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In-situ investigation on the microstructure evolution and plasticity of two magnesium alloys during three-point bending

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ABSTRACT

Three-point bending represents important straining in metal forming, and is an ideal loading condition for *in-situ* investigation of complex microstructure evolution and plasticity of magnesium alloys. Two extruded alloys with different initial texture, AZ31 (Mg–3%Al–0.5%Zn[1]) and AM30 (Mg–3%Al–0.3%Mn), were studied in three-point bending with *in-situ* electron backscatter diffraction (EBSD) observations, to reveal the role of strain gradient and deformation compatibility in the plasticity of magnesium alloys. The results indicate that strain gradients in macro-scale from tension to compression can lead to a graded microstructure and texture evolution in the samples during bending. At the intergranular and intragranular levels, the volume fraction of twins was influenced by the slip-induced twinning behavior and strain compatibility among the surrounding grains except for Schmid factor relating to grain orientation. Slip-induced twinning behavior and its surrounding effects on the twinning volume fraction is much more profound in materials with weak textures. The AM30 alloy with a weaker texture shows better deformation compatibility (and, thus, formability) during three-point bending compared to AZ31 alloy with a stronger texture in this study.

1. Introduction

Wrought magnesium (Mg) alloys have attracted increasing attentions as potential lightweight materials in the transportation industries (Agnew and Duygulu, 2005; Agnew and Nie, 2010; Luo et al., 2010). Mg sheet and extrusion components often need to be processed under multi-directional straining, such as stamping and flow-forming (Wong et al., 2003), with substantial strain gradients formed along the thickness direction. Understanding the deformation mechanisms of Mg alloys under complex loading and the role of strain gradient in plasticity is crucial to achieving optimized processing parameters and end products. In stamping or flow-forming processes, the material flow behavior and its models in forming simulation appear to be dependent on the material length scale (Abu Al-Rub and Voyiadjis, 2006; Roy et al., 2009), i.e., the dependence of

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[1] All composition in wt.% except otherwise stated.

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mechanical response on microstructure sizes. Intergranular or intragranular deformation gradients due to grain size or grain orientation during processing have important effects on the formability of the materials. However, the lack of experimental and simulation work correlating strain gradient to the material plasticity is an obstacle for understanding the deformation mechanisms and improving formability of Mg alloys under complex loading.

Extensive discussions on the deformation mechanisms of Mg alloys under uniaxial loading can be found in literature (Agnew et al., 2003; Jiang et al., 2007; Ma et al., 2012; Sun et al., 2013). Due to the lower critical resolved shear stress (CRSS) values, the dislocation slip on basal plane and the $\{10\bar{1}2\}[\bar{1}011]$ extension twinning are two dominant deformation modes at room temperature (Kelley and Hosford, 1968). Therefore, wrought Mg alloys, such as AZ31 (Mg–3%Al–0.5%Zn), which usually have a significant fraction of grains orientated with their c-axes nearly perpendicular to the prior working (rolling or extrusion) direction (Barnett et al., 2004; Bohlen et al., 2005; Jiang et al., 2007), exhibit the well-known tension-compression yield asymmetry (Avedesian and Baker, 1999; Jain et al., 2010; Sun et al., 2013). The deformation behavior of Mg alloys under multi-directional loading is more complex than uniaxial loading, despite the same basic deformation modes in these loading conditions. Under multi-directional loading, the graded microstructure evolution and the deformation behavior are difficult to be captured due to the strain gradients in the alloy samples or components.

