International Journal of Plasticity 47 (2013) 49–64

Contents lists available at SciVerse ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Modeling inelastic behavior of magnesium alloys during cyclic loading–unloading

H. Wang [a], P.D. Wu [a], J. Wang [b,*]

[a] Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7
[b] Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ARTICLE INFO

Article history:
Received 13 October 2012
Received in final revised form 7 December 2012
Available online 26 January 2013

Keywords:
Inelasticity
B. Cyclic loading
A. Twinning
B. Crystal plasticity
Magnesium

ABSTRACT

The inelastic behavior presenting in magnesium alloys during cyclic loading–unloading have been investigated through the finite strain elastic viscoplastic self-consistent (EVPSC) model for polycrystals (EVPSC-TDT), which has been updated by implementing the twinning and de-twinning (TDT) model. Corresponding to the existing experiments of extruded bars of Mg alloys, we constructed the extruded bars of magnesium alloys with different initial textures in our simulations to study the effects of initial textures and deformation processes (tension and compression) on inelastic behavior during cyclic loading and unloading. Taking the advantage of numerical modeling, the evolution of the instantaneous gradients, the activity of the deformation mechanisms and the evolution of twin volume fraction are characterized to interpret the inelastic behavior. We found that the alternation of deformation mechanisms corresponds to the inelastic behavior; in particular, the inelastic behavior becomes more pronounced when twinning and de-twinning are activated. Thus, a strong extrusion texture reduces the hysteresis loops of the loading–unloading cycle under uniaxial tension, while magnifies the inelastic behavior under uniaxial compression, because twinning and de-twinning are more active for extrude bars with the strong extrusion texture under compression. The simulated results are in agreement with the available experimental observations.

Published by Elsevier Ltd.

1. Introduction

Inelastic behavior, in a general sense, is referred to as the non-linearity in the loading–unloading stress strain curve, which might originate from different deformation mechanisms, such as phase transformations in shape-memory alloys (Ranieckl and Lexcellent, 1994; Wang and Shen, 2000; Van Humbeeck, 2003; Brinson et al., 2004), crystal reorientation in nanocrystalline materials (Tsuchiya et al., 2009), and the alternation of dominant deformation mechanisms in hexagonal close packed (HCP) metals (Gharghouri et al., 1999). The response of magnesium and its alloys under cyclic loading–unloading is often characterized by inelastic behavior. Understanding the inelastic behavior is deemed important for both static and dynamic mechanical designs of structural components made of magnesium and its alloys because the influence of the inelastic strain on the springback behavior and the designing constants of elastic modulus and damping coefficient is significant (Duerig and Zadno, 1990; Wagoner et al., 2013).

Significant unsymmetrical strain hysteresis (anelasticity or inelasticity) has been observed in various experiments of magnesium and its alloys (Gharghouri et al., 1999; Cáceres et al., 2003; Mann et al., 2007; Lou et al., 2007). Two important features represent the inelastic behavior, (a) strong inelastic deformation occurs during unloading and (b) the instantaneous

* Corresponding author. Tel.: +1 (505) 667 1238.
E-mail addresses: wangj6@gmail.com, wangj6@lanl.gov (J. Wang).

0749-6419/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ijplas.2013.01.007

gradient ($d\sigma/d\varepsilon$) during unloading is less than the Young's modulus E. Cáceres et al. (2003) and Mann et al. (2007) observed a similar behavior in the cast AZ91 magnesium alloys, the pure magnesium and Mg–Zn magnesium alloys. They found that the inelastic strain increases up to the plastic strain of 1–2% and slightly decreases at larger strains, and ascribed inelastic behavior to both deformation mechanisms of extension twin ($\{10\bar{1}2\}\langle\bar{1}011\rangle$) and slip mechanisms (Gharghouri et al., 1999; Cáceres et al., 2003). More recently, Muránsky et al. (2009) carried out a cyclic loading–unloading test of an extruded AZ31 magnesium alloy by using the in situ neutron diffraction technique and showed that the inelastic response during unloading is more pronounced under compression than tension. The decrease of the measured diffraction intensity of $\{0001\}$ during unloading of compression indicates the activation of de-twinning during unloading, which could be another contributor to inelastic behavior. Li and Enoki (2008) reported a similar behavior observed in pure magnesium. Therefore, we could hypothesize that inelastic behavior occurring in Mg and Mg alloys might originate from the difference of dominant deformation mechanisms (different slips) during loading and unloading, particularly, twinning and de-twinning if they have been activated. In turn, inelastic behavior would be strongly dependent on texture and strain history.

