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Demonstration of alloying, thermal activation, and latent hardening effects on quasi-static and dynamic polycrystal plasticity of Mg alloy, WE43-T5, plate

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ABSTRACT

The mechanical response of rare earth containing Mg alloy, WE43, plates is found to be more isotropic, as compared to conventional alloys like AZ31, despite a moderately strong texture. In order to understand the grain-level deformation mechanisms which are responsible, the elastoplastic self-consistent (EPSC) polycrystal plasticity code, including the recently developed twinning–detwinning (TDT) model, is used to describe the homogeneous plastic flow of WE43-T5, plate at quasistatic and dynamic strain rates. Latent hardening of the slip modes is based on a recent discrete dislocation dynamics study in order to reduce the number of empirical fitting parameters without sacrificing model fidelity. The approach accounts for the presence of the initial texture and its evolution during deformation. The observed flow stress, strain, and strain hardening anisotropies and asymmetries are well-described. A single set of parameters was used to fit the entire set of results, at a given strain rate, thus enabling determination of strain rate sensitivities of individual deformation modes. Basal slip and extension twinning are rate-insensitive, within the strain rate regime examined, whereas the prismatic and <c+a> slip exhibit strain rate sensitivities of 0.008 and 0.005, respectively. Various strengthening mechanisms such as precipitation, grain refinement and solid solution hardening effects on each individual deformation modes are assessed. The softer modes, basal slip and extension twinning, are greatly strengthened in this alloy, as compared to the harder modes such as prismatic and <c+a> slip, which renders this material more isotropic, even at the grain-level, as compared to conventional Mg alloys.

1. Introduction

Recent ballistic tests carried out by Army Research Laboratory (ARL) have shown that the rare earth (RE) containing magnesium alloy WE43 have superior properties compared to Al–Mg alloy, 5083, and conventional Mg alloy, AZ31 (Cho et al., 2009). Thus, it is considered to be a potential armor material. In an earlier study (Agnew et al., 2014), the constitutive behavior of this alloy was examined and it was found that this material exhibited a more isotropic response as compared to AZ31 and AM30,

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despite being moderately textured. Moreover, it showed some tension-compression strength asymmetry which was highest along the normal direction (ND) of the plate. Furthermore, the strain rate sensitivity was found to be a function of loading direction as well as strain level. Recent studies by Tucker et al. (2009) and Ulacia et al. (2010) demonstrated the strong role that texture plays in the dynamic response of Mg alloy sheets and plates respectively. The goal of the present study is to determine the role of individual deformation modes, which render this material more isotropic in spite of being moderately textured. Crystal plasticity modeling is an effective technique to study the grain-level deformation mechanisms. Such technique allows one to assess the strength and strain hardening behavior of individual slip systems. Thus, for the present study, an elasto-plastic self-consistent (EPSC) model (Turner and Tomé, 1994) has been employed. Importantly, the crystal plasticity model itself is completely rate independent. By determining the model parameters which describe the experimental response at different strain rates, the strain rate sensitivities of individual deformation modes are evaluated. This information is, in turn, used to inform our understanding of how the various strengthening mechanisms affect the individual deformation modes.

WE43 (containing 3.7–4.3 wt% yttrium, 2.4–4.4 wt% neodymium and at least 0.4 wt% zirconium) alloy is a precipitation hardenable alloy, which exhibits good age-hardening response among Mg alloys. The precipitation hardening behavior in Mg alloys is quite complicated as compared to face centered cubic alloys e.g. heat treatable Al alloys, because of multiple deformation modes that are active in Mg alloys. Moreover, for a given deformation mode, the effect of precipitation hardening depend on the shape and orientation of the precipitates with respect to the matrix. In WE43, primarily, plate shaped precipitates form on the prismatic planes (Nie and Muddle, 2000; Nie et al., 2001). The effects of precipitate shape on the deformation behavior of Mg alloys have been investigated in several prior works (Nie, 2003; Robson et al., 2011, 2012), where calculations based upon the Orowan bowing mechanism has been used to obtain the shear resistance imposed by the precipitates. These calculations reveal that the prismatic plates, such as those in WE43 alloys, are most effective in blocking basal <a> type dislocations. Using in-situ neutron diffraction and EPSC modeling Agnew et al. (2013) studied the effect of age-hardening on the deformation of an as-cast WE43 alloy, and found that basal <a> slip is considerably strengthened as compared to prismatic and <c+a> pyramidal slip. Interestingly, a possible reduction in the critical resolved shear stress (CRSS) for twinning with age-hardening was reported.