Furthermore, current descriptions and related models of the plasticity of Mg alloys are primarily based on the Schmid factor and the CRSS effects where the behavior of individual grains could represent the polycrystalline bulk materials. It is well known that the mechanical behavior of polycrystalline metals is a collective response of individual crystals (grains). However, during deformation, polycrystalline materials develop internal strains/stresses characteristic of three length-scales, i.e., macro-, intergranular and intragranular (Agnew et al., 2003; Reimers et al., 2008). For the intergranular scale, strain mismatch between grains with different orientations due to the elastic and plastic anisotropy at the grain level will result in stress relaxation in individual grains and then activate various intragranular deformation modes. The development of a macroscopic model embedded with lattice strains is hindered by the difficulties in describing the local microstructure evolution in terms of macroscopic mechanics (Abu Al-Rub and Voyiadjis, 2006). It is important to utilize experimental techniques to characterize the intergranular-scale deformation behavior of polycrystalline metals. Non-Schmid effects and grain boundary (GB) effects on twinning had been mentioned in an investigation of AM30 (Mg–3%Al–0.3%Mn) alloy, but the flow asymmetry under tension and compression of the alloy were discussed (El Kadiri et al., 2013). Thereafter, non-Schmid twin variant and twin–twin transfer behavior were also observed in AZ31 (Mg–3%Al–0.5%Zn) alloy sheet (Guo et al., 2014). Digital image correlation (DIC) was used to evaluate the plastic strain distribution in intergranular and intragranular scales of a Mg–Zn–Gd alloy (Martin et al., 2013) and AZ31 alloy (Aydıner and Telemez, 2014) under uniaxial deformation, and the strain from intragranular to macro scales were analyzed but multi-directional loading was not addressed in these studies.

Three-point bending provides a complex loading condition similar to stamping and flow forming because stress and strain gradients exist in sample under the three-point bending tests. With *in-situ* microstructure observations during bending, the localized microstructure evolution in the sample can be captured and the intergranular-scale deformation behavior can be understood. *In-situ* neutron diffraction has been used for studying the lattice strain in deformation of polycrystalline (Agnew et al., 2013; Brown et al., 2013; Lee et al., 2012). But the *in-situ* neutron diffraction technique could not capture the micro-level information at the same time. By using *in-situ* electron backscatter diffraction (EBSD), it is possible to obtain local information on crystal orientations, internal deformation twinning or other deformation modes. Three-point bending tests with *in-situ* EBSD had been performed on AZ31 rolled sheet with a strong basal texture, localized twin bands were observed (Baird et al., 2012), but no further investigation has been reported on the deformation gradients in wrought Mg alloys.

In this study, three-point bending tests were performed at room temperature on AM30 and AZ31 alloys with different initial textures. AM30 is a newly developed wrought Mg alloy with improved formability and similar strength compared to commercial AZ31 alloy (Luo and Sachdev, 2007). *In-situ* EBSD and scanning electron microscopy (SEM) techniques were applied to investigate the microstructure evolution in macro-, intergranular and intragranular scales. The graded microstructure evolution in the samples was characterized, and the texture-induced deformation behavior and plasticity of the two Mg alloys were analyzed. In addition, the deformation modes in individual grains and their interactions with surrounding grains were discussed based on the quantitative data from the *in-situ* observations, revealing the role of strain gradient and deformation compatibility in the plasticity of Mg alloys. As a baseline for understanding the basic deformation modes, extruded pure Mg was also studied for microstructure evolution under uniaxial tensile and compressive loading.

2. Experimental procedure

The materials studied in the current work are AM30 and AZ31 alloy tubes prepared using hot extrusion. The *in-situ* bending was performed using a micro-test system provided by Deben UK Ltd. with a load cell of 5 KN capacity, installed inside a LEO™ 1450 SEM fitted with a TSL™ EBSD camera. Fig. 1 presents a schematic view of the EBSD data collection system with the *in-situ* test fixtures, the sample preparation for three-point bending and the initial microstructure of AM30 and AZ31 alloy samples. The sample of 35 mm × 3 mm × 3 mm size is cut from the tube as shown in Fig. 1(a). The loads are applied perpendicular to the initial extrusion direction (ED) of the tubes. The texture intensity of AM30 sample is lower than that of AZ31 as shown in Fig. 1(f), where the distinct texture provides an ideal condition for analysis of texture-induced anisotropy in three-point bending tests.