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On twinning and anisotropy in rolled Mg alloy AZ31 under uniaxial compression

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ABSTRACT

The mechanical anisotropy of hot-rolled Mg alloy AZ31 is investigated both experimentally and numerically. First, five different specimen orientations with tilt angles of $\alpha = 0°$, 30°, 45°, 60° and 90° between the normal direction and longitudinal specimen axis are used to experimentally study the mechanical anisotropy under uniaxial compression. Then, the Elastic Visco-Plastic Self-Consistent (EVPSC) model, with the recently developed Twinning and De-Twinning (TDT) description, is applied to simulate the uniaxial compression tests. It is demonstrated that accounting for the initial texture and calibrating the EVPSC-TDT model using in-plane uniaxial tension and compression along the rolling direction permits prediction of the strength anisotropy and strain hardening behavior along all the five orientations, for cases in which the contribution of twinning is dominated, negligible and intermediate.

1. Introduction

Crystal plasticity-based approaches for modeling the constitutive behavior of textured Mg alloys have proliferated over the past decade or so (see e.g., Abdolvand and Daymond, 2012; Agnew et al., 2001, 2006; Brown et al., 2005; Clausen et al., 2008; Graff et al., 2007; Guillemer et al., 2011; Gu et al., 2014; Guo et al., 2013; Hama et al., 2012; Jain et al., 2013; Kabirian et al., 2015; Kim et al., 2013; Knezevic et al., 2010; Lee et al., 2014; Levesque et al., 2010; Li et al., 2010; Muránsky et al., 2008, 2009, 2010a, 2010b; Proust et al., 2009; Staroselsky and Anand, 2003; Wang et al., 2010c, 2011, 2012b, 2013b, 2013c; Wu et al., 2014). In many cases, the crux of the problem has involved correctly accounting for the behavior of the main deformation twinning mechanism, which produces shear along the $\langle 10.1\rangle$ directions on the $\{10.2\}$ planes. Recently, some of the present authors illustrated that the Elastic Visco-Plastic Self-Consistent (EVPSC) model of Wang et al. (2010a), with the Twinning and De-Twinning (TDT) description later introduced by Wang et al. (2012a, 2013a), can describe the yielding and strain hardening anisotropy observed experimentally for an extruded Mg alloy, ZK60, plate (Qiao et al., 2015a). Notably, the model parameters were fit to the uniaxial straining behavior along the extrusion direction, and then, the model was able to successfully predict the response along the plate transverse and normal directions. What is particularly promising about this modeling development is the ability to accurately predict the constitutive response under limiting cases where the straining is essentially twinning dominated and essentially devoid of twinning, as well as intermediate cases where twinning is a moderate contributor to the strain.

Most all prior validation studies, of which the authors are aware, involved uniaxial straining along directions of orthotropic symmetry, including the aforementioned work on extruded Mg alloy, ZK60 (Qiao et al., 2015a). The work of Oppedal et al. (2013) is a notable exception, where the authors performed uniaxial compression testing along off-axis directions within an extruded bar of Mg alloy, AM30. Oppedal et al. (2013) employed these data to illustrate the need for a new model, which specifically accounts for the dislocation density evolution, as well as the "transmutation" of that dislocation density due to twinning. By this, they mean to account for the dislocation density within the twin (on the aft side of a twin boundary which is advancing into a previously dislocated matrix grain).

The present paper is similar to the latter studies by Oppedal et al. (2013) and Kabirian et al. (2015) in that off-axis testing is employed to explore cases of intermediate levels of twinning on the yield strength and hardening behavior of a textured, wrought Mg alloy. In turn, these experimental results are modeled using the EVPSC-TDT scheme. The implications for our understanding

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of the anisotropy and hardening behavior of Mg alloys are discussed. One novel aspect of the work lies in the demonstration that dislocation density-based approaches to hardening are not required for modeling the monotonic hardening response of textured Mg alloys, however, such approaches may be beneficial for modeling strain path changes. Another aspect of the present modeling approach, which will be beneficial for modeling such cases of strain path change, is the fact the TDT model accurately accounts for the volume fraction of material which is reoriented by twinning, at all stages in the deformation. This is distinct from the much more frequently employed and more computationally efficient predominant twin reorientation (PTR) scheme advanced by Tomé et al. (1991), which only reorients grains after a threshold volume fraction of twinning is met within the grain.

