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ScienceDirect
Acta Materialia 80 (2014) 380–391
Acta MATERIALIA
www.elsevier.com/locate/actamat

Influence of orientation on twin nucleation and growth at low strains in a magnesium alloy

M.R. Barnett [a,*], A. Ghaderi [a], J. Quinta da Fonseca [b], J.D. Robson [b]

[a] *ARC Centre for Excellence for Design in Light Metals, Institute for Frontier Materials, Deakin University, Geelong, Australia*
[b] *School of Materials Science, University of Manchester, Manchester, UK*

Received 10 January 2014; received in revised form 11 June 2014; accepted 6 July 2014

Abstract

The resolved shear stress is believed to play an important role in twin formation. The present study tests this idea for an extruded magnesium alloy by examining "tension" twinning in different grain orientations. Electron backscatter diffraction analysis is employed for alloy AZ31 tested in compression along the extrusion axis to strains between 0.008 and 0.015. For heavily twinned grains, it is seen that twinning occurs on 2.3 twin systems per grain on average. The active systems are also most commonly those with, or very near to, the highest Schmid factor. The most active system in multiply twinned grains accounts on average for ~0.6 of the twinning events. In addition, it is found that the twin habit plane falls within 6° of the K_1 plane. Orientations with the highest Schmid factors (0.45–0.5) for twinning display twin aspect ratios greater by ~40% and twin number densities greater by ~10 times than orientations with maximum Schmid factors for twinning of 0.15–0.2. Thus the Schmid factor for twinning is seen to affect nucleation more than thickening in the present material. Viscoplastic crystal plasticity simulations are employed to obtain approximations for the resolved shear stress. Both the twin aspect ratio and number density correlate quite well with this term. The effect of the former can be assumed to be linear and that of the latter follows a power law with exponent ~13. Increased aspect ratios and number densities are seen at low Schmid factors and this may relate to stress fluctuations, caused most probably in the present material by the stress fields at the tips of blocked twins. Overall, it is evident that the dominance of twinning on high Schmid factor systems is preserved at the low strains examined in the present work, despite the stress fluctuations known to be present.

Keywords: Twin nucleation and growth; EBSD; Magnesium; Crystal plasticity

1. Introduction

Twinning can play a large role in determining the yield stress of sharply textured magnesium alloys (e.g. [1–5])). To control the strength in such cases it is necessary to understand the factors that impact on twinning. In particular, it is desirable to understand the separate contributions of twin nucleation and growth, both of which typically respond to stress differently [6]. One manifestation of the importance of this is the variation of twin density and size seen over differently oriented grains in a polycrystal [7–9].

The Schmid tensor provides a theoretical link between grain-scale stresses and the resolved shear stress. Because grain-level stresses are not typically known, the scalar Schmid factor, expressed in sample co-ordinates, has been widely employed to help rationalise the influence of grain orientation on twinning [7–10]. Electron backscatter diffraction (EBSD) studies [7–9] have shown that $\{10\bar{1}2\}$ twins (the only twin mode that will be considered in the present work) nucleate in a manner that depends

* Corresponding author.
E-mail address: barnettm@deakin.edu.au (M.R. Barnett).

http://dx.doi.org/10.1016/j.actamat.2014.07.013
1359-6454/

imprecisely on the Schmid factor. This arises from local variations in stress and the stochastic nature of the nucleation event(s) [11,12]. The former has been explored to some extent using full-field models [13–15] that capture local grain interactions arising from elastic and plastic anisotropy. Our interest in the present work is in the twinning that takes place immediately following macroscopic yielding, and it is not clear to what extent these previous findings relate to this particular case.

Following macroscopic yielding, the numbers of twins per grain will generally be low, especially if the grain size is fine [16]. This means that any influence of other twinning events in the same parent grain [17] will also be low. No stress fluctuations are likely to arise from elastic compatibility because magnesium is nearly elastically isotropic. And, when the texture is strongly in favour of twinning, the impact of ‘early’ microyielding by basal slip [18] on local stress variation is likely to be minor, simply because the number of basal slipping grains will be low. Such conditions are favourable for “deterministic” twin formation and probably account for the good agreement we found previously between the $\{10\bar{1}2\}$ twin volume fraction and viscoplastic crystal plasticity predictions made without consideration of local effects [19]. However, it remains to be seen how the finding relates to the underlying processes of nucleation and growth. Answering this question is the motivation for the present paper.

