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# Initiation and strain compatibility of connected extension twins in AZ31 magnesium alloy at high temperature

Xiao Liu [a,b], Biwu Zhu [a], Guangjie Huang [c], Luoxing Li [b,*], Chao Xie [d], Changping Tang [a]

[a] Key Laboratory of High Temperature Wear Resistant Materials Preparation Technology of Hunan Province, Hunan University of Science and Technology, Xiangtan, Hunan 411201, China
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, China
[c] College of Materials Science and Engineering, Chongqing University, Chongqing, Chongqing 400045, China
[d] Faculty of Mechanical Engineering and Mechanics, Ningbo University, Ningbo 315211, China

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ABSTRACT

Uniaxial compression tests were carried out at 350 °C and a strain rate of 0.3 $s^{-1}$ on as-extruded AZ31 magnesium alloy samples. At a true strain of −0.1, extension twin pairs in a grain and twin chains across adjacent grains were detected. The orientation of selected twins and their host grains were determined by electron backscattered diffraction (EBSD) techniques. The Schmid factors (SFs), accommodation strains and geometric compatibility factors ($m'$) were calculated. Analysis of the data indicated that the formation of twin pair and twin chain was related to the SF and $m'$. Regarding to twin chain across adjacent grains, accommodation strain was also involved. The selection of twin variants in twin chain was generally determined by $m'$. When the twins required the operation of pyramidal slip or twinning in adjacent grain, the corresponding connected twins with a relative high $m'$ were selected in this adjacent grain.



## 1. Introduction

The deformation of magnesium alloys is more complicated than that of cubic metals because of the hexagonal close-packed (hcp) structure. Twinning is an important deformation mechanism for these alloys, as they increase the number of deformation modes available during straining [1–4]. Therefore, it is necessary to understand twinning behavior under various deformation conditions. The twinning behavior was investigated by deforming extruded AZ31 specimens along the extrusion direction (ED) at room temperature [5]. They found that the SF mainly affected the nucleation of twinning.

{10−12} extension twins and {10−11} contraction twins, each with six variants, are most commonly observed twin types in Mg alloys [4,6,7]. One of the important questions relating to the formation of these twins is that of variant selection [4,7–19]. The SF is usually used to analyze the selection of twin variants [9,13,19,20]. S. Godet et al. [9] deformed specimens of AM30 under different strain paths and indicated that the choice of extension twin variants was mainly dominated by the SF criterion. Chapius et al. [13] carried out two successive in-plane compression tests along two different directions of hot rolled AZ31 at room temperature. They found that the selection of twin variants obeyed the Schmid law during compression and recompression. However, many investigations of the deformation of Mg alloys have shown that the variants with low SF were selected [10,12–14,20].

The role of accommodation strain on the formation of twin variants was detailed described by Jonas et al. [10] through carrying out uniaxial compression on AZ31 and AM30 at room temperature. They found that the twins with potential high SF were absent and that some very low SF twins appeared instead. They explained that the absent potential high SF would require amounts of accommodation work, while the selected low SF twins demanded much less accommodation work. Somewhat similar results were reported in the selection of twin variants in Ti [12,14]. In previous work, isolated twins were observed by deforming AZ31 specimens at 400 °C with a strain rate of 0.3 $s^{-1}$ [19]. We found that four out of ten selected grains activated non-Schmid twins and these twins were controlled by the accommodation strain. These investigations were focused on the criteria for choice of isolate twins. However, the intersecting twins in a grain and twin chain (more than two connected twins) across different adjoining grains are usually detected.

The geometric compatibility factor ($m'$) is defined to describe the compatibility between active slip systems in adjacent grains [21]. Recently, the effect of the geometric compatibility factor on the initiation of connected twins was described in details by Guo et al. [11,16] through conducting ambient temperature deformation on AZ31 magnesium alloy. They noted that the paired {10−12} extension twins with high SF and compatibility factor were likely formed and propagated across the grains, and these twins can transfer to more neighboring grains. They also indicated that geometric compatibility factor played more important role in the selection of twin variants in twin pairs or twin chains.

* Corresponding author.
*E-mail addresses:* liuxiao0105@163.com (X. Liu), luoxing_li@yahoo.com (L. Li).

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Liu et al. [17] bent friction stir welded AZ31 at ambient temperature and found that the formation of connected twins was related to the geometric compatibility factor.

In the present study, aiming to understand the formation of connected twins during hot compression, cylindrical samples of AZ31 were subjected to uniaxial compression along the extrusion direction (ED) at a strain rate of 0.3 $s^{-1}$ and 350 °C, i.e. at a temperature well above those at which twin selection is generally investigated. The twin variants in each grains of interest were determined. The SFs for all the six possible variants, accommodation strains and geometric compatibility factors ($m'$) between twin variants were calculated in each grains of interest. The twin pairs in a grain and twin chains across neighboring grains were analyzed combining the SF, accommodation strain and geometric compatibility factor ($m'$). Under high temperature, multiple slip is activated. Thus, the effect of dislocation slip on the formation of connected twins was also discussed.

## 2. Experimental and Calculation Methods

### 2.1. Experimental Methods

The alloy used in the present investigation was AZ31 (3.19 wt.% Al and 0.81 wt.% Zn). The material was received in the form of extruded bars with a diameter of 25 mm. The bars were annealed at 470 °C for 3 h. Cylindrical specimens with a diameter of 8 mm and a height of 12 mm were machined from the centers of the as-extruded bars. The specimens were compressed along the extrusion direction (ED) to a strain of −0.1 at 350 °C and a strain rate of 0.3 $s^{-1}$. During each test, the true strain rate was maintained constant.