The paper is organized as follows. Section 2 introduces the EVPSC-TDT model. In Section 3 we describe very briefly the experimental method. Section 4 shows both the experimental and predicted results with emphasizing on relationships between twinning and anisotropy in the material under uniaxial compression. Finally, we draw conclusions in Section 5.

2. Constitutive model

The EVPSC-TDT model is applied to simulate the uniaxial compression test data. In this section, we briefly recapitulate the EVPSC-TDT model, mainly for the purpose of definition and notation. For details, we refer to Wang et al. (2010a, 2013a), respectively. The plastic deformation of a crystal is assumed to be due to crystallographic slip and twinning on crystallographic system ($\boldsymbol{s}^\alpha, \boldsymbol{n}^\alpha$), with $\boldsymbol{s}^\alpha$ and $\boldsymbol{n}^\alpha$ being the slip/twinning direction and the normal of the slip/twinning plane for system α, respectively. For Mg alloys, Basal $\langle a\rangle$ ($\{0001\}\langle 11\bar{2}0\rangle$), Prismatic $\langle a\rangle$ ($\{10\bar{1}0\}\langle 11\bar{2}0\rangle$) and Pyramidal $\langle c+a\rangle$ ($\{\bar{1}\bar{1}22\}\langle\bar{1}\bar{1}23\rangle$) slip systems, and the $\{10\bar{1}2\}\langle\bar{1}011\rangle$ extension twin system are usually considered. The plastic strain rate tensor for the crystal is formulated as

$$\boldsymbol{d}^p = \sum_\alpha \dot{\gamma}^\alpha \boldsymbol{P}^\alpha \tag{1}$$

where $\dot{\gamma}^\alpha$ is the shear rate and $\boldsymbol{P}^\alpha = (\boldsymbol{s}^\alpha\boldsymbol{n}^\alpha + \boldsymbol{n}^\alpha\boldsymbol{s}^\alpha)/2$ is the Schmid tensor for system α. For both slip and twinning, the resolved shear stress $\tau^\alpha = \boldsymbol{\sigma} : \boldsymbol{P}^\alpha$ is the driving force for shear rate $\dot{\gamma}^\alpha$. Here, $\boldsymbol{\sigma}$ is the Cauchy stress tensor.

For slip, we have

$$\dot{\gamma}^\alpha = \dot{\gamma}_0 \left|\tau^\alpha/\tau_{cr}^\alpha\right|^{\frac{1}{m}} \mathrm{sgn}(\tau^\alpha) \tag{2}$$

in terms of a reference shear rate $\dot{\gamma}_0$, the critical resolved shear stress (CRSS) τ_{cr}^α, and the strain rate sensitivity m.

The TDT model is used to describe twinning. The TDT model assumes that a grain has four potential operations associated with twinning and detwinning. Operation A is twin nucleation and initiates a twin band or 'child'. Operation B is a propagation of the child into the parent grain. Operations A and B increase the twin volume fraction and thus correspond to twinning. Operation C is a propagation of the parent into the child. Operation D splits the twin band and decreases the twin volume fraction through re-twinning. Operations C and D decrease the twin volume fraction and thus correspond to detwinning.

In the TDT model, the evolution of twin volume fraction associated with twinning system β is governed by:

$$\dot{f}^\beta = f^0(\dot{f}^{\beta A} + \dot{f}^{\beta C}) + f^\beta(\dot{f}^{\beta B} + \dot{f}^{\beta D}) \tag{3}$$

where f^0 is the volume fraction of the parent, i.e. $f^0 = 1 - f^{tw} = 1 - \sum_\beta f^\beta$, and superscripts A, B, C and D represent for Operations A, B, C and D, respectively.

