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# Effect of twinning and detwinning on inelastic behavior during unloading in a magnesium alloy sheet

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ABSTRACT

We investigate the nonlinear response arising during unloading under in-plane uniaxial compression of a rolled magnesium alloy sheet using a crystal plasticity finite-element method, focusing on the effects of twinning and detwinning, and discuss the mechanism that causes the nonlinear response to be more pronounced under uniaxial compression than under uniaxial tension. In the simulation, we employed a twinning and detwinning model recently proposed by the authors. From numerical experiments, we confirmed that, as already noted in previous studies, detwinning activity plays an important role in the nonlinear response during unloading. However, we also found that the basal slip could become very active during unloading because of the dispersion of crystallographic orientations caused by twinning activity during loading, which is another factor in the pronounced nonlinear response during unloading under uniaxial compression. We conclude that the nonlinear response during unloading is more pronounced under uniaxial compression than under uniaxial tension because of these two factors—i.e., the detwinning activity and the pronounced basal slip activity—which are not present under uniaxial tension.



## 1. Introduction

Lightweight materials are increasingly in demand to reduce the environmental impact of transport equipment [1,2]. Magnesium (Mg) alloys, the lightest metals used for structural components, recently have received much attention and the formability of Mg alloy sheets has been studied extensively [3–10].

It is well established that most rolled Mg alloy sheets show characteristic deformation behaviors, including an asymmetric deformation behavior between tension and compression [11,12] and an anisotropic work-hardening behavior [13,14], because of the hexagonal close-packed (hcp) structure. A strong nonlinear response during unloading is also a well-known characteristic behavior. Cáceres et al. [15] and Mann et al. [16] first examined this behavior in detail experimentally and concluded that the observed nonlinear response could be understood in terms of the partial reversal of $\{1\,0\,\bar{1}\,2\}$ twinning, i.e., detwinning, during unloading. Thereafter, other researchers studied this behavior, with similar conclusions [17,18]. A detailed survey of the literature on this behavior can be found in Hama and Takuda [19].

Previously, we experimentally examined the nonlinear response during unloading under various loading paths, such as under tension, compression, and compression followed by tension (compression–tension) [20]. We found that the nonlinear response was much more pronounced when the twinning and the detwinning were active, i.e., under compression and compression–tension, respectively, than it was when they were not active, i.e., under tension. Similar results were reported in Muránsky et al. [18]. Clearly, the mechanism causing the nonlinear response during unloading would be different under tension and compression. The difference in the detwinning activity during unloading may be responsible for the difference in the nonlinear response between tension and compression as explained in the previous study [20], but the detailed mechanism of the nonlinear response is still unclear. For instance, twinning activity involves a significant change in texture during deformation. Such a significant change in the texture also would affect the nonlinear deformation during unloading because the initial texture of the material affects the deformation during unloading [19,21]. However, the effect of the texture change during loading on the nonlinear deformation during unloading has not been investigated.

Crystal plasticity models are powerful tools that can be used to understand the interaction between mesoscopic crystalline and macroscopic deformation in metals. An increasing number of studies have actively employed the models to analyze the deformation of Mg alloys [14,19,21–44]. The present authors simulated

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the deformation during unloading of a rolled Mg alloy sheet using a crystal plasticity finite-element method [19]. The nonlinear response under in-plane uniaxial tension was predicted well in the simulation and the simulation result indicated that this nonlinear deformation is attributable to the activity of the basal slip during unloading. It should be noted that detwinning was neglected in the simulation because no well-established detwinning model existed at the time of the simulation. However, detwinning should be taken into account when the unloading process under in-plane uniaxial compression is simulated with a significant amount of twinning activity. Recently, Wang et al. [21] proposed a detwinning model and simulated the deformation of extruded Mg alloys during cyclic loading–unloading. They reported that detwinning activity was the most important factor in nonlinear deformation during unloading when twinning was activated during loading. However, the effect of the texture change during loading on the nonlinear deformation during unloading was not investigated in their study.

Recently, the present authors also proposed a simple detwinning model and showed that the stress–strain curves under various loading paths, including compression–tension and tension–compression–tension, could be predicted well [37]. Such progress in the simulation technique permits a study that numerically examines the effect of twinning and detwinning on the nonlinear response during unloading.

In the present study, a simulation of the loading–unloading process in a rolled Mg alloy sheet under uniaxial compression was performed using the crystal plasticity finite-element method that considers detwinning, and the effect of twinning and detwinning on the deformation during unloading was examined. We also discuss the mechanism that causes the nonlinear response to be more pronounced under uniaxial compression than under uniaxial tension.

## 2. Crystal plasticity finite-element method

### 2.1. Basic formulation

The crystal plasticity finite-element method used in the present study follows that used in our previous studies [14,19]. The new detwinning model [37] is also employed. In the following, the formulations for the crystal plasticity model are explained briefly. The reader is referred to the literature [14,19,37] for detailed information.