In parallel to characterizing the change of deformation mechanisms in experimental study (particularly using in situ optical microscopy and in situ neutron diffraction technique), numerical models will be the other power tools in revealing the origination of inelastic behavior. Hama and Takuda (2011) modeled the inelastic behavior of AZ31 magnesium alloy sheets under tension using the crystal plasticity finite-element method. They observed the clear inelastic behavior during unloading, but the magnitude of the hysteresis was smaller than that in the experiment. One major reason might be the lack of deformation twinning/de-twinning mechanisms in their model. Thus, the models that are able to capture the inelastic behavior of magnesium alloys must hold the capability of dealing with all deformation mechanisms, including slips, twinning and de-twinning.

However, the current crystal plasticity models were not specifically developed to describe all deformation mechanisms, i.e. slip, twinning and de-twinning (e.g. Van Houtte, 1978; Tomé et al., 1991; Lebensohn and Tomé, 1993; Kalidindi, 1998; Staroselsky and Anand, 2003; Agnew and Duygulu, 2005; Wu et al., 2007; Clausen et al., 2008; Signorelli et al., 2009; Wang et al., 2010d). Recently, Guillemer et al. (2011) have proposed a crystal plasticity model including both twinning and de-twinning in which they assumed that twinning and de-twinning can only be respectively activated by negative and positive hydrostatic pressure. In past few years, Tomé and his collaborators have proposed and continuously developed the composite grain models that can deal with slips, twinning and de-twinning in HCP materials (Proust et al., 2007, 2009; Wang et al., 2012a, submitted for publication). In particular, the recent model, a physics-based crystal plasticity model for HCP crystals including both twinning and de-twinning (TDT), has been implemented into the finite strain elastic viscoplastic self-consistent (EVPSC) model for polycrystals, referred to as EVPSC-TDT, and successfully applied to study the twinning and de-twinning behavior of magnesium alloys (Wang et al., 2012a, submitted for publication).

In this paper, we reanalyze the experimental data of the loading–unloading Mg alloys by using the EVPSC-TDT model. The purpose is to quantitatively reveal the dependence of inelastic behavior on the texture and strain history (cyclic tension and cyclic compression). The extrusion textures with different strengths of the basal texture are obtained by simulating the extrusion process. These constructed textures, together with measured one, are used as the initial textures in the loading–unloading simulations during the cyclic tension and the cyclic compression. Correspondingly, the paper is organized as follows. The TDT model is briefly described in Section 2. Results and discussions are presented in Section 3. Finally, we draw the conclusions in Section 4.

2. TDT model

The slip or twinning direction $\boldsymbol{s}^\alpha$ and the slip or twinning (de-twinning) plane normal $\boldsymbol{n}^\alpha$ are usually used to represent the slip or twinning system α. If the shear rate $\dot{\gamma}^\alpha$ for the system is known, then the plastic strain rate tensor for the crystal can be expressed as:

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

where $\boldsymbol{P}^\alpha = (\boldsymbol{s}^\alpha \boldsymbol{n}^\alpha + \boldsymbol{n}^\alpha \boldsymbol{s}^\alpha)/2$ is the Schmidt tensor for system α. The shear rate of a system is driven by the revolved shear stress $\tau^\alpha = \boldsymbol{\sigma}: \boldsymbol{P}^\alpha$ regardless of slip or twinning, where $\boldsymbol{\sigma}$ is the Cauchy stress tensor. For slip (Asaro and Needleman, 1985),

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

According to Wang et al. (2012a, submitted for publication), TDT model treats a twin as a new grain. The initial orientation of the new grain associated with twinning system α is related to the orientation of the untwined region by the rotation tensor $\boldsymbol{Q} = 2\boldsymbol{n}^\alpha \otimes \boldsymbol{n}^\alpha - \mathbf{1}$. The weight of the new grain $w^{g\alpha}$ is the product of the twin volume fraction f^α and the weight of the twin free grain w^g, i.e. $w^{g\alpha} = f^\alpha w^g$. The influence of both twinned region (twin) and untwined region (matrix) on the deformation twinning and de-twinning is taken into account. Therefore four operations associated with twinning and de-twinning are introduced, i.e. twin nucleation, twin growth, twin shrinkage and re-twinning. After introducing a new twin by twin nucleation (TN), the grain is split into an un-twinned region (matrix) and twinned region (twin). Both the stresses inside twin and matrix can drive twinning and de-twinning. Correspondingly, the deformations due to twinning or