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Microstructure and mechanical behavior of ECAP processed AZ31B over a wide range of loading rates under compression and tension

Xia Yu [a], Yulong Li [a,*], Qiuming Wei [b], Yazhou Guo [a], Tao Suo [a], Feng Zhao [c]

[a] *Department of Structural Engineering, School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, PR China*
[b] *Department of Mechanical Engineering, University of North Carolina at Charlotte, Charlotte, NC 28223-0001, USA*
[c] *The Peac Institute of Multiscale Sciences, Chengdu, Sichuan 610207, PR China*

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ABSTRACT

In this work, a commercial magnesium alloy, AZ31B in hot-rolled condition, has been subjected to severe plastic deformation via four passes of equal channel angular pressing (ECAP) to modify its microstructure. Electron backscatter diffraction (EBSD) was used to characterize the microstructure of the as-received, ECAPed and mechanically loaded specimens. Mechanical properties of the specimens were evaluated under both compression and tension along the rolling/extrusion direction over a wide range of strain rates. The yield strength, ultimate strength and failure strain/elongation under compression and tension were compared in detail to sort out the effects of factors in terms of microstructure and loading conditions. The results show that both the as-received alloy and ECAPed alloy are nearly insensitive to strain rate under compression, and the stress–strain curves exhibit clear sigmoidal shape, pointing to dominance of mechanical twinning responsible for the plastic deformation under compression. All compressive samples fail prematurely via adiabatic shear banding followed by cracking. Significant grain size refinement is identified in the vicinity of the shear crack. Under tension, the yield strength is much higher, with strong rate dependence and much improved tensile ductility in the ECAPed specimens. Tensile ductility is even much larger than the malleability under compression. This supports the operation of $\langle c+a \rangle$ dislocations. However, ECAP lowers the yield and flow strengths of the alloy under tension. We attempted to employ a mechanistic model to provide an explanation for the experimental results of plastic deformation and failure, which is in accordance with the physical processes under tension and compression.

1. Introduction

Magnesium alloys hold promising future in many structural applications because of their ultra-low density (the density of pure Mg is only 1.74 gm/cm^3) and high specific strength and stiffness (Avedesian and Baker, 1999; Mabuchi et al., 1997; Mukai et al., 2001; Steglich et al., 2012; Yamashita et al., 2001). They also exhibit excellent conductivity, damping capacity and electromagnetic shielding properties which may entail wide applications in communication, wiring, aviation and spaceflight (Bajargan et al., 2013; Liu, 2010; Yang et al., 2008).

Up to date, many researchers have been working strenuously to improve the ductility and strength of magnesium alloys through various approaches. It has been found that grain refinement (Del Valle et al., 2006; Figueiredo et al., 2007; Langdon, 2013; Yang et al., 2008),

* Corresponding author.

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among which equal channel angular pressing or extrusion (ECAP/ECAE) has stood out to be the most popular technical approach to concurrently improve the strength and ductility of Mg-alloys (Agnew et al., 2005; Beausir et al., 2008; Biswas et al., 2010; Chen et al., 2008; Del Valle and Ruano, 2008; Del Valle et al., 2006; Ding et al., 2008; Eddahbi et al., 2005; Figueiredo and Langdon, 2009; Figueiredo et al., 2007; Furui et al., 2007; Han and Langdon, 2005; Kim et al., 2003; Matsubara et al., 2003; Mukai et al., 2001; Yuan et al., 2013). Barnett et al. (2004b) altered the grain size of Mg-alloy AZ31 (nominal composition 3%Al, 1%Zn, both wt.%, balance Mg) by varying the extrusion temperature and concluded that a transition from twinning to slip dominated flow occurred with decreasing grain size and increasing temperature. Ding et al. (2008) processed AZ31 via ECAP and the average grain size obtained was ~370 nm. These fine-grained Mg-alloy samples exhibit yield and ultimate tensile strengths (UTS) on the order of 372 and 445 MPa, respectively when tested along the extrusion direction, with a tensile ductility of 10%. Recently, Foley et al. (2011) processed AZ31 following a five-step hybrid ECAP route and they only presented compression responses of the worked material, with a maximum yield strength of 350 MPa. Razavi et al. (2012) achieved an average grain size down to 350 nm through ECAP. The maximum tensile yield strength of 385 MPa and ultimate tensile strength of 455 MPa accompanied with 13% tensile ductility were achieved in the processed alloy. Yuan et al. Yuan et al. (2013) employed a combinatory approach to alter the microstructure of AZ91. The alloy was solution treated prior to ECAP. After ECAP, the alloy went through aging treatment. They found that for tensile specimens with grain size of ~500 nm, the yield strength is ~270 MPa, the tensile strength is 408 MPa and the elongation to failure is 15.1%.

