Journal of Alloys and Compounds 737 (2018) 549–560

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Twin-twin interactions and contraction twin formation in an extruded magnesium alloy subjected to an alteration of compressive direction

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ARTICLE INFO

Article history:
Received 5 August 2017
Received in revised form
2 December 2017
Accepted 5 December 2017
Available online 8 December 2017

Keywords:
Magnesium alloy
Twinning
Detwinning
Extension twin
Contraction twin
Twin-twin interaction

ABSTRACT

Twinning and detwinning represent major deformation mechanisms in hexagonal close-packed (hcp) metals. The aim of this study was to identify twin-twin interactions and contraction twin formation in an AZ31 magnesium alloy when the compressive direction was changed from the extrusion direction (ED) to the normal direction (ND) via electron backscatter diffraction (EBSD) and Schmid factor analysis. $\{10\bar{1}2\}$ extension twins of multiple variants were observed after compressive deformation of 4.3% along ED. The detwinning of $\{10\bar{1}2\}$ extension twins occurred along with the formation of $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ contraction twins, when the compressive direction was changed to ND. The extension twins in some grains almost fully vanished, making the grains back to a twin-free state. A new twin-twin interaction mechanism being different from double twinning (defined as twins within a twin) was identified, due to the impingement of $\{10\bar{1}1\}$ contraction twins nucleated in the matrix grain on a pre-existing $\{10\bar{1}2\}$ extension twin.

1. Introduction

Magnesium (Mg) alloys have drawn a lot of interest due to their low density, high specific strength, and superior damping capacity, making them suitable for potential lightweighting structural applications [1,2]. Nevertheless, because of an inadequate number of slip systems [3,4], twinning becomes a major deformation mode in Mg alloys, due to a lower critical resolved shear stress (CRSS) in comparison with some slip systems (e.g., prismatic $<a>$ slip and pyramidal $<c+a>$ slip) [5,6]. Wrought Mg alloys contain strong basal texture [7], which leads to the anisotropy of mechanical properties, and the limited formability at room temperature (RT) [8,9]. When loaded along a favorable direction (i.e., the tensile loading is applied parallel to the *c*-axis of the hcp unit cell or compressive loading is applied perpendicular to the *c*-axis [10]), $\{10\bar{1}2\}$ extension twinning has been characterized by the nucleation and growth of the twin lamellas [11,12]. However, the reverse motion of $\{10\bar{1}2\}$ extension twin boundaries, also referred to as detwinning [13,14], occurs under a stress that is lower than the stress required for its growth [15]. This could be linked to the high back stress formed in the alloy matrix during twin formation, which acts as an additional driving force for detwinning [16,17]. An applied compressive stress along the *c*-axis of a grain is thus susceptible to the detwinning [18]. Other twinning features could also be observed under such a loading condition such as contraction twinning, of which $\{10\bar{1}1\}\langle10\bar{1}2\rangle$ type was widely reported [19–21]. In addition, it has been stated in Refs. [22,23] that a continuous increase of the compressive strain under the same condition might lead to the development of secondary $\{10\bar{1}2\}\langle\bar{1}011\rangle$ extension twinning within the primary $\{10\bar{1}1\}\langle10\bar{1}2\rangle$ contraction twins, resulting in $\{10\bar{1}1\}-\{10\bar{1}2\}$ double twins.

Further observations have also been reported in the literature regarding this: the twin-twin interactions and the formation of twin boundary (TB) junctions [24–26], the dislocation-TB interaction [27,28], the twinning shear [29], and the grain size effect on dislocation and twinning [30]. Among these studies, Yu et al. [24] introduced a quilted-looking twin structure based on which twin-twin interactions could be correlated with strain hardening behavior. However, to the best of the authors' knowledge, the impingement of $\{10\bar{1}1\}$ contraction twins on a pre-existing $\{10\bar{1}2\}$ twin and its impact on the hosting grain have not yet been reported in Mg and its alloys due to the difficulty of observing imperceptible

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https://doi.org/10.1016/j.jallcom.2017.12.043
0925-8388/

$\{10\bar{1}1\}$ contraction twin lamellas when encountering the abundant $\{10\bar{1}2\}$ extension twins. When trying to depict the $\{10\bar{1}1\}$ contraction twins, most studies in the literature such as [18] and [19] opted for a gradual increase of deformation along the extrusion direction (ED) aiming to generate extension twins. Then gradual loading along the normal direction (ND) led to the shrinkage of the extension twins formed during pre-straining along with the formation of some contraction twins or double twins. It remains unclear how different the twinning-detwinning kinetics would be in the case of pre-deformation followed by a sudden change in the loading direction, and whether twinning interaction scenarios could be identified under this configuration. Overall, the analysis on the $\{10\bar{1}1\}$ contraction twinning is limited compared to the $\{10\bar{1}2\}$ extension twinning, and twin-twin interactions in the presence of contraction twins have not been well understood. It is still not clear how such highly mobile contraction twin boundaries, compared to the relatively stable extension twin boundaries, would influence the twin formation behavior. The purpose of this study was, therefore, to identify the change of the twinning features after first introducing "enough" deformation along ED and then immediately changing the loading direction, and discuss the mechanisms of twin-twin interactions between the extension and contraction twinning.