A static finite-element method based on an updated Lagrangian rate formulation is used [45,46]. The rate-dependent crystal plasticity model [47,48] explained below is incorporated into each Gauss point in finite elements. The rate tangent modulus method [47] is used for explicit time integration. The so-called $r_{min}$-strategy [49] is employed and the size of an increment is limited to prevent an excessive increase of the nonequilibrium between external and internal forces.

The crystalline slip is assumed to follow Schmid's law. The slip rate $\dot{\gamma}^{(\alpha)}$ of the $\alpha$-slip system is assumed given by the viscoplastic power law as follows:

$$\frac{\dot{\gamma}^{(\alpha)}}{\dot{\gamma}_0} = \left|\frac{\tau^{(\alpha)}}{\tau_Y^{(\alpha)}}\right|^{1/m} sign(\tau^{(\alpha)} - \tau_{kin}^{(\alpha)}), \quad \tau^{(\alpha)} = \boldsymbol{s}^{(\alpha)}\cdot\boldsymbol{\sigma}\cdot\boldsymbol{m}^{(\alpha)}, \quad \dot{\tau}_Y^{(\alpha)} = \sum_{\beta} q_{\alpha\beta} h \left|\dot{\gamma}^{(\beta)}\right|, \tag{1}$$

where $\tau^{(\alpha)}$ is Schmid's resolved shear stress, $\tau_Y^{(\alpha)}$ is the current slip resistance of the $\alpha$-slip system with $\tau_Y^{(\alpha)} = \tau_0$ initially, $\dot{\gamma}_0$ is the reference strain rate, $m$ is the rate-sensitivity exponent, and $q_{\alpha\beta}$ with $\alpha = \beta$ and with $\alpha \neq \beta$ are the self- and latent-hardening moduli, respectively. The unit vectors $\boldsymbol{s}^{(\alpha)}$ and $\boldsymbol{m}^{(\alpha)}$ are the slip direction and the slip plane normal, respectively. $h$ is the rate of hardening; the hardening laws will be explained later.

It is established that kinematic hardening plays an important role when metals are subjected to reverse loading [50–52]. On the other hand, it was also reported that the effect of kinematic hardening on the deformation of a Mg alloy sheet during unloading under in-plane tension was negligible [19]. Therefore, to simplify the simulation model, the kinematic hardening is not taken into account in the present study.

### 2.2. Slip systems

Following previous studies [14,19,24,37], families of basal $\langle a \rangle$ slip systems, prismatic $\langle a \rangle$ slip systems, and pyramidal-2 $\langle a+c \rangle$ slip systems, and one family of $\{1\,0\,\bar{1}\,2\}$ tension twinning systems, are used to model the mechanical behavior of a Mg alloy sheet. There are three basal, three prismatic, six pyramidal-2, and six tension-twinning systems. The slip/twinning plane normal and slip direction vectors for the employed systems are shown in Table 1. A treatment of twinning systems will be explained in the next section.

Two evolution laws are used for the rate of hardening, $h$ [Eq. (1)], in the forms:

$$h = h_0 \tag{2}$$

and

$$h = h_0\left(1 - \frac{\tau_0}{\tau_\infty}\right) exp\left(-\frac{h_0\bar{\gamma}}{\tau_\infty}\right), \tag{3}$$

where $\bar{\gamma}$ is the cumulative shear strain on all the slip systems and is given by

$$\bar{\gamma} = \sum_{\alpha} \int \left|\dot{\gamma}^{(\alpha)}\right| dt. \tag{4}$$

Linear hardening [Eq. (2)] is assumed for the basal slip and Voce hardening [Eq. (3)] is assumed for the prismatic slip and the pyramidal-2 slip.

### 2.3. Twinning systems

In the framework of crystal plasticity analysis, several twinning models have been proposed [53–59], whereas the number of detwinning models is much smaller [28,60]. In the present study, we employ a twinning model originally proposed by Van Houtte [53] and a detwinning model recently proposed by the authors [37]. The detwinning model was developed by extending the twinning model to detwinning. In the present models, the twinning systems are assumed to represent the twin boundary and the activity of the $\alpha$-twinning system is assumed to be described in terms of the resolved shear stress, $\tau^{(\alpha)}$, on the twin boundary, i.e., the plane of the $\alpha$ twinning system. The idea is described briefly as follows.

In the twinning model, twinning is assumed to have a polar character, in which each system can be activated only by tension of the $c$-axis ($(\tau^{(\alpha)} > 0)$). Because the shear strain that arises in a grain

**Table 1**
Plane normal and slip direction vectors of slip and twinning systems used in the present study.

| | Slip/twinning plane | Slip direction/shear direction due to twinning |
|---|---|---|
| Basal | $(0\,0\,0\,1)$ | $\langle 1\,1\,\bar{2}\,0 \rangle$ |
| Prismatic | $\{1\,0\,\bar{1}\,0\}$ | $\langle 1\,1\,\bar{2}\,0 \rangle$ |
| Pyramidal-2 | $\{1\,1\,\bar{2}\,2\}$ | $\langle 1\,1\,\bar{2}\,3 \rangle$ |
| Twinning | $\{1\,0\,\bar{1}\,2\}$ | $\langle 1\,0\,\bar{1}\,1 \rangle$ |