Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 68 (2014) 310–324

Acta MATERIALIA

www.elsevier.com/locate/actamat

A cluster-type grain interaction deformation texture model accounting for twinning-induced texture and strain-hardening evolution: Application to magnesium alloys

Sijia Mu [a,*], Florian Tang [b], Günter Gottstein [c]

[a] Research and Development, Lightweight Design, e-Drive Group, Daimler AG, 89081 Ulm, Germany
[b] Institute for Materials Applications in Mechanical Engineering, RWTH Aachen University, 52056 Aachen, Germany
[c] Institute of Physical Metallurgy and Metal Physics, RWTH Aachen University, 52056 Aachen, Germany

Received 21 August 2013; received in revised form 4 December 2013; accepted 6 December 2013
Available online 4 March 2014

Abstract

Twinning plays two important roles in deformation texture evolution: it reorients the twinned volume of a grain discontinuously, thus causing a texture change; and the lamellar structure of twins reduces the mean free path for dislocation slip, which effectively promotes work-hardening. To correctly predict the texture evolution of materials in which twinning plays an important role, both effects of deformation twinning must be taken into consideration. In the current work, both effects are accounted for in the cluster-type deformation texture grain interaction (GIA) model. Slip-induced strain-hardening was considered by employing a one-parameter hardening model, which calculates the flow stress evolution for each slip system. Twinning-induced strain-hardening was incorporated into the model by treating twin lamellae as ellipsoidal inclusions formed by alternating layers of twin and matrix domains. The twin–matrix interfaces provide barriers and define a directional mean free path for the propagations of subsequent slip or further twinning. The modified GIA model is called the GIA-TW-HD model. It was applied to predict the deformation behavior and texture evolution of Mg alloy AZ31 at 100 °C. The predicted texture evolution as well as strain-hardening curves were compared with experimental results. Overall good agreement between simulation and experiment was obtained.

Keywords: Magnesium; Twinning; Texture

---

1. Introduction

Twinning plays two important roles in deformation texture evolution: (1) twinning reorients the twinned volume of a grain discontinuously and thus affects the texture evolution; and (2) the activation of twinning can effectively promote work-hardening, since the lamellar structure of twins introduces additional boundaries into the microstructure, which reduce the mean free path of gliding dislocations and further twinning [1–3]. To correctly predict the texture evolution of materials in which twinning plays an important role, both effects of twinning must be considered.

In a former study [4], we used the predominant twin reorientation (PTR) scheme proposed by Tomé et al. [5] to handle the twinning-induced lattice rotation in one of the most advanced cluster-type deformation texture models, the grain interaction (GIA) model. The modified GIA model, the GIA-TW model, takes only the lattice rotation of extension twins into account, since they have a major effect on texture evolution, whereas contraction twins have

---

* Corresponding author. Address: Research and Development, Daimler AG, 89081 Ulm, Germany. Tel.: +49 17640209311.
E-mail addresses: sijia.mu@daimler.com, judymu2004@126.com (S. Mu).

http://dx.doi.org/10.1016/j.actamat.2013.12.007

only a minor effect on texture development and are thus neglected. The growth of extension twins and its gradual effect on texture evolution are also accounted for in the model by employing two different critical resolved shear stresses (CRSSs) for twin nucleation and growth, respectively, with $\tau_{\mathrm{ETW}}(nucleation) > \tau_{\mathrm{ETW}}(growth)$ [6]. At first, $\tau_{\mathrm{ETW}}(nucleation)$ is employed in all extension twinning systems. Once an extension twinning system is activated in a grain, $\tau_{\mathrm{ETW}}(growth)$ is applied to this activated twinning system in this specific grain. More details of this model are given elsewhere [7,8]. The GIA-TW model has been applied to simulate deformation texture evolution of Mg alloy AZ31 at different temperatures. An overall good agreement between simulation and experiment was observed, although the PTR scheme predicts that the twinning process will proceed faster than observed experimentally.

