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# Single and double twin nucleation, growth, and interaction in an extruded magnesium alloy

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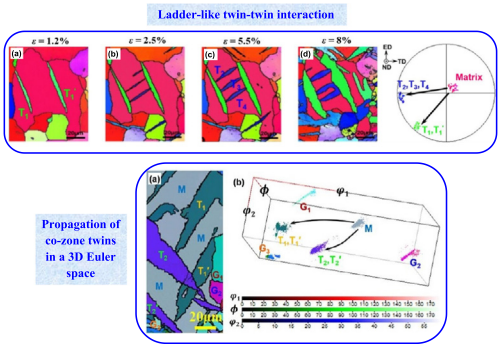
## HIGHLIGHTS

- $11\bar{2}1$ embryonic twin structures have been experimentally observed in a Mg alloy.
- $11\bar{2}1$ embryonic twin vanishes via the formation of $10\bar{1}2$ extension twins in it.
- New ladder-like and branching-like twin-twin interactions are identified.
- Branching-like structures involve non-co-zone $10\bar{1}2$ extension twin variants.
- Apparent crossing of a $10\bar{1}1$ contraction twin to two $10\bar{1}2$ extension twins is observed.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The objective of this study was to identify twinning characteristics and mechanisms in an extruded AZ31 magnesium alloy under favorable conditions of profuse $\{10\bar{1}2\}$ extension twinning using in-situ optical microscopy, electron backscatter diffraction, and X-ray diffraction analysis. The propagation of a single twin variant led to a relatively fast saturation of twin nucleation after which the increase in strain was predominantly accommodated by the growth of existing twin lamellas. For distinct twin variants, the intersecting twins led to the confinement of the spaces constrained by the fine twin lamellas. Embryonic twin structures acknowledged theoretically or through atomistic simulations were experimentally observed, including the vanishing of primary$\{11\bar{2}1\}$ embryonic twin via the nucleation and growth of either single or multiple $\{10\bar{1}2\}$ secondary extension twin variants during deformation. Newly identified twin-twin interaction scenarios included the ladder-like and branching-like twinning structures which occurred depending on the applied strain, incoming twin paths, and their impingement on the pre-existing twin boundaries. The formation of the branching-like structures involved three or more non-co-zone $\{10\bar{1}2\}$ extension twin variants where the activation and growth of one variant among them were found to be favored by the external stresses via Schmid factor analysis.



## 1. Introduction

The intrinsic properties of magnesium alloys, such as low density, high specific strength, and superior damping capacity, are the key for

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their attractiveness in the lightweighting structural applications [1–4]. Wrought magnesium alloys, however, contain strong basal textures resulting in the anisotropy of mechanical properties, and have limited formability at room temperature (RT) because of the inadequate number of basal slip systems [5–7]. The lower critical resolved shear stress (CRSS) of twinning, compared to other slip systems (e.g., prismatic $\langle a \rangle$ slip and pyramidal $\langle c + a \rangle$ slip) [8,9], justifies its important role in the plastic deformation. Twinning has become the subject of extensive studies in the literature [10–18]. Niezgoda et al. [17] introduced twinning in general as a "two-step" process of a nucleation event followed by propagation. El Kadiri et al. [12] focused on the nucleation and growth of $\{10\bar{1}2\}$ extension twins while identifying the influence of the number of activated twins in a given grain. Liu et al. [19] studied the promotion of twin chains by high geometric compatibility factor, low boundary angle and small grain size. Wang and Agnew [18] explored the dislocation transmutation reaction at the $\{10\bar{1}2\}$ twin boundaries using TEM. Dislocations inside a twin were considered through a defect structure in the vicinity of twin boundary and discussed in terms of stress state. Several other models were introduced to help comprehend the twinning behavior. For instance, Popova et al. [20] introduced a model based on dynamic recrystallization (DRX) to account for the effect of twinning on the final texture. Levesque et al. [2] proposed a simplified model to account for deformation twinning where the twinned zones and parent matrix are allowed to rotate independently. Khosravani et al. [16] modeled the twinning activity and deformation limits at RT and moderately elevated temperatures and varying strain paths.

