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Spatio-temporal characteristics of propagative plastic instabilities in a rare earth containing magnesium alloy

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ABSTRACT

An experimental investigation of the spatio-temporal characteristics of propagative plastic instabilities in quasi-static, room-temperature tensile tests of fully annealed Mg ZEK100, a rare earth containing Mg alloy (0.2 wt.% Nd), is presented with the aid of stereo digital image correlation. Results from specimens aligned with the sheet transverse direction revealed the nucleation of a Lüders band at the fixed specimen end, followed by continuous propagation to, and ultimate termination at, the moving end during yield point elongation (YPE). Serrations in tensile flow curves, observed both during and after YPE, were attributed to propagating deformation bands, similar to the Type A Portevin-Le Châtelier (PLC) bands. Both strain and strain-rate contours enabled exploration of band nucleation and quantification of band kinematics. We also used TEM, EBSD, and electron diffraction to examine microstructural evolution during tensile deformation. Results were used to determine which, if any of the commonly cited microstructural mechanisms, such as diffusing solute pinning of mobile dislocations, precipitate shearing of dislocations, or solute locking of dislocations by a rare earth addition, is responsible for the observed Lüdering and PLC behavior. We found evidence that Lüdering is due to twinning. Although we could not definitively demonstrate a microstructural mechanism that is responsible for PLC effect, pinning and depinning of dislocations via diffusing Zn solute clouds could not be ruled out as the underlying cause. Implications of the experimental results for theoretical model development are discussed.

1. Introduction

Magnesium (Mg) alloys have attracted considerable attention as potential replacement materials for heavier steel and aluminum alloys in various products. However, the use of wrought Mg alloys has been limited by poor room-temperature (RT) ductility which results from the large difference in critical resolved shear stresses between basal and prismatic slip in the hexagonal close packed (HCP) lattice (Yasi et al., 2011). Consequently, two independent basal slip systems ($1/3\langle 11\bar{2}0\rangle$) and twinning ($\{10\bar{1}2\}\langle 10\bar{1}1\rangle$) are the only active deformation mechanisms at RT (Sandlöbes et al., 2011). The nearly ideal c/a ratio promotes twinning, rather than basal or prismatic slip at RT. One approach to improving properties (e.g. ductility, creep- and corrosion resistance) of Mg alloys is through the addition of rare earth (RE) elements, such as La, Ce, Nd, and Pr, often in the form of misch metal (Mishra et al., 2008; Nie, 2012; Rokhlin, 2003). Improved RT ductility results from

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softening of the recrystallization texture along with increased activity of otherwise inactive deformation mechanisms: $\{10\bar{1}1\}\langle 10\bar{1}2\rangle$ compression twins, $\{10\bar{1}1\}$ $\{10\bar{1}2\}$ double twinning, and pyramidal $\langle c+a\rangle$ dislocation slip (Al-Samman and Li, 2011; Sandlöbes et al., 2011).

Yield point elongation (YPE) is commonly observed in metal alloys, such as mild steels, (Lomer, 1962; Butler, 1962) subjected to tension. Associated with YPE is the appearance of a single Lüders band (Hall, 1970), or phase-transformation band in the case of shape memory alloys (Shaw and Kyriakides, 1997), which is a propagative instability. A Lüders band typically nucleates at a stress concentration in a tensile specimen (e.g. a gripper end) during elongation (Louche and Chrysochoos, 2001). This is followed by a period of stable propagation under constant load to the opposite end of the specimen after a decrease in flow strength from σ_U, also referred to as the unpinning stress (Zhang and Jiang, 2005; Jonhston, 1962). However, a recent study (Hallai and Kyriakides, 2013) on the material response of Lüders-like instabilities shows that the true stress response of a material (e.g. NiTi) exhibiting Lüders banding is up-down-up (increase, decrease then increase) during YPE, followed by hardening, although the observed nominal stress–strain curve shows a plateau. Theoretical and experimental work (Hahn, 1962) has suggested that Lüders band propagation is related to the injection of mobile dislocations from the band into grain boundaries ahead of the band. Lüders band propagation terminates at a stress σ_L when the gauge section of the tensile specimen is uniformly deformed to the Lüders strain, $\Delta\varepsilon_L$, after which point hardening usually commences. Both σ_U and σ_L can vary non-monotonically with strain rate, although $\Delta\varepsilon_L$ increases with increasing strain rate in mild steel as reported by Wenman and Chard-Tuckey (2010). Certain Mg alloys with RE additions also exhibit YPE. For example, Stanford et al. (2010) observed YPE when the Gd content in a hot-rolled Mg alloy exceeded 2.75%. This was attributed to Gd solutes locking dislocations during a recrystallization annealing process before tensile testing. Alternatively, in their study of cast Mg–Nd binary alloys, Yan et al. (2008) found no indication of a solute locking mechanism involving Nd during tensile elongation. Zhang et al. (2010) observed upper and lower yield points in RT tensile tests of a semi-continuously cast/extruded Mg–Zn–Zr alloy with Er additions. Yield point elongation occurred when the Er content exceeded 2%, but the origin of YPE was not elucidated. The drop in stress from σ_U and the subsequent YPE in BCC metals (mild steels in particular) is closely related to static strain aging (SSA) in which a strained specimen is unloaded, aged, and then reloaded (Estrin and Kubin, 1995). The formation of solute clouds on dislocations increases with aging time, thereby requiring a larger stress to depin the dislocations from the clouds, a process often referred to as Cottrell aging (Cottrell and Bilby, 1949). Static strain aging in low carbon steel (for example) results from diffusion of C and N, both interstitial solutes, to pinned dislocations (Kyriakides and Miller, 2000; Kyriakides, 2001). Other mechanisms associated with SSA are Snoek ordering in BCC alloys (Evans and Douthwaite, 1973) and Suzuki locking in FCC alloys (Suzuki, 1957). Of note is a recent study by Barnett et al. (2012) who investigated Lüders phenomenon during compression of extruded Mg AZ31 with a fine (5–15 μm) grain size. Lüders band propagation was induced via a "triggering" effect: each twin must induce at least one additional twin in a neighboring grain. Copious twinning was observed in the wake of a Lüders band.

