Introduction of a Texture Component Crystal Plasticity Finite Element Method for Anisotropy Simulations**

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We present a physically based and time efficient method to include and predict elastic–plastic anisotropy during complex metal forming operations. The new method is based on the direct integration of crystallographic texture components into a nonlinear finite element model. The approach is designed for performing fast simulations of industry-scale metal forming operations of textured polycrystalline materials including texture update. Instead of yield surface concepts or large sets of discrete grain orientations we use a small set of discrete and mathematically compact Bessel-type Gaussian texture components to map the orientation distribution information directly onto the integration points of a viscoplastic crystal plasticity finite element model. This method increases the computing speed dramatically and hence represents a feasible approach to simulate anisotropic behavior at the industrial scale. The article gives a concise overview of existing anisotropy concepts, provides an introduction to the new texture component crystal plasticity finite element method, and gives examples of its application.

Concepts for Integrating Plastic Anisotropy into Finite Element Models for Simulating Metal Forming: Performing realistic large strain finite element simulations of forming operations of polycrystalline matter requires a constitutive description of the material’s elastic–plastic anisotropy. Important aspects of industry-scale forming simulations with respect to anisotropy effects are shape and flow optimization (e.g., earing), residual stresses, spring back, texture, and failure phenomena.

Present approaches for mapping plastic anisotropy into finite element formulations can be grouped into five strategies, namely, empirical anisotropic yield surface concepts (Fig. 1a), physically based anisotropic yield surface concepts

Fig. 1. Current approaches for mapping plastic anisotropy into finite element formulations can be grouped into five strategies: a) empirical anisotropic yield surface concepts, b) physically (texture) based anisotropic yield surface concepts, c) integration of continuum and crystal plasticity homogenization models, d) crystal plasticity finite element formulations, e) texture component crystal plasticity finite element formulations. Abbreviations used in the figure: YS: yield surface, FEM: finite element method, M: Taylor factor, ui,j: displacement gradient, f(g): texture, c: crystallographic shear, ni: slip plane normal vector, bj: Burgers vector, gi: orientation matrix.

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[**] Authors are grateful to Dr. Jürgen Hirsch from VAW aluminium Bonn for providing the experimental data and giving helpful comments.
(Fig. 1b), integration of continuum and crystal plasticity homogenization models (Fig. 1c), crystal plasticity finite element formulations (Fig. 1d), and texture component crystal plasticity finite element formulations (Fig. 1e). Overviews of the different approaches reviewing details beyond the basics outlined below are given in the literature.[1–4]

**Empirical Anisotropic Yield Surface Concepts:** The yield surface is the generalization of the yield point (e.g., $R_{p0.2}$), known from uniaxial tensile testing, to general states of stress. Extending the yield point into a yield surface is only required if the material under investigations reveals anisotropic plastic response, i.e., if it deforms differently in different directions. Plastic anisotropy is the rule and not the exception for real materials.

The first empirical mathematical description of an anisotropic yield surface was suggested in 1928 by von Mises in the form of a quadratic function.[5] This approach, which was originally designed to describe the plastic anisotropy of single crystals was generalized in 1948 by Hill.[6] The shape coefficients of Hill’s quadratic yield function can be fitted from experimentally obtained mechanical data taken along different directions of the sample, such as the Lankford coefficients $R_0$, $R_{45}$, and $R_{90}$. The scaling is given by the yield stress obtained from uniaxial tensile testing. While the Lankford coefficients and the yield stress can be determined from tensile testing, the direct measurement of mechanical response under complex loads is an intricate task. A number of optimized empirical anisotropic yield surface concepts have been proposed in the last decades, such as those introduced by Barlat et al.[7] which are particularly suited for aluminum and related face centered cubic alloys and those of Hill[8] which often match mechanical behavior of body centered cubic steels (Fig. 1a).

The main advantages of empirical anisotropic yield surface functions as constitutive laws in metal forming finite element simulations are short calculation times and (for special cases with stable textures) robust results. The main disadvantage lies in the fact that the anisotropy of metals changes during forming due to the evolution of texture. It must be noted in that context that the texture changes differently in different regions of the same specimen owing to the spatial differences in strain state and strain path. Translating this into the yield surface concept means that each region of a plastically strained sample reveals a different yield surface and potentially also a different yield surface evolution. It is, therefore, the major drawback of the yield surface concept, that these changes in the physical origin of anisotropy are not mapped by a corresponding change of the shape of the yield surface individually at each integration point. In other words, the same yield surface shape is used throughout one finite element simulation, i.e., for each strain path and each material portion without update.