To date, numerous efforts have been undertaken on magnesium and Mg-alloys toward the microstructure and mechanical property relationship (Agnew and Duygulu, 2005; Barnett et al., 2004b; Ishikawa et al., 2005b; Kim and Kim, 2004). However, there have only been sporadic investigations on the effect of strain rate on the mechanical behavior of this important type of ultralight structural material (Agnew et al., 2014; Ishikawa et al., 2005a,b; Prasad et al., 2014; Ulacia et al., 2010). Tucker et al. (2009) studied the anisotropic effects on the strain rate dependence of AZ31 alloy. They found that the compressive yield stress, hardening rate and strain-to-failure in the normal direction increase as the strain rate increases. However, along the rolling and transverse directions, the yield stress exhibits no strain rate dependence though the hardening rate increases as the strain rate increases. Also, as the strain rate increased, the twin density increased in all three orientations. Zhao et al. (2010) studied the compressive properties of cast AZ31 magnesium alloy at different temperatures and strain rates and came to the conclusion that both the strength and ductility increase with increasing strain rate and the peak stress decreases with increasing temperature at a fixed strain rate.

In this paper the mechanical properties of hot-rolled and ECAP processed AZ31B under compression and tension were examined. Loading at different strain rates was actualized by adopting different loading system; then, strain rate dependence of the mechanical properties was analyzed. Under each loading condition, two kinds of specimens with different microstructural characters were tested. The microstructure and texture were examined through EBSD.

2. Experimental procedures

2.1. Materials and specimen preparation

The material used in the present study was a commercial Mg–Al–Zn alloy, AZ31B (chemical composition: Mg–3.28Al–1Zn–0.44Mn, all in wt.%, balance Mg), and was received as a hot-rolled plate of 10 mm thickness. Billets with dimensions 9.8 mm × 9.8 mm × 60 mm were cut along the original rolling direction (RD) of the plate for ECAP processing. The ECAP die has an internal angle α of 90° and an outer angle β of 20° between the vertical and horizontal channels, as shown in Fig. 1. The equivalent strain involved in ECAP can be calculated (Iwahashi et al., 1996) to be ~1.1595 upon each EACP pass. The billets were rotated 90° clockwise about the longitudinal (or extrusion) axis between consecutive passes (route Bc (Gholinia et al., 2000)). Repetitive pressings of the same sample were performed up to 4 passes, reaching a total equivalent strain of ~4.638. ECAP was carried out at 553 K (280 °C) in the first two passes, followed by 538 K (265 °C) and 523 K (250 °C) extrusion for the third and fourth passes, respectively. ECAP was performed at a constant pressing speed of 20 mm/min. Before each pass, the billet was preheated for 5 min in the die which was maintained at the targeted ECAP temperature. The exact temperature of the die was monitored through a thermocouple placed near the intersection of the two channels. Graphite was used as the lubricant between the billet and the die.

After the ECAP process, specimens for mechanical testing were cut from both the as-received alloy and the alloy after four passes of ECAP. The compressive and tensile specimens for quasi-static test were prepared along the rolling/extrusion direction with dimensions as shown in Fig. 2(a) and (b). Moreover, the dimensions of the dynamic compressive and tensile specimens were shown in Fig. 4(a) and (b). They are also cut along the rolling/extrusion direction.

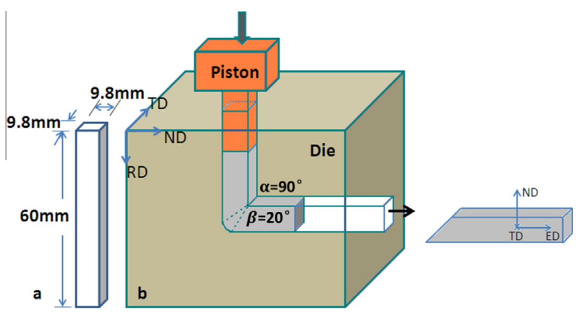

Fig. 1. Schematic of (a) shape and dimension of the initial billet prior to ECAP and (b) ECAP tooling.