Predicting texture evolution accounts only for one aspect of deformation. Another important aspect is twinning-induced hardening. It raises even more challenges for simulation, since it requires both consideration of the microstructural refinement induced by twins and the interactions between the various slip and twinning modes. In the work of Kalidindi [9,10], it was assumed that the activation stresses of slip and twinning systems evolve with strain, and the interactions between slip and twinning were introduced by employing a latent hardening coefficient as a function of the coplanarity between twin and slip planes. This latent hardening scheme was also implemented in a viscoplastic self-consistent code and applied for Zr [11] and Mg [12] deformed at room and liquid nitrogen temperature. However, the latent hardening scheme describes the twin–slip interactions only in an empirical way and disregards the directionality of grain refinement by twinning. Moreover, in the PTR scheme, it is difficult to account for the directional barriers that twins impose on the propagation of subsequent slip and further twinning [13], since the PTR scheme considers either the initial orientation or the completely twinned orientation at any one time. By contrast, in other approaches [13–15], twins are treated as an increasing number of small flat inclusions, whose thickness remains constant and within which no further slip or twinning is allowed. This assumption is applicable, for example to twinning in Cu alloys or contraction twinning in Mg alloys, where the increase of the twinned volume fraction is mainly due to nucleation. However, it cannot be applied to extension twinning in Mg alloys, where the increase of the twinned volume fraction mainly occurs by twin growth. Therefore, a more physical description of the evolution of twinning, and thus of texture and deformation behavior, needs to be based on crystallography.

In the current work, slip- and twinning-induced strain-hardening effects were implemented into the above-mentioned GIA model. The slip-induced strain-hardening was considered by employing a one-parameter model of work-hardening, which calculates the flow stress evolution for individual slip systems based on its dislocation density and mean free path for dislocation glide. The twinning-induced strain-hardening was incorporated into the model by treating twin lamellae as inclusions formed by alternating layers of twin and matrix domains, with thicknesses e_{tw} and e_{mat}, respectively. In addition, the model also considers the different characteristic microstructures of the two most often observed twinning types in Mg alloys, namely extension twinning and contraction twinning, individually. In the case of contraction twins where twinning mainly occurs by nucleation, the twins are considered as inclusions of constant thickness, and the increase of the twinned volume occurs by an increase of the total number of inclusions. In the case of extension twinning where twinning mainly occurs by growth, the number of inclusions is kept constant instead, but the thickness of the inclusions grows steadily as twinning proceeds. By considering the above-mentioned crystallography of twinning in Mg alloys, it is possible to specifically implement the twin–matrix interfaces into the model by defining the directional mean free path for the propagation of subsequent slip or further twinning. The interactions between slip and twinning were calculated for each slip system individually. The modified GIA model will be referred to as the GIA-TW-HD model.

The GIA-TW-HD model was applied to predict the deformation behavior and texture evolution of Mg alloy AZ31 at 100 °C. In order to demonstrate the influence of initial texture on the activation of twinning and its effects on strain-hardening, two sets of specimens, namely types C and E, were chosen, in which the activation of twinning was promoted and suppressed, respectively. In order to test the validity of this model, the predicted texture evolution, as well as the computed strain-hardening curves, were compared with experimental results.

2. Modification of the GIA-TW model to account for twinning-induced strain-hardening

2.1. Microstructural refinement by twinning

As shown in Fig. 1a, alternating twin–matrix interfaces provide barriers which decrease the mean free paths for subsequent dislocation glide, depending on slip direction. Obviously, slip on planes parallel to the twin boundaries will not, or will hardly, be affected by the twin lamellae, whereas slip on planes intersecting the twin boundaries will become more difficult as its mean free path is reduced by the twin lamella. In other words, twinning causes effectively a grain refinement, which introduces “directional” hardening for subsequent slip.

The microstructural refinement caused by twinning was implemented into the GIA-TW-HD model by using a composite grain scheme proposed in Ref. [13]. In this scheme, twins are treated as impenetrable obstacles formed in alternating twin–matrix lamellae, with mean thicknesses of twin e_{tw} and matrix e_{mat}, respectively, and an average spacing between two twin lamellae $t_{tw} = e_{tw} + e_{mat}$, as schematically illustrated in Fig. 1a.