**Physically Based Anisotropic Yield Surface Concepts:** Poly-crystalline alloys subject to metal forming operations typically develop or inherit morphological textures (e.g., elongated grains or second phases with directional effects) as well as crystallographic textures (orientation distribution of the crystallites constituting polycrystalline matter). While the former are often less relevant in typical commercial sheet material, the latter strongly determine the overall anisotropy. Orientation distributions can directly serve as input data for the calculation of the crystallographically determined portion of the yield surface shape using Taylor–Bishop–Hill theory or rate-sensitive derivatives of these approaches. This applies for a single crystal yield surface as well as for the homogenization bounds of the polycrystal yield surface.[9–11] Details about deriving the yield surface from the crystallographic texture of polycrystals are well documented in the work of Van Houtte and coworkers[9–11] (Fig. 1b). The required experimental input textures can be easily determined using X-ray, neutron, or electron diffraction.

Since texture-based yield surface approximations use the complete crystallographic anisotropy information of a specimen they are often superior to empirical approaches, which rely on a comparatively small set of mechanical parameters. However, since the texture information is again not updated during the finite element simulation, texture-based yield surface functions also have the shortcoming of neglecting possible texture changes during forming.

**Integration of Continuum and Crystal Plasticity Homogenization Models:** Gottstein and coworkers[14–16] recently introduced a combination of a Taylor model and finite element simulations. In this approach the deformation tensor after each strain increment is used to prescribe the boundary conditions for a corresponding Taylor simulation using a full constraints or coupled full constraints/grain interaction homogenization model. Each of the finite elements contains its representative crystallographic texture information in the form of a large set of discrete grain orientations. The Taylor factor calculated from homogenization is fed back into the finite element simulation as a correction factor for the flow stress in the ensuing simulation step (Fig. 1c).

The particular strength of this method lies in the exact simulation of texture evolution under intricate boundary conditions. With respect to engineering applications a weakness of the approach lies in the fact that a large set of discrete grain orientations is required for a mathematically correct representation of the texture. This entails long computation times when simulating large strain metal forming operations with complete texture update.

**Crystal Plasticity Finite Element Model:** A direct implementation of crystal plasticity theory into finite element models was first suggested by Peirce, Needleman, and Asaro.[17–20] Based on their early work a fully-implicit time-integration scheme was developed by Kalindiri et al.[21] and implemented in commercial finite element software. This model provides a direct means for updating the material state via integration of the evolution equations for the crystal lattice orientation and the critical resolved shear stress. The deformation behavior of the grains is at each integration point determined by a crystal plasticity model, which accounts for plastic deformation by crystallographic slip and for the rotation of the crystal lattice during deformation. The crystal kinematics follow those
described by Asaro and the rate-dependent formulation follows that developed by Peirce. The equations can be cast in an updated or total Lagrangian framework. The method has been used to study plate rolling, channel-die deformation, sheet forming, and hydroforming. Pioneering examples can be seen in the work of Mathur and Dawson, Smelser and Becker, and Beaudoin et al. (Fig. 1d).

Crystal plasticity finite element models represent elegant tools for detailed simulation studies of texture evolution under realistic boundary conditions. Each integration point can represent one single orientation or even a large set of discrete grain orientations. Although the latter case (mapping of a representative texture on one integration point) is principally feasible, it entails long calculation times, rendering the method less practicable for industry-scale applications.

The following chapter presents a new method to modify the crystal plasticity finite element approach with respect to applications in the field of metal forming simulations. Its basic idea consists in using a more effective way of describing the texture of macroscopic samples at each integration point, turning the method into a texture component crystal plasticity finite element method.

Basic Approach of the Texture Component Crystal Plasticity Finite Element Method: The major challenge of directly integrating constitutive polycrystal plasticity laws into finite element approaches lies in identifying an effective method of mapping a representative crystallographic texture on a finite element mesh using a compact mathematical form, which permits individual texture update separately at each integration point during straining.

There are four commonly used mathematical approaches to reproduce the crystallographic texture of polycrystalline matter in terms of the orientation distribution function. The first group of techniques is referred to as direct inversion methods. These approaches obtain the texture from the direct integration of the fundamental equation using a large number of pole figure points. The second class comprises Fourier type series expansion methods on the basis of spherical harmonics. The third method is the approximation of either of the two aforementioned functions by a large set of discrete grain orientations. The fourth class which is referred to as texture component method comprises approaches, which fit the orientation distribution function (approximated by either of the above methods or given in terms of a number of pole figures) using Gauss- or Lorentz-type model functions with individual amplitude and individual full width at half maximum. Overviews of the various approaches can be found in the literature.