The deformed samples were sectioned along the compression axis and then subjected to metallographic preparation using SiC papers. Polishing was carried out with diamond pastes of 3 and 1 μm. This was followed by etching using a solution containing 10 ml $HNO_3$, 30 ml acetic acid, 40 ml $H_2O$ and 120 ml alcohol. The EBSD micrographs were determined on a Philips VP 3000N SEM equipped with the HKL data acquisition system.

### 2.2. Calculation Methods

For the present purpose, the geometrical compatibility factor $m' = \cos\psi \times \cos\kappa$ was applied to analyze the strain compatibility between paired twins (here, $\psi$ and $\kappa$ are the angles between (i) the twinning plane normal of two neighboring grains and (ii) the twinning shear direction of two neighboring grains, respectively) [11,16,22]. The value of the geometrical parameter may vary between −1 and 1. For $m' = 1$, complete strain compatibility exists on the boundary, indicating that the twinning planes and directions in each twin will be parallel. Such deformation would be expected to be easily transmitted across the boundary. In contrast, $m' = 0$ suggests that the shear is independent and such systems would be expected to result in unfavorable conditions at the boundaries and $m' = -1$ arises when the shears oppose each other exactly.

In order to calculate the geometrical compatibility factor, it is necessary to be able to express the appropriate directions in grain 1 in the coordinate system of grain 2. Therefore, two sets of reference frames are involved: i) the crystallographic frame of the grain 1 $\{C^1\}$; and ii) the crystallographic frame of the neighboring grain 2 $\{C^2\}$. The misorientation matrix $m_{12}$ was used to transform the orientation $g_1$ of twin 1 matrix crystal frame $\{C^1\}$ into that $g_2$ of the neighboring grain crystal frame $\{C^2\}$:

$$m_{12} = g_2 * g_1^{-1}$$

Here, grains 1 and 2 are the matrix grains of twins 1 and 2, respectively.

Each twinning system ($g_{twinc}$) in the matrix grain crystal frame $\{C\}$ was characterized by the habit plane normal (HPN), twinning shear direction (SD), and the shear plane normal (SPN). The regarding procedures can be found in Refs. [10].

Thus, twin 1 ($g_{twin1c^1}$) in the matrix grain 1 crystal frame $\{C^1\}$ and twin 2 ($g^{c^2}_{twin2}$) in the matrix grain 2 crystal frame $\{C^2\}$ can be expressed as:

$$g^{c^1}_{twin1} = \left[ M^{c^1}_{SD1}\, M^{c^1}_{SPN1}\, M^{c^1}_{HPN1} \right]$$

$$g^{c^2}_{twin2} = \left[ M^{c^2}_{SD2}\, M^{c^2}_{SPN2}\, M^{c^2}_{HPN2} \right]$$

Twin 1 ($g^{c^1}_{twin1}$) was then transformed into the neighboring grain 2 crystal frame using the following equation:

$$g^{c^2}_{twin1} = m_{12} \cdot g^{c^1}_{twin1} = \left[ M^{c^2}_{SD1}\, M^{c^2}_{SPN1}\, M^{c^2}_{HPN1} \right]$$

Here, $g^{c2}_{twin1}$ is used to express twin 1 in the coordinate system of grain 2.

Thus, the geometrical compatibility factor $m'$ between twin 1 and twin 2 was then calculated from the following relation:

$$m' = \frac{M^{c^2}_{SD1} \cdot M^{c^2}_{SD2}}{\left| M^{c^2}_{SD1} \right| \times \left| M^{c^2}_{SD2} \right|} \times \frac{M^{c^2}_{HPN1} \cdot M^{c^2}_{HPN2}}{\left| M^{c^2}_{HPN1} \right| \times \left| M^{c^2}_{HPN2} \right|}$$

## 3. Results and Discussion

### 3.1. Microstructure

Eight distinct 200 × 260 μm scans were collected on the sample deformed at 350 °C and the corresponding inverse pole figure maps are shown in Fig. 1. Here, thick black lines are corresponding to grain boundaries (θ > 15°), red lines correspond to {10−12} extension twins, ED indicates the extrusion direction and RD is the radial direction. Substantial {10−12} extension twins can be observed, most of which propagated completely across their host grains. The formation of such high temperature twins in Mg alloys has previously been reported by Chapius and Driver [23] and Cho et al. [24] during deformation at 425 °C.

{10−12} extension twins have six twin variants (see Table 1). The schematic diagram, showing the geometric position of these six potential twin variants on {0001} pole figure, is displayed in Fig. 2. It can be seen that there are three positional relations among the six twin variants: i) twin variants v1 and v2 are in the para-position (called as PP pair); ii) twin variants v1 and v3 (or v6) are in the ortho-position (called as OP pair); and iii) twin variants v1 and v4 (or v5) are in the meta-position (called as MP pair).

In the present case, connected twins can be detected, and some of the twins are across the grain boundary (GB) and connect to another twin in neighboring grain. When two twins intersect with each other in a grain, the strain transmission between these two twins is expected to affect the growth of twins [25]. Xie et al. [26] introduced a novel approach based on the local strain within twin bands to study the mechanisms of twin intersection and cracking. It can be deemed as a general theory applicable for any material with local transformations and approves above effect on twin growth. If the twin nucleates and propagates into grain boundaries, it will resolve the strain onto neighboring grains. Therefore, the activation of the connected twins in adjacent grains will be influenced. The transmission of twins through GBs is expected to play a dominant role in the deformation behavior of magnesium at ambient temperature [11,16]. At a high temperature, the interaction of connected twins will be of interest to be investigated.

For this purpose, twin pairs in the same grains and twin chains across different neighboring grains in Fig. 1 were discussed. The