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Mechanical behavior of Mg subjected to strain path changes: Experiments and modeling

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ABSTRACT

Two-step tension tests with reloads along different directions are performed on rolled Mg alloy sheet at room temperature. The experimental yield stress at reloading is systematically lower than before unloading. Such a behavior is captured by a microstructure-based hardening model accounting for dislocation reversibility and back-stress. This formulation, embedded in the Visco-Plastic Self-Consistent (VPSC) model, links the dislocation density evolution throughout the deformation with hardening. The predicted results agree well with the experimental data in terms of flow stress response and texture evolution. The effects of texture anisotropy and back-stress on the mechanical response during the strain path change are discussed.

1. Introduction

Magnesium alloys have low density and high specific strength and have been applied in lightweight structural parts of fuel efficient vehicles during the last two decades (Li et al., 2014; Mayama et al., 2011; Paliwal and Jung, 2014; Sánchez-Martín et al., 2014). However, the highly directional plastic properties of HCP crystals, and the fact that slip and twinning modes exhibit large differences in their activation stresses, makes the plastic response of HCP metals complex and very anisotropic (Agnew et al., 2001; Agnew and Duygulu, 2005; Brown et al., 2005, 2012; Chapuis et al., 2014; Ma et al., 2012; Piao et al., 2012; Schoenfeld et al., 1995; Zhang et al., 2011). In particular, the restricted number of "soft" primary slip modes limit their formability at room temperature. HCP metals show better ductility and formability at higher temperature or moderate strain rates due to the low flow resistance and the activation of secondary slip systems (Jain and Agnew, 2007; Khan et al., 2011; Khosravani et al., 2013; Neil and Agnew, 2009; Oppedal et al., 2012; Proust et al., 2007, 2009; Wang et al., 2011, 2013).

Because most forming processes involve strain path changes, the present work investigates the mechanical behavior of Mg at room temperature associated with strain path changes. Usually, when a metallic material is plastically reloaded following a previous deformation path, it exhibits significant changes in the reloading yield stress and hardening evolution depending on the mode and direction of reloading (Beyerlein and Tomé, 2007; Knezevic et al., 2013; Rauch et al., 2007, 2011; Xue et al., 2007). This behavior has been characterized in many studies done on cubic materials (e.g. Lee et al.

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(2010) and Stout and Rollett (1990) for Copper; Rossiter et al. (2010) and Yoon et al. (2005) for Aluminum; Rauch et al. (2007, 2011) and Barlat et al. (2011) for low carbon steel; Schwartz et al. (2013) for stainless steel). Two features of materials being reloaded along a different strain path are: their yield stress at reload differs from the flow stress previous to unloading, and the subsequent flow stress evolution exhibits a relatively extended transition in the form of a flow plateau. The former is a generalized Bauschinger effect and takes place during the initial 1% or 2% reload strain. It is associated with the presence of internal back stresses which help activate mobile dislocations created during the pre-load. The latter effect can involve large strain intervals, and is related with the dissolution of the dislocation structure created during preload and its replacement by a new structure characteristic of the reload strain path. In previous work we concentrated in modeling the latter mechanism for BCC low-carbon steel (Rauch et al., 2007, 2011; Kitayama et al., 2013). Rauch et al. (2011) proposes a hardening model (RGVB model from now on) based on generation and annihilation laws for three different dislocation populations, namely, forward, reversible and latent dislocations. Strain path changes alter the character of those dislocations, and this leads to changes in the flow stress. Because the RGVB model is formulated for a continuum, it does not account explicitly for texture effects, and the information about path changes has to be introduced explicitly during the simulations. A crystallographic model based on RGVB ideas is proposed by Kitayama et al. (2013). The latter describes the generation and annihilation of forward and reversible dislocations in each crystallographic system of each grain. As a consequence, it accounts explicitly for the directionality and reversibility of slip, and for the hardening of individual systems in each grain. Such crystallographic model is implemented in the Visco-Plastic Self-Consistent (VPSC) polycrystals code, which accounts for grain interaction with the surroundings and also for texture effects and anisotropic plastic response. Here, we present a combined experimental and numerical study which extend the Kitayama et al. model to HCP Mg alloy AZ31, and which accounts for both, the short and the long range effects of pre-load onto reloading. We should note that the RGBV and the Kitayama et al. (2013) models do not account for the back-stress effects. In the present work, the back stress is accounted for by assuming that its effect is to lower the effective CRSS required to activate reversible dislocations in any given slip system.

In this work, a rolled Mg AZ31 sheet is preloaded in tension along the Rolling Direction (RD), and then reloaded in tension at different angles with respect to the RD. Stress strain response, texture evolution, and Lankford coefficient evolution are measured. The hardening model described above is used to interpret and predict the experimental data in terms of dislocation glide and activity in the basal and prism systems. Pyramidal slip and tensile twinning are allowed but do not make a relevant contribution to the mechanical response observed.

2. Experimental study

Large dog-bone samples are cut from a rolled and annealed AZ31 Mg alloy sheet, with gauge length of 300 mm and width of 60 mm, and then subjected to uniaxial tensile test for a pre-strain of $\varepsilon_p = 7\%$. The pre-straining was carried out along the rolling direction (RD) in an Instron 4208 universal testing machine with a maximum load capacity of 150 kN. The cross-head speed (test speed) was 20 mm/min, which corresponds to an initial strain rate of $\dot{\varepsilon} = 10^{-3}\ \mathrm{s}^{-1}$. Reloading was performed by uniaxial tensile tests done on ASTM standard tensile specimens with 10 mm width cut from the pre-deformed material. The samples were cut at 0° (RD), 15°, 30°, 45°, 60°, 75° and 90° (TD) from the RD using as a guidance the striations left by rolling on the rolling plane. The main texture axes of the pre-deformed sample turned out to be tilted 9° with respect to the RD striations, which explains the near coincidence between the 75° and 90° stress response, since they actually correspond to 84° and 99° with respect to the main texture axes. The Shimadzu AG-50 kN tensile test machine was used for reloading tests and a videoextensometer ME 46 was used for strain measurement in two directions, namely longitudinal and transverse. All tests were performed at room temperature.

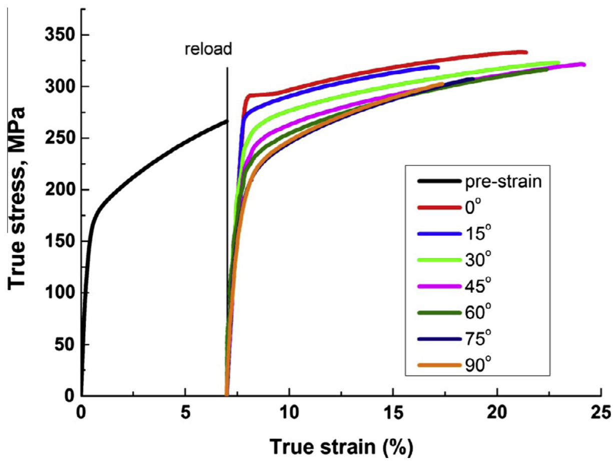

Fig. 1. Experimental true stress-true strain curves for tension–tension tests with different reloading angles from RD.

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