Crystal plasticity finite element approaches, which permit texture update require a discrete representation of the orientation distribution function at each integration point. When taking an engineering perspective at the problem it is obvious that an appropriate mapping of such a discrete texture requires the reduction of the information content to a level at which complex deformation processes can be simulated without the help of a supercomputer. Hence, the fourth reproduction method using small sets of texture components (1–5) is superior to the third reproduction method using large discrete sets of discrete grain orientations (1000–5000).

The texture component method was originally introduced by Lücke et al. It uses symmetrical spherical Gaussians for the approximation of the orientation distribution function. This approach provides a small set of texture components, which are characterized by simple parameters of physical significance (Euler angle triple, volume fraction, full width at half maximum). Using this method, only a few texture components are needed to describe the orientation distribution function. This data reduction increases computing efficiency dramatically. Details of the method are discussed below using drawn cups as examples (Fig. 2).

Application of the Texture Component Crystal Plasticity Finite Element Method: Two sets of experimental texture data of commercially pure aluminum were selected. Both samples were hot rolled and coiled at 315°C. Sample B was additionally cold rolled with a thickness reduction of 88% in order to obtain a texture different from sample A. Deep drawing tests were carried out and the ear profiles were measured on both samples. The initial experimental textures of the two samples are given in Figure 3 in the form of (111) and (200) pole figures. Sample A shows a strong recrystallization texture, which is dominated by the so-called cube orientation. Sample B reveals a typical plane strain deformation texture.

Simulation Procedure: The experimentally determined textures of sample A and B were analyzed using the component method of Helming using a discretized form of spherical Bessel–Gauss texture functions. The pole figure projections as obtained by the component fit are given in Figure 4. While only one texture component was sufficient to reproduce the texture of sample A, two components were necessary for
sample B. Both reproduced textures show good agreement with the experimental pole figures (Fig. 3). In this context it must be noted that minor portions of the texture are not relevant for the plastic response and can be excluded from the fit. The used texture component parameters are listed in Table 1. Owing to the orthorhombic sample symmetry each texture component had to be balanced by three additional symmetrically equivalent texture components in order to correctly predict the materials physical response in the crystal plasticity finite element calculations. Consequently, each of these components was assigned one quarter of the volume fraction of the original component.

The finite element calculations were carried out using the commercial finite element program ABAQUS in conjunction with the user defined material subroutine UMAT. The deformation behavior of the material was determined by a crystal plasticity model, which accounts for plastic deformation by crystallographic slip and for the rotation of the crystal lattice during deformation. An implicit crystal plasticity procedure developed by Kalidindi was implemented and used for the time integration of the constitutive equations.

Kalidindi’s original constitutive approach permits homogenization at each integration point, i.e., locally the Taylor hypothesis may apply. This means that—if a set of orientations is considered at one integration point—the local deformation gradient in each of these grains (represented by their rotational matrix) is homogeneous and identical to the macroscopic deformation gradient at this particular material portion with all grains having equal volume fraction. In the modified crystal plasticity finite element method presented here, the volume fraction of each individual texture component has to be taken into account separately. The random background part of the texture is not used in the finite element approach, but the volume fractions of the components are re-scaled to add up to unity (see next chapter).

The Cauchy stress at each integration point is taken as

$$T = \sum_{i=1}^{N} T_i v_i$$

where $\bar{T}$ is the average Cauchy stress and $N$ is the number of texture components at the integration point. $T_i$ and $v_i$ represent the
Cauchy stress and volume fraction of each texture component, respectively.

Figure 5a shows the mesh configuration, in which 515 three-dimensional linear elements are used. Owing to the symmetry of the experimental setup and of the texture distribution in the samples, only a quarter of the circle plate is selected for the simulation. Figures 2 and 5b–d show the progress of earing for sample B during the finite element simulation. The color coding in Figure 5 represents the von Mises equivalent stress.

