of these factors for the two models could be given.

The TS model is perhaps the most promising one of the three, since it not only reduces the anisotropy to a realistic amount, but also leads to a small computational effort.

References

[1] ABAQUS/Standard. Hibbitt, Karlsson & Sorensen, Inc. (2008)

[2] Böhlke, T., Risy, G., Bertram, A.: A texture component model for anisotropic polycrystal plasticity. Comp. Mat. Science 32, 284–293 (2005)

[3] Böhlke, T., Risy, G., Bertram, A.: Finite element simulation of metal forming operations with texture based material models. Modelling Simul. Mater. Sci. Eng. 14, 1–23 (2006)

[4] Engler, O., Kalz, S.: Simulation of earing profiles from texture data by means of a visco-plastic self-consistent polycrystal plasticity approach. Materials Science and Engineering A 373, 350–362 (2004)

[5] Eschner, T.: Texture analysis by means of modelfunctions. Textures and Microstructures 21, 139–146 (1993)
[6] Matthies, S.: Standard functions in texture analysis. Phys. Stat. Sol. B 101, K111–K115 (1980)
[7] Raabe, D., Roters, F.: Using texture components in crystal plasticity finite element simulations. Int. J. Plast 20, 339–361 (2004)
[8] Böhlke, T., Risy, G., Bertram, A.: A micro-mechanically based quadratic yield condition for textured polycrystals. ZAMM 88 5, 379–387 (2008)
[9] Sachs, G.: Zur Ableitung einer Fließbedingung. Z. Verein dt. Ing. 72, 734–736 (1928)
[10] Taylor, G.: Plastic strain in metals. J. Inst. Metals 62, 307–324 (1938)
[11] Mises, R.v.: Mechanik der plastischen Formänderung bei Kristallen. Z. angew. Math. Mech. 8(3), 161–185 (1928)
[12] Böhlke, T., Bertram, A.: The evolution of Hooke's law due to texture development in polycrystals. Int. J. Solids Struct. 38(52), 9437–9459 (2001)
[13] Bertram, A.: Elasticity and Plasticity of Large Deformations, 2nd edn. Springer, Berlin (2008)
[14] Risy, G.: Modellierung der texturinduzierten plastischen Anisotropie auf verschiedenen Skalen. Ph.D. thesis, Otto von Guericke Universität Magdeburg (2007)