2. Material and experimental procedure

An extruded AZ31 magnesium alloy, with a composition (in wt.%) of 3.1 Al, 1.05 Zn, 0.54 Mn, 0.0035 Fe, 0.0007 Ni, 0.0008 Cu and Mg (balance), was selected in the present investigation. The extruded material was provided by General Motors Research and Development Center in Warren, Michigan, USA, with the bulk shape and sizes of the material after extrusion given in Refs. [31,32], where the extrusion was conducted in a temperature range of 360−382 °C at an exit speed of 50.8 mm/s and an extrusion ratio of ~6. After that, orthorhombic samples with dimensions of 5 mm × 4 mm × 6 mm (ED × TD × ND) were machined from a 7 mm thick plate, with the ED × ND (5 mm × 6 mm) surface initially polished via standard metallographic techniques, followed by electro-polishing for electron backscatter diffraction (EBSD) examinations. An electrolyte of 10 ml nitric acid and 40 ml ethanol was used for about 35 s at 20 V and RT. Compression tests along the ED and then ND were conducted using a computerized Instron machine at the same compressive strain of 4.3% at a strain rate of $1 \times 10^{-4}\ s^{-1}$ and at RT. The strain was measured on the basis of the crosshead displacement of the test apparatus, where the crosshead displacement included the deformation coming from the sample, load train and testing machine frame. When evaluating the stress-strain curves, to obtain the actual deformation amount of the test samples, the deformation coming from the test apparatus was eliminated using a calibration curve which was acquired directly through the upper compression plate against the lower compression plate in the absence of any sample. The reported values throughout this study are actual strain values of the test samples with the machine deformation amount excluded using the plate-to-plate calibration curve. EBSD observations were carried out via Oxford integrated AZtecHKL advanced EBSD system with Nordlys-Max[2] and AZtecSynergy along with a large area analytical silicon drift detector. A step size of 0.2 μm was used to investigate on the fine twining structures. Schmid factor calculations and the identification of the traces of the distinct twin variants were conducted

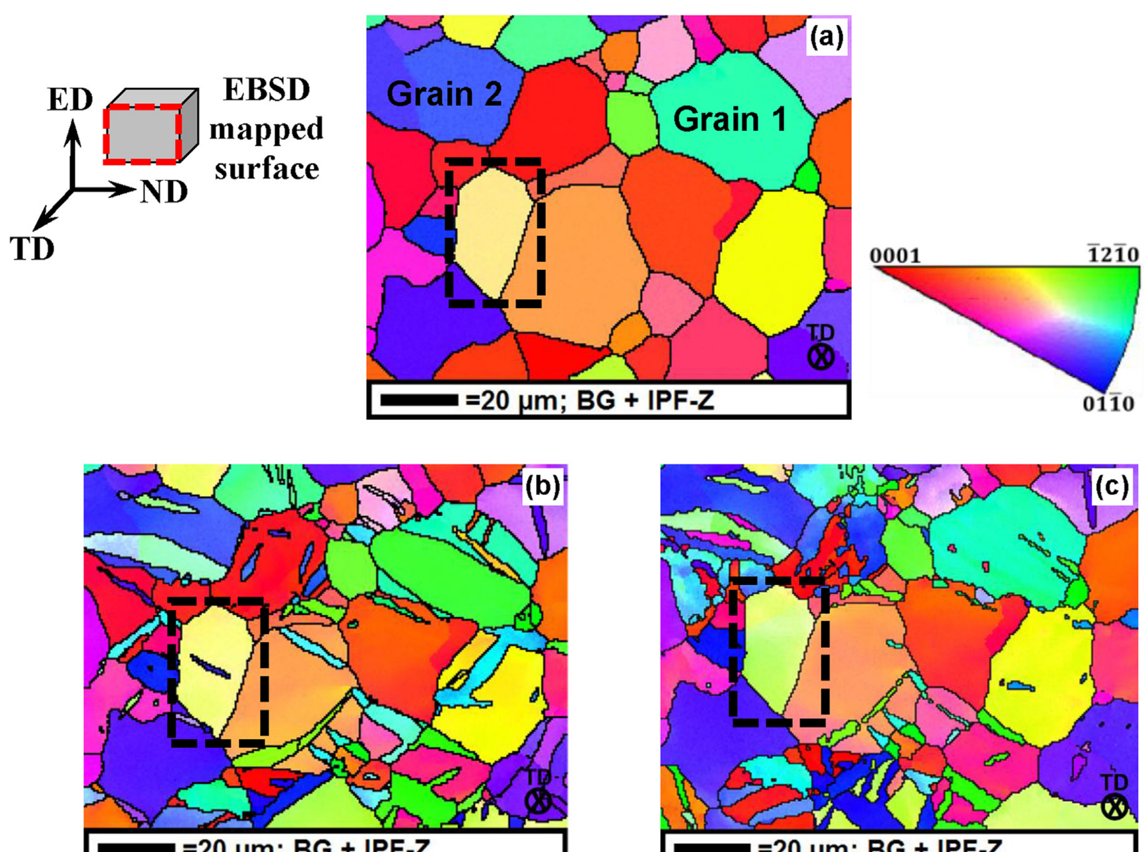

Fig. 1. Normal-projected EBSD orientation maps of the extruded AZ31 Mg alloy sample compressed at (a) 0%, (b) 4.3% ED, and (c) 4.3% ED − 4.3% ND.