Statistical treatments of nucleation [11] and the rather limited experimental data available (e.g. [16]) suggest that the following rate law should hold for twinning at grain boundaries in the present material:

$$N_a = \frac{a}{a_0}\left(\frac{\tau}{\tau_0}\right)^n, \tag{1}$$

where N_a is the number of twins forming over grain boundary interface area a, τ is the resolved shear stress, n is a rate exponent, and a_0 and τ_0 are reference values. In the absence of significant local effects, and so long as nucleation has not saturated, one might expect to obtain this relationship from an inspection of the twin number densities in differently oriented grains over a polycrystal. This of course requires a means of obtaining the resolved shear stress in the different grain families, something that is not trivial. In the present case we will use crystal plasticity simulations to provide an estimate.

Twin growth comprises (i) the initial burst or propagation of the twin until it either impinges upon an obstacle or “exhausts” the driving stress, and (ii) twin thickening. Here, we focus on the latter. Such thickening has been reported to be more “well behaved” than nucleation. The statistical study by Beyerlein et al. [7] found good correlation between twin thickness and the Schmid factor. However, El Kadiri et al. [20] have shown that for two grains with similar Schmid factors, considerable differences in twin thicknesses (and number densities) can be obtained, depending on the number of active systems. In a previous study two of us found that the twin aspect ratio (defined in the present work as thickness over length; hence, a thick twin has a high aspect ratio) scales roughly with the stress for samples with different grain sizes [16]. Although this is in general agreement with Eshelby-type back-stress arguments, it was seen that the magnitudes of the measured aspect ratios are well in excess of the values expected from an elastic Eshelby analysis. This was ascribed to “plastic relaxation” [21,22]. That is, plasticity at the twin tips serves to relax the back-stress in the twin interior, which allows the twin to adopt a larger aspect ratio. Bulk neutron diffraction data (e.g. [2]) show that after only a moderate strain (>∼4%), the back-stresses relax completely. Thus one might expect correlations of different strength between twin aspect ratio and Schmid factor depending on the strain level.

The current work examines $\{10\bar{1}2\}$ twin nucleation and thickening at low strains by employing EBSD to determine twin aspect ratio, twin number density, twin trace and twin variant for various parent orientations, defined by commonality of their Schmid factors for twinning. Compression of extruded AZ31 along the extrusion direction to axial strains of 0.008–0.015 is employed. Viscoplastic crystal plasticity calculations are used to estimate the resolved stress.

2. Methodology

The study employs material and methods used in a previous paper [19]. Alloy AZ31 with composition Al 2.87, Zn 0.83, Mn 0.45 (wt.%) was used. As-received extruded material was extruded to 8 mm diameter bar at 300 °C with a ram speed of 0.1 mm s^{-1}. This was followed by air cooling and annealing at 450 °C for 1 h. The microstructure after a strain of 0.011 is shown in the “raw” uncorrected EBSD map in Fig. 1a along with an inverse pole figure representation of the texture (Fig. 1b)—calculated after removing the twins. The mean linear intercept grain size, d, established over the ∼14,000 grains examined, is 12.6 μm and the dominating texture component is a fibre of orientations with a $\langle 10\bar{1}0\rangle$ pole in the extrusion direction. The distribution of the inclination of the c-axis of the initial orientations to the extrusion direction is shown in Fig. 1c.

Compression testing was carried out parallel to the extrusion direction at room temperature at a strain rate of 10^{-3} s^{-1}. Tests were halted at plastic strains of 0.008, 0.011 and 0.015 (determined using a commercial non-contact extensometer). With a strain of 0.008, the Lüders band that is seen in this material has traversed the sample [23]. A test to failure was also performed and the stress–strain curves are shown in Fig. 2. Mid-sections of the samples were prepared for EBSD analysis using standard techniques. Two EBSD maps each of ∼2300 grains (see Fig. 1) were measured for each of the three strains examined.