Numerical study of inelastic behavior of magnesium alloy sheets during cyclic loading-unloading

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Abstract. Magnesium alloys exhibit significant inelastic behavior during unloading, especially when twinning and detwinning are involved. It is commonly accepted that noteworthy inelastic behavior will be observed during unloading if twinning occurs during previous loading. However, this phenomenon is not always observed for Mg sheets with strong rolled texture. Therefore, the inelasticity of AZ31B rolled sheets with different rolled textures during cyclic loading-unloading are numerically investigated by elastic viscoplastic self-consistent polycrystal plasticity model. The incorporation of the twinning and detwinning scheme enables the treatment of detwinning, which plays an important role for inelastic behavior during unloading. The effects of texture, deformation history, and especially twinning and detwinning on the inelastic behaviors are carefully investigated and found to be remarkable. The simulated results are in good agreement with the available experimental observations, which reveals that the inelastic behavior for strongly rolled sheets is very different than that for extruded bars.

1. Introduction
Because of its high strength-to-density ratio, magnesium (Mg) alloys are considered to be the possible structural materials to significantly lower the vehicle weight, and further reduce the pressure from both environment and energy. However, the application of Mg alloys is still limited partially because of their deformation characteristics at room temperature, such as tension-compression asymmetry [1], loading path dependency [2], anisotropic work hardening [3], and inelastic response during cyclic loading-unloading [4]. Among them, the inelastic behaviour of a material is considered important for mechanical design of structural components because it affects the springback behaviour, the designing factors of elastic modulus, damping coefficients, etc. [5].

Noteworthy inelastic behaviours have been discovered in numerous experiments of Mg and its alloys [1, 6-8]. Both inelastic strains and normalized instantaneous gradients \((d\sigma/E\varepsilon)\) with \(E\) the Young’s modulus that less than 1 during unloading have been observed by Cáceres et al. [9] and Mann et al. [10] have observed for cast AZ91 alloys, pure Mg and Mg-Zn alloys. Gharghouiri et al. [6] and Cáceres et al. [7] have ascribed the inelastic behaviour to both deformation mechanisms of extension twin and slip...
mechanisms. Muránsky et al. [9] have experimentally studied the inelastic behaviour of extruded AZ91 Mg alloys by using the in-situ neutron diffraction techniques and showed that the inelastic response during unloading is more pronounced under compression than tension because of de-twinning. A similar behaviour has been observed by Li and Enoki in pure Mg [10]. Hama et al. [11,12] numerically studied the inelastic behavior of Mg alloy sheets through crystal plasticity finite element method. Wang et al. [13,14] have proposed a physics-based crystal plasticity model for hexagonal close packed (HCP) crystals including both twinning and de-twinning (TDT). In conjunction with the elastic viscoplastic self-consistent (EVPSC) model [15] (denoted as EVPSC-TDT), Wang et al. [16] have numerically studied the inelastic behavior of Mg alloy extruded bars. The EVPSC-TDT model has captured clearly the inelastic behaviour of AZ31 extrusion bars during unloading, which becomes more profound when twinning is activated. For the case of compression of the extruded bars, de-twinning was the dominant deformation mechanism during unloading. In addition to extruded bar, rolled sheets, which have different grain orientation distributions, are also typical wrought magnesium alloy parts widely used in the industry. The basal poles of both sheets and bars are nearly perpendicular to the processing directions (i.e., rolling direction (RD) and extrusion direction (ED) for sheets and bars, respectively). However, the basal poles of sheets are aligned along the normal direction of the sheet plane, while those of bars are distributed within the plane with normal direction of ED. Different inelastic behaviors are expected for rolled sheets because of their grain orientation distributions. Therefore, more studies on the inelastic behaviours associated with Mg alloy sheets are highly required.

2. TDT model

The plastic behaviors of Mg alloy sheets have been intensively studied through the EVPSC-TDT model [13,14]. Four operations associated with twinning and detwinning were introduced by TDT model. They are twin nucleation (TN), twin growth (TG), twin shrinkage and re-twinning. Twin nucleation creates a fresh twin in a grain and the grain is then split into untwined domain (matrix) and twinned domain (twin). The nucleated twin will grow with further loading. Both stresses associated with matrix and twin drive the growth of the twin, which are corresponding to matrix reduction (MR) and twin propagation (TP), respectively. TN and TG increase the twin volume fraction and are therefore associated with twinning. Detwinning occurs through the operations of twin shrinkage and re-twinning. Twin shrinkage is the reverse mechanism of twin growth, while re-twinning is corresponding to twin nucleation in a twin. Twin shrinkage is comprised of two detwinning mechanisms, matrix propagation (MP) and twin reduction (TR). TDT model enforces small volume fraction associated with both twin nucleation and re-twinning. After introduction of the twin variants via twin nucleation, the main deformation mechanisms regarding twinning and detwinning are twin growth and twin shrinkage.

3. Results and discussions

Figure 1. The rolled textures simulated by rolling process with different levels of strain component $\epsilon_{33}$ and rolled texture measured by Jain and Agnew [19].
The EVPSC-TDT model is capable of studying both the elastic and plastic behaviors (associated with twinning, detwinning and slip mechanisms) of materials [17,18]. The textures of rolled sheets are strongly dependent on the rolling reduction ratio of rolling process. Rolled textures associated with different rolling reduction ratios are generated by simulating the rolling processes from a random texture, whose boundary condition is prescribed to be: \( \dot{\varepsilon}_{ij} = 0 \), except that \( \dot{\varepsilon}_{33} = -\dot{\varepsilon}_{11} = -0.001 \text{s}^{-1} \) (with 1-RD, 2-TD, and 3-ND). The hardening parameters associated with the rolling process and the subsequent cyclic loading-unloading are taken from Wang et al. [16]. The generated textures with the rolled strain \( \varepsilon_{33} \) of 0%, -5%, -10%, -15%, -20%, -40% and -60% are displayed in terms of pole figures in Fig. 1. Stronger rolled textures are obtained with increasing the magnitude of the rolling strains. An experimentally rolled texture of AZ31B sheet is also included in Fig. 1 for comparison purpose. Subsequently, these textures are used to study the inelastic behavior of AZ31B sheets.

The stress strain curves during the compressive loading-unloading along RD are shown in Fig. 2. The typical plateau of the stress as a function of the strain during loading are observed because twinning occurs for all the initial rolling textures. Stronger rolling textures favor more twinning during loading, however favor less de-twinning during unloading. This phenomenon is very different than the inelastic behavior of extrusion bars [16]. The hysteresis loops are broader with stronger extruded textures but are narrower with stronger rolled textures up to strain of 0.04.

![Figure 2. The stress strain curves under compressive loading-unloading along RD for various rolled textures.](image1)

![Figure 3. Activities and twin volume fractions predicted by EVPSC-TDT model for AZ31B sheets with different initial textures under compressive loading-unloading.](image2)
4. Conclusions
The inelastic behavior of Mg alloy sheets has been numerically studied by the EVPSC-TDT model. The effect of texture, loading path, loading history, twinning and detwinning on the inelastic behavior is carefully studied. The stress strain curves, the activity of the deformation mechanisms, and the evolution of twin volume fraction are predicted by the model. Mg alloy sheets exhibit different inelastic behaviors than those of extruded bars.

Acknowledgement
This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the Ontario Ministry of Research and Innovation. DL acknowledges the support of the National Natural Science Foundation of China (No. 51675331).

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