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Modeling texture evolution during hot rolling of magnesium alloy AZ31

Tom Walde *, Hermann Riedel

Fraunhofer Institute for Mechanics of Materials, Wöhlerstr. 11, 79108 Freiburg, Germany

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Abstract

The texture evolution during hot rolling of the magnesium alloy AZ31 is simulated using a visco-plastic self-consistent model including crystallographic slip, twinning and recrystallization. This combined model is shown to capture the main features observed in mechanical tests and in X-ray diffraction measurements of the texture. The model is implemented in the commercial finite element code ABAQUS/Explicit®, and hot rolling is simulated. Although the strain field exhibits considerable gradients over the sheet thickness and strong shear components at the sheet surface, the basal texture, as it is commonly observed in rolled magnesium sheets, predominates over the whole thickness.

Keywords: Finite-element analysis; Modeling; Recrystallization; Texture; Magnesium alloys

1. Introduction

The anisotropic mechanical behavior of hexagonal close packed materials like magnesium is strongly influenced by the crystallographic texture evolving during the forming process. For example, rolled sheets of the magnesium alloy AZ31 show a significant asymmetry of the flow stresses in tension and compression. This is because the strong basal texture of rolled material, for reasons of crystal symmetry, allows twinning in compression, but not in tension. The basal texture and the concomitant tension–compression asymmetry are usually undesired, and therefore the technological goal is to avoid them. Several authors have already dealt with the mechanisms of this plastic anisotropy and the associated strain hardening [1–3] just as with the development of internal strain and stress [4,5]. The aim of this paper is to provide a model for a detailed understanding of texture evolution and the associated mechanical properties in magnesium alloys. Since magnesium sheets are usually manufactured by hot rolling, the simulation should consider not only slip and twinning, but also recrystallization as a mechanism contributing to texture development.

In Section 2 of this paper the main aspects of the visco-plastic self-consistent (VPSC) texture model [6] are described. Since twinning is an important deformation mechanism also at the temperatures used for hot rolling [7], it must be considered in the model, which is done here by the predominant twin reorientation (PTR) model [8] described briefly in Section 3. In Section 4 the recrystallization texture model [9] is introduced. The implementation of the VPSC model in an explicit finite element code is described in Section 5. Section 6 is devoted to the adjustment of the model parameters to measured hardening curves and pole figures. The influence of strain variations over the sheet thickness is explored by a coupled finite-element analysis of hot rolling in Section 7, and finally the results are discussed and summarized.

2. Deformation texture model

The visco-plastic self-consistent texture model by Lebensohn and Tomé is used for the simulation of the development of the deformation texture [6]. Since the model is described elsewhere, we only detail the parts of the model which are necessary for understanding its coupling with the recrystallization model and the FE-code ABAQUS/Explicit®.

In the VPSC model the texture is represented by a set of orientations/crystals, each orientation having a weight. The response of a single crystal is described by a rate sensitive constitutive power law of the form

$$\dot{\varepsilon}_{ij}^{\mathrm{pl}} = \left\{ \dot{\gamma}_0 \sum_{s=1}^{S} \frac{m_{ij}^s m_{kl}^s}{\tau^s} \left(\frac{m_{mn}^s \sigma'_{mn}}{\tau^s} \right)^{n-1} \right\} \sigma'_{kl} = M_{ijkl}^{\mathrm{c(sec)}}(\boldsymbol{\sigma}') \sigma'_{kl}. \tag{1}$$

* Corresponding author. Present address: Plansee SE, Technology Center, 6600 Reutte, Austria. Tel.: +43 5672 600 2359; fax: +43 5672 600 514.
E-mail address: tom.walde@plansee.com (T. Walde).

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where $\dot{\varepsilon}^{\mathrm{pl}}$ is the plastic strain rate of the grain, $\dot{\gamma}_0$ a reference strain rate, τ^s a reference stress for the slip system s, S the number of slip systems, $\mathbf{m}^{\mathrm{s}}$ the geometric Schmid tensor, $\boldsymbol{\sigma}'$ the deviatoric stress tensor in the grain and n is the stress exponent. $\mathbf{M}^{\mathbf{c(sec)}}$ is the secant visco-plastic compliance tensor of the grain.

The relation between the macroscopic plastic strain rate tensor $\dot{\mathbf{E}}^{\mathrm{pl}}$ and the macroscopic stress deviator $\boldsymbol{\Sigma}'$ can also be described by a secant visco-plastic compliance tensor $\mathbf{M}^{(\mathbf{sec})}$, which will be determined from the self-consistency condition later:

$$\dot{\mathbf{E}}^{\mathrm{pl}} = \mathbf{M}^{(\mathbf{sec})}\boldsymbol{\Sigma}'. \tag{2}$$

Based on the Eshelby solution for an ellipsoidal inclusion [10] and its (approximate) extension to power-law materials [11], one obtains the relation between the macroscopic stress $\boldsymbol{\Sigma}'$ and the stress $\boldsymbol{\sigma}'$ in the grain:

$$\boldsymbol{\sigma}' = \mathbf{B}^{\mathrm{c}}\boldsymbol{\Sigma}', \tag{3}$$

where $\mathbf{B}^{\mathbf{c}}$ is the accommodation tensor (see [6]), which also enters into the self-consistency equation

$$\mathbf{M}^{(\mathbf{sec})} = \left\langle \mathbf{M}^{\mathbf{c(sec)}}\mathbf{B}^{\mathbf{c}} \right\rangle, \tag{4}$$

where the brackets mean the average over all grains.