As can be seen in Table 1 the component fit divides the experimental textures into two parts, one set of discrete texture components and one single random background texture component. The latter component behaves plastically isotropic. While the texture component crystal plasticity finite element simulation yields the correct ear profile, the ear height has to be rescaled using the random part of the texture. Equation 2 is introduced to normalize the ear height as received from the finite element model.

\[
H = H_{\text{FEM}} \sum_{i=1}^{N} v_i + H_{\text{ave}} \left(1 - \sum_{i=1}^{N} v_i\right)
\]

where \(H\) is the normalized ear height and \(H_{\text{FEM}}\) is the ear height as calculated from the texture component crystal plasticity finite element model. \(H_{\text{ave}}\) is the average value of the ear height. \(N\) is the number of texture components, and \(v_i\) is the volume fraction as calculated by the component fit procedure. Other approaches to directly account for the random scattering background component already in the finite element simulation are given in the literature.[32]

Results obtained from drawing simulations, particularly shape predictions, may depend on details of the contact situation between workpiece and tool. The present simulations were conducted under the assumption that the circular blank being drawn had an initial radius of 100 mm and an initial thickness of 0.82 mm (Fig. 6). The blank was modeled using 432 elements of type C3D8 and 80 elements of type C3D6. The interaction between the blank and the blank holder was assumed as a so-called soft contact to impose the proper clamping pressure in the thickness direction of the element between blank, die and blank holder. In the present simulations we used an exponential soft contact function. Different friction properties (\(\mu = 0\) to 0.2) were checked and the results showed that friction properties had under these boundary conditions only little influence on the relative ear height. Consequently the \(\mu = 0\) case was selected to save computing time. The weak influence of the friction coefficients can in the present case essentially be attributed to the use of a soft contact function. The influence of friction might be significantly different under different boundary conditions.

**Results and Evaluation**: The simulation results of sample A are shown in Figure 7. The relative ear height is used for comparing the simulation with experiment (solid line). The curve simulated directly from finite element modeling (0% random portion) qualitatively reproduces the experimental ear shape, though much sharper than the true profile. After normalization (71% random portion as obtained from texture component fit, see Table 1) the simulated curve is in very good agreement with the corresponding experimental data, both, in terms of shape and height.

![Simulation results obtained by using TCCP–FEM showing the evolution of earing during deep drawing. The color scheme in the diagrams indicates the von Mises stress in units of MPa.](image-url)
Figure 8 shows the simulation results for sample B. Qualitative agreement between simulation and experiment is obtained even without normalization (0% random portion). After normalization (32% random portion as obtained from texture component fit) the simulated ear curve is still sharper than the experimental one. Best correspondence between simulation and experiment is found when using 68% random portion, which is larger than suggested by the texture component fit procedure. The differences in agreement between simulation and experiment of samples A and B are interpreted in terms of differences in symmetry and scatter widths of the used texture components and in terms of grain-to-grain interaction phenomena, which generally give a damping of texture sharpness and anisotropy. While the texture of sample A essentially consists of a highly symmetric cube orientation, sample B with its deformation texture reveals lower symmetry.

Besides the prediction of the final sample shape a major advantage of the present new approach is its computational efficiency. While earlier integrated texture–finite-element simulations used large sets of individual discrete crystal orientations (1000–5000 orientation matrices) to properly map an experimental input texture onto each integration point, the new texture-component based finite-element method works with small sets of texture distributions of Bessel–Gauss type (1–5 texture components). The theoretical enhancement in computational efficiency hence is of the order of 200–1000. Taking into account the code complexity of crystal-plasticity–finite-element formulations and the necessity to also map the scatter width of the texture distributions onto the finite element mesh an efficiency ratio of 100 seems realistic. The comparison of the quality of the texture predictions obtained by the different simulation methods is covered elsewhere.\cite{32,33}

In summary, crystallographic texture components, which represent an efficient and compact method of describing orientation distributions in textured materials have been integrated for the first time into crystal plasticity finite element modeling. The validity of the method and of the computational procedure have been verified by comparing earing predictions with corresponding experimental results. The new approach, which is referred to as texture component crystal plasticity finite element method (TCCP–FEM), represents a highly efficient way of predicting plastic anisotropy of textured polycrystals at the industrial scale.

Received: June 8, 2001

Communications


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**Application of a Texture-Based Plastic Potential in Earing Prediction of an IF Steel**

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Finite element (FE) method has been widely used in industries for evaluation of material performance and for product design. Since most sheet metals exhibit noticeable plastic anisotropy, the use of an appropriate anisotropic plasticity model is important in order to predict accurately and efficiently the anisotropic deformation behavior, such as the undulations of cup height (i.e., earing behavior) in a deep drawing operation and the non-unity Lankford parameter (i.e., r-value) in a uniaxial tensile test.

In the literature, various phenomenological yield criteria have been proposed to account for the plastic anisotropy (see the survey of Bacroix et al.[1]) The coefficients of the yield crite-

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[**] This investigation was accomplished within the framework of the research project (Contract BRPR-CT97-0492) financed by the European Commission.