Portevin-Le Châtelier (PLC) bands are usually considered to be distinct from a Lüders band, and they are classified into three generic types: A (propagating bands), B (hopping bands), and C (static bands) (Ananthakrishna, 2007). The Type A PLC bands continuously propagate along a tensile specimen and usually (but not always) nucleate from a geometry-induced stress concentration (e.g. a gripper end). They are associated with low-amplitude serrations in tensile flow curves (Zavattieri et al., 2009). The Type B PLC bands are characterized by hopping in that band nucleation occurs ahead of an existing PLC band (Hong et al., 2005). The Type C PLC bands are associated with large amplitude serrations in tensile flow curves, and they spontaneously grow and die out in a localized way, and generally do not propagate (Tong and Zhang, 2007). Portevin-Le Châtelier (PLC) bands are usually attributed to dynamic strain aging (DSA) (Curtin et al., 2006) which involves the repetitive pinning and depinning of dislocations by diffusing solute clouds. The PLC effect has been reported in Mg alloys without RE additions, such as AZ31B and AZ91, and RE containing Mg alloys. For example, Corby et al. (2004) found that serrated flow in AZ91 is due to the combined effects of Al and Zn. Aluminum was identified as the dominant diffusing species in AZ91 with Zn acting to enhance both prismatic slip and forest dislocations through which Al can diffuse (pipe diffusion). In their investigation of a Mg–0.5Zn (at.%) alloy single crystal under compression, Miura et al. (2000) observed serrated flow only at temperatures at or in excess of 373 K, and attributed this to the formation of Zn solute clouds around dislocations. Gao et al. (2009a) attributed serrated flow in a Mg–3.11 wt.% Gd alloy at 250 °C and 10^{-3} s^{-1} strain rate to DSA due to dislocation interactions with diffusing Gd solutes. Gao et al. (2009b) also observed serrated flow in Mg–Y alloys and attributed it to interactions between mobile solutes and dislocations but made no comment regarding the extent to which Y might be involved in this process. Miura et al. (2008) also reported serrated flow in Mg–Y single crystals at 473 K. Zhu and Nie (2004) reported serrated flow in a Mg–Y–Nd alloy within the 150–225 °C temperature range. Serrated flow could not be attributed to Y and Nd additions, possibly a result of their diffusivities being dramatically lower than that for Mg self-diffusion over the temperature range considered, and precipitate formation (Rzychoń and Kiełbus, 2007). Nevertheless, there is another explanation for the serrated flow: precipitate shearing (associated with stress drops in serrations) by moving dislocations. In Mg alloys, Nie (2002) has shown that precipitate plates may also be sheared by dislocations as the local stress concentration induced by accumulated dislocations exceeds the yield strength of the precipitates. However, Chmelík et al. (1998) reported that although precipitate shearing may occur, it does not necessarily result in serrated flow of the peak-aged Al–Li alloy investigated.

The present paper is an experimental investigation of the spatio-temporal characteristics of propagative instabilities, viz., Lüders and PLC-like bands, in quasi-static, room-temperature tensile deformation of Mg ZEK100-O, a rare earth containing Mg alloy (0.2 wt.% Nd) alloy, with the aid of stereo digital image correlation (DIC). Post-processing of the DIC results provided