Provided that the macroscopic plastic strain rate is prescribed, the stresses in each grain are calculated in the following iterative way: the iteration is started by making the Taylor assumption that the plastic strain rate in each grain is equal to the macroscopic plastic strain rate. The associated stresses are calculated solving Eq. (1).

Then the self-consistency Eq. (4) is solved by two nested iterative procedures. In the inner loop the crystal secant moduli $\mathbf{M}^{\mathbf{c(sec)}}$ are calculated according to (1) and as a first guess for $\mathbf{M}^{(\mathbf{sec})}$ a Voigt average is done:

$$(\mathbf{M}^{(\mathbf{sec})})^{-1} = \left\langle (\mathbf{M}^{\mathbf{c(sec)}})^{-1} \right\rangle. \tag{5}$$

Subsequently the value for $\mathbf{M}^{(\mathbf{sec})}$ derived in the previous step is used to calculate the accommodation tensor $\mathbf{B}^{\mathbf{c}}$. Then Eq. (4) is solved iteratively by using the average $\langle \mathbf{M}^{\mathbf{c(sec)}}\mathbf{B}^{\mathbf{c}} \rangle$ as an improved guess for $\mathbf{M}^{(\mathbf{sec})}$. The iteration is repeated until the average is equal with the input tensor (within certain limits). Then the inner loop is terminated and the new macroscopic stress is calculated with the new $\mathbf{M}^{(\mathbf{sec})}$:

$$\boldsymbol{\Sigma}' = (\mathbf{M}^{(\mathbf{sec})})^{-1}\dot{\mathbf{E}}^{\mathrm{pl}}. \tag{6}$$

In the outer loop the stress in each grain is recalculated and the iterations are stopped if the average of the grain stresses coincides with the macroscopic stress and if the microscopic stresses converge.

In the VPSC model a modified Voce law is used for the description of the development of the reference stress due to strain hardening [12]:

$$\hat{\tau}^s = \tau_0^s + (\tau_1^s + \theta_1^s \Gamma)\left(1 - \exp\left(-\frac{\theta_0^s \Gamma}{\tau_1^s}\right)\right). \tag{7}$$

Here τ_0^s, τ_1^s, θ_0^s and θ_1^s are the parameters, Γ the cumulative shear on all slip systems of the grain, and the function $\hat{\tau}^s$ is used to calculate the increment of the reference stress according to

$$\Delta\tau^s = \frac{\mathrm{d}\hat{\tau}^s}{\mathrm{d}\Gamma}\sum_{s'} h^{ss'}\Delta\gamma^{s'}. \tag{8}$$

The diagonal elements of the hardening matrix $h^{ss'}$ describe self hardening, while the off-diagonal elements describe latent hardening. In this paper all elements are set to 1, except if s' is a twinning mode, in which case $h^{ss'}$ is set to 1.8.

3. Consideration of twinning

Twinning is an important deformation mechanism in magnesium alloys even at elevated temperatures [7] and it must therefore be considered in the simulation. For this purpose the predominant twin reorientation model of Tomé et al. [8] is used in this work. It is described briefly in this section.

The rate at which the twinned volume fraction of a grain changes is:

$$\dot{g}^{n,t_i} = \frac{\dot{\gamma}^{n,t_i}}{\gamma_{t_i}} \tag{9}$$

Here $\dot{\gamma}^{n,t_i}$ is the shear rate of orientation n which is realized by the twinning system t_i and γ_{t_i} is the characteristic shear of the twin. The volume fraction of twinned material in grains of orientation n in relation to the whole polycrystal changes at a rate

$$\dot{f}^{n,t_i} = f^n \dot{g}^{n,t_i}, \tag{10}$$

where f^n is the volume fraction of orientation n.

A summation over all twinning systems and orientations gives the volume fraction F_{R} of the twins of the polycrystal

$$F_{\mathrm{R}} = \sum_n f^n \sum_{t_i} g^{n,t_i} \tag{11}$$

where g^{n,t_i} is the time integral of $\dot{g}^{n,t_i}$. Further, the sum over all grains that have already changed their orientation due to twinning is calculated

$$F_{\mathrm{E}} = \sum_m f^m \tag{12}$$

and used to define a threshold value

$$F_{\mathrm{T}} = X + Y\frac{F_{\mathrm{E}}}{F_{\mathrm{R}}} \tag{13}$$

where X and Y are model parameters to be determined later. In each time step the twinned volume fraction g^{n,t_i} of each orientation is compared with the threshold value. If g^{n,t_i} is greater than F_{T}, the orientation of the grain is transferred to the orientation of the twin. After reorientation the twinned grain can undergo twinning again.

A feature of the PTR model is that mainly grains with the highest deformation activity change their orientations. Another characteristic is that, if F_{E} grows faster than F_{R}, the threshold F_{T}