The interactions of twin variants with each other in relation to grain orientation, shape and loading conditions have also been reported [10,11,13]. Yu et al. [10] discussed the quilted-looking twin structures, and concluded that twin-twin interactions could be correlated well with strain hardening behavior, which was further investigated by Proust et al. [21] by implementing a new law for twinning. Twinning threshold stress was monitored with respect to the shear accommodated by each slip mode [21]. Beyerlein and Tome [22] defined double twinning as the nucleation of a secondary twinning at parent twin-twin interfaces simultaneously or in sequence. The most commonly reported double twin structures are the secondary $\{10\bar{1}2\}$ twins within a primary $\{10\bar{1}1\}$ or $\{10\bar{1}3\}$ twins [22–25]. Kwon et al. [25] studied the possibility of different double twin variants based on the geometric compatibility between secondary $\{10\bar{1}2\}$ and parent $\{10\bar{1}3\}$ twins. Embryonic twin structures consisting of the formation of $\{11\bar{2}1\}$ twin embryos in order to assist in the growth of $\{10\bar{1}2\}$ extension twins were of interest through molecular dynamics [15]. However, to the authors' knowledge, $\{11\bar{2}1\}$ embryonic structures have not yet been experimentally observed in Mg and its alloys due to the difficulty of observing such imperceptible twin lamellas [15]. Hence it remains unclear how the $\{11\bar{2}1\}$ twins vanish when $\{10\bar{1}2\}$ twins are formed and whether it would persist as a single twin during deformation. The analysis on the $\{10\bar{1}1\}$ contraction twinning is limited compared to the $\{10\bar{1}2\}$ extension twinning and sometimes lacks experimental evidence. Twin-twin interactions in the presence of contraction twins and for different paths of incoming twins have not been well understood. It is still unclear how the highly mobile twin boundaries of contraction twins, in comparison with the relatively stable extension twins, would influence the twin formation behavior. The purpose of this study was, therefore, to first provide an experimental background and evidence for some of the features that have only been acknowledged theoretically or through atomistic simulations, then to identify new mechanisms of twin-twin interactions (i.e., ladder-like and branching-like structures), examine the growth of different twin variants, and study the formation of twin-twin boundaries, embryonic twin structures, and the eventuality of twin crossing.

## 2. Material and experimental procedure

The investigated material was 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). AZ31 plates, having a 7 mm

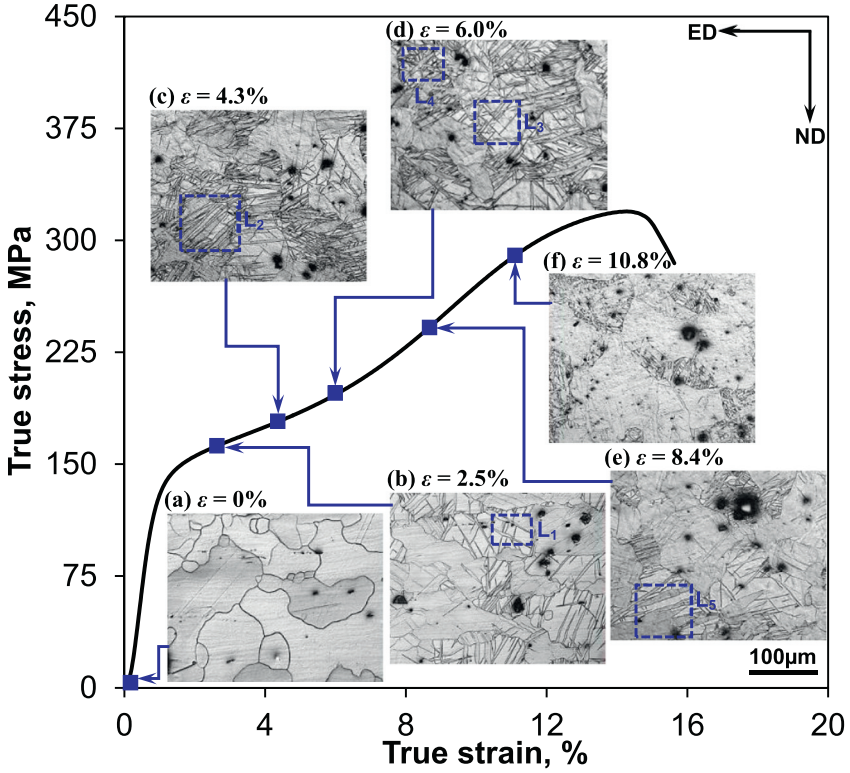


**Fig. 1.** Typical compressive true stress-true strain curve along with microstructural changes at varying true strains of (a) 0%, (b) 2.5%, (c) 4.3%, (d) 6.0%, (e) 8.4%, and (f) 10.8%.