It is important to note that the twin nucleation by Operation A has to be driven by the stress state of the parent, since there is not yet a twin/child. Computationally, the driving force τ^β is calculated from the true stress tensor $\boldsymbol{\sigma}$ of the parent grain and the Schmid tensor $\boldsymbol{P}^\beta$ associated with the lattice of the parent grain for system β. The detwinning by Operation C is also driven by the stress state of the parent, since it is a propagation of the parent into the child. Therefore, inside the parent and associated with twinning system β, we define the shear rates and the evolution of the twin volume fraction due to Operations A and C as

$$\begin{aligned}
&\text{Operation A}: \ \dot{\gamma}^{\beta A} = \begin{cases} \dot{\gamma}_0\left|\tau^\beta/\tau_{cr}^\beta\right|^{\frac{1}{m}} & \tau^\beta > 0 \\ 0 & \tau^\beta \leqslant 0 \end{cases}, \quad \dot{f}^{\beta A} = \left|\dot{\gamma}^{\beta A}\right|/\gamma^{tw} \\
&\text{Operation C}: \ \dot{\gamma}^{\beta C} = \begin{cases} \dot{\gamma}_0\left|\tau^\beta/\tau_{cr}^\beta\right|^{\frac{1}{m}} & \tau^\beta < 0 \\ 0 & \tau^\beta \geqslant 0 \end{cases}, \quad \dot{f}^{\beta C} = -\left|\dot{\gamma}^{\beta C}\right|/\gamma^{tw}
\end{aligned} \tag{4}$$

where γ^{tw} is the characteristic twinning shear strain, $\dot{\gamma}_0$ is a reference shear rate, τ^β and τ_{cr}^β are the resolved shear stress and its critical value.

Similarly, the shear rates and the evolution of the twin volume fraction inside a child due to Operations B and D are defined as

$$\begin{aligned}
&\text{Operation B}: \ \dot{\gamma}^{\beta B} = \begin{cases} -\dot{\gamma}_0\left|\tau^\beta/\tau_{cr}^\beta\right|^{\frac{1}{m}} & \tau^\beta < 0 \\ 0 & \tau^\beta \geqslant 0 \end{cases}, \quad \dot{f}^{\beta B} = \left|\dot{\gamma}^{\beta B}\right|/\gamma^{tw} \\
&\text{Operation D}: \ \dot{\gamma}^{\beta D} = \begin{cases} \dot{\gamma}_0\left|\tau^\beta/\tau_{cr}^\beta\right|^{\frac{1}{m}} & \tau^\beta > 0 \\ 0 & \tau^\beta \leqslant 0 \end{cases}. \quad \dot{f}^{\beta D} = -\left|\dot{\gamma}^{\beta D}\right|/\gamma^{tw}
\end{aligned} \tag{5}$$

It is clear that Operation D, taking place inside a twinned domain, has to be driven by the stress state of the twinned region or the child. This means that the driving force τ^β is calculated from the true stress tensor $\boldsymbol{\sigma}$ of the child and the Schmid tensor $\boldsymbol{P}^\beta$ associated with the lattice of the child for system β. Therefore, that the resolved shear stresses τ^β for Operation D should be computed from the child stress state. Furthermore, since Operation B is a propagation of the child into the parent, it is appropriate to use the resolved shear stress τ^β calculated from the child stress state. It is interesting to note that Operation D was recently observed by Morrow et al. (2014).

A threshold twin volume fraction is defined in the model to terminate twinning because it is rare that a grain can be fully twinned. Correspondingly, the TDT model introduces two statistical variables: accumulated twin fraction V^{acc} and effective twinned fraction V^{eff}. More specifically, V^{acc} and V^{eff} are the weighted volume fraction of the twinned region and volume fraction of twin terminated grains, respectively. The threshold volume fraction V^{th} is defined as $V^{th} = \min\left(1.0,\ A_1 + A_2\frac{V^{eff}}{V^{acc}}\right)$, where A_1 and A_2 are two material constants. This aspect of the model may be viewed as accounting for sharp increase in the resistance to continued twin growth by the surrounding medium, once the threshold value is reached. It is imagined that these threshold parameters will have a strong grain size dependence to account for observed changes in the flow curve shape for cases of twinning dominated flow in samples of different grain sizes (see e.g., Barnett et al., 2012).

For both slip and twinning, the evolution of the critical resolved shear stress (CRSS) τ_{cr}^β is given by:

$$\dot{\tau}_{cr}^\beta = \frac{d\hat{\tau}^\beta}{d\Gamma}\sum_\chi h^{\beta\chi}\left|\dot{\gamma}^\chi\right| \tag{6}$$

where $\Gamma = \sum_\beta \int |\dot{\gamma}^\beta| dt$ is the accumulated shear strain in the grain, and $h^{\beta\chi}$ are the latent hardening coupling coefficients, which