Besides age-hardening, solutes can have a profound impact on the active deformation modes (e.g. Akhtar and Teghtsoonian, 1969; Raeisinia et al., 2010). Using first principles calculation, Yasi et al. (2010) tabulated the potency of 29 solutes for strengthening basal slip, including Y. Regarding non-basal slip and twinning modes, only recently, some investigations have started to shed light on the effects of RE solutes. For instance, Stanford et al. (2014) used in-situ neutron diffraction and EPSC modeling to investigate the deformation of binary Mg–Y alloys and found that Y solute can significantly increase the CRSS of <c+a> pyramidal slip. Nie et al. (2013) using HAADF STEM have shown Gd segregation in tensile twin boundaries, leading to retardation in twin growth during subsequent deformation. Lentz et al. (2014, 2015), while studying WE54 using in-situ neutron diffraction and EPSC modeling, found that the strength of the twinning mode is significantly higher than that in conventional Mg alloys. Stanford et al. (2015) recently observed that Y addition leads to reduced $\{10\bar{1}2\}$ extension twinning activity and can even lead to the formation of $\{11\bar{2}1\}$ twins in Mg–10Y alloys. All these aforementioned works indicate a significant effect of precipitates and solutes on the deformation behavior of RE containing Mg alloys. One goal of this paper is to investigate the effects of these strengthening mechanisms on individual deformation modes under dynamic loading conditions, with a goal of informing researchers interested in maximizing the ballistic performance of Mg alloys.

Despite possessing superior mechanical properties than AZ31, the dynamic behavior of WE43 alloy is less extensively investigated. Nevertheless, one of the earliest published high-strain-rate deformation studies on Mg alloys was performed on WE43 (Mukai et al., 1998). They showed that a significant improvement in energy absorption could be achieved by strong grain refinement (down to 1.4 μm) via conventional extrusion. This fine-grained WE43 exhibited high ductility, which resulted in significantly higher energy absorption per unit mass due to the low density of Mg alloys.

Asgari et al. (2014) recently examined the high strain rate behavior of Mg alloy, WE43, and employed the visco-plastic self-consistent (VPSC) model (Lebensohn and Tomé, 1993) to simulate texture evolution during in-plane and ND compression. However, they did not seek to simulate the constitutive response (flow stress or plastic anisotropy), nor did they consider prismatic slip in their simulations, which is known to be active in Mg alloys and has recently been reemphasized as an important contributor to deformation texture evolution (Steiner et al., 2015). Furthermore, they suggested that the activity of extension twinning decreases with increase in strain rate, based upon EBSD data (Asgari et al., 2014). Finally, they suggested a higher activity of pyramidal <c+a> slip with increasing strain rate and attributed this to adiabatic heating during dynamic deformation, although the extent of temperature rise was not mentioned.

The goal of the present study is to determine the strength, hardening behavior, and rate sensitivity of individual deformation (slip and twinning) modes. These mode-level behaviors are interpreted in terms of various operative strengthening mechanisms (solute, precipitates, grain size, etc.). The relative effects of texture and deformation mode behavior in determining the constitutive behavior are discussed.

2. Experimental methods

2.1. Materials, texture and microstructure

Two 38 mm (1.5 inch) thick plates of WE43B alloy in T5 (artificially peak aged at 210 °C for 48 h) condition were used in this study. The details of the processing technique are described elsewhere (Agnew et al., 2014). X-ray diffraction was used to