Analyses on Compression Twins in Magnesium

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The orientation relationships between the compression twins and their matrices in magnesium were investigated using EBSD technique. Schmid factor analyses were applied to determine the orientation dependency of compression twins and the condition for double twinning. Results show that thin compression twin bands of {1011} type lose easily their exact twin relation of 56°/{1120} to ~40°/{1120} due to the instability of twin orientation and immobility of twin boundaries. And the basal orientation with TD-rotation tends to induce tension twinning in compression twins. [doi:10.2320/matertrans.MRA2007242]

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1. Introduction

Basal slip and tension twinning of the {1012} type are dominant deformation mechanisms of polycrystalline magnesium at low temperature. However, fracture originates mainly from compression twins or shear bands developed from compression twins.¹⁻³ As both basal slip and tension twinning lead to basal texture which possesses a high Schmid factor for compression twinning during compressing or rolling, the formation of compression twins is inevitable. In addition, the (dynamic) recrystallization nucleation⁶ at compression twins or shear bands was observed to be more effective than that at tension twins or grain boundaries. Thus, the understanding of compression twinning is crucial for both in preventing crack formation and in optimizing annealing process.

Different types of compression twins were reported in magnesium including the {1011}, the {1013}, the {3034} or even {1015} type.²⁻⁵⁻⁷ Double twinning of the {1011} type followed by the {1012} type was found to be a particular feature of compression twins. The {1011} twin is believed to be dominant among different types of compression twins, although Yoshinaga et al. reported that {1015} twins were main twins at room temperature.⁵ Most of the previous works were based on the trace analysis on single crystals. Recently, EBSD technique has been used to analyze compression twins through the determination of the twin orientation relationships (OR).⁸⁻⁹ To date, the analysis on compression twin has been less reported than that of tension twin, and the variety of compression twin types as well as the condition of double twinning is still not clearly understood. This is because the compression twin analysis has three challenges: (1) The compression twins are very thin in nature (normally less than 1 μm), it is hard to confirm their types on a large scale; (2) unlike the very mobile boundaries of tension twins which leads to stable OR of 86.3°/{1120}, the immobile twin boundaries of the compression twins and their unstable orientation against basal slip or tension twinning can cause frequent change in twin orientation; (3) In some cases, it is not easy to exactly confirm the twin forms by detecting the OR, for example, the OR of 38.7°/{1120} for double twinning is similar to the OR of 41°/{1120} for {1015} twins. Therefore, massive collection of the OR data is needed for the determination of the compression twins and their evolution into the shear bands. This work aims to investigate compression twins by firstly comparing their morphologies with tension twins, secondly determining their ORs with matrices and misorientations in matrices around compression twins; Finally Schmid factor analysis is applied to inspect the tendency to basal slip versus tension twinning within compression twins.

2. Experimental

Materials used are commercial AZ31 alloys, pure magnesium, respectively. To facilitate the occurrence of compression twin, rectangular samples (15 mm × 10 mm × 6 mm) with initial basal or TD-rotated basal textures were sectioned from hot rolled plates or extruded bars. These samples were either uniaxial compressed (for pure magnesium) or plane-strain compressed (for AZ31) below 200 °C with a strain rate of 0.01 s⁻¹. Samples were ground with #2000 SiC paper. An AC-2 electrolyte (a kind of electrolyte applicable for most Magnesium alloys vended by Struers Ltd Co) was used for sample electro-polishing with a voltage of 20 V for about 60 s at room temperature, samples were then etched with a solution of 5 g picric, 100 ml ethanol, 10 ml glacial acetic acid and 5 ml distilled water for about 20 s, subsequently ion-bombarding on etched sample surface was applied to improve Kikuchi band quality for EBSD measurement. HKL Channel system installed on LEO-1450 and ZEISS SUPRA 55 FE-SEM were used, the voltage of 20kV and spot size of 450 were used in LEO-1450 and 20 kV and diaphragm size of 60 μm in ZEISS SUPRA 55 FE-SEM. All the samples were observed from their transverse direction (TD) in this paper, and compression direction (CD) is vertical and extension direction (ED) is parallel.

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3. Results and Discussion

3.1 Morphological features of compression twins

Figure 1 shows morphological features of compression twins and their microstructural evolution. As a comparison, tension twins are shown in Fig. 1(a). From Fig. 1(b), it can be seen that the compression twins appeared mainly in basal-oriented grains of (0001) | compression plane, and they are thin bands (as shown using arrows), reflecting the rather low boundary mobility. Figure 1(c) shows the grain fragment within compression twins at relatively high deformation temperature, indicating that twins are easy to change their orientations. Figure 1(d) depicts shear bands evolved from compression twins at 185°C at high strain, which may be regarded as a continuous dynamic recrystallization. Note that even at the early stage of formation, shear bands contain a group of parallel compression twins. Figure 1(e) shows the compression twins formed in samples with TD-rotated initial basal texture. Since the concurrent basal slip at matrix twin boundaries became curved, the nature of coherent twin boundary should be totally lost.

3.2 Determination of twin orientation and orientation relationships (ORs)

Since the orientation of compression twin may change easily during further loading, the orientation determination was performed on a slightly compressed Mg with large initial grain size, see Fig. 2. Theoretical ORs of [1011] twin and [1013] twin are 56°(1120) and 64°(1120) respectively, and the double twinning of them will lead to the ORs of 38.7°(1120) and 22°(1120). The misorientation data in Fig. 2 reveal that most misorientation angles are larger than those of two types of compression twins (56° and 64°). This is in contrast to the fact that exact tension twin OR of 86.3°(1120) is easy to be measured. It is suggested that double twinning has not been produced in this region. It is most probably that the [1011] twins have been formed.

Figure 3(a) displays a typical orientation mapping on AZ31 compressed by a strain of 0.15. Figure 3(b) shows that dominant ORs concentrate at about 40°(1120) which is much smaller than the exact OR of 56°(1120). It is noted that a small region T1 was detected with an OR of 56°(1120) whereas other regions in twin have the OR of ~40°(1120), see Fig. 3(c), (d), and (e). Therefore, double twinning should occur. In Fig. 3(d) the green line depicts twin boundaries with the compression twin OR and pink lines reveal
boundaries with double twinning relationship. The high quality of Kikuchi bands in some region denotes the easy process of double twinning. Figure 3(e) demonstrates that compression twinning converts matrix orientation M to the orientation $T_1$ around the axis $[11\overline{2}0]$ for $\gamma/C_2\overline{4}$. The further strain changed the orientation $T_1$ to $T_2$ by tension twinning of $86.3^\circ$ around the same axis $[11\overline{2}0]$. After this double twinning the scattered basal orientation of matrix became closer to basal orientation and therefore became more stable. Small misorientation angles across twins are determined as shown in Fig. 3(d). The stronger the shearing along twin bands, the higher the misorientation angles across twins should be. The higher misorientations promote either fracture or recrystallization nucleation.

Figure 4 shows another example of orientation mapping on sample AZ31. Again compression twins (variants $T_1$ and $T_2$) are detected in matrix with rotated basal orientation. Dominant OR of $\gamma/40^-\langle 11\overline{2}0 \rangle$ is found, see Fig. 4(d). Comparing Fig. 4(a) with Fig. 1(d), it can be seen that a shear band consists of a group of parallel compression twins and a part of matrix between them. This means that shear bands contain orientations of both compression twins and matrices. It is further noted that the matrix orientations within compression twins (the pink region within twin bands in Fig. 4(b) and the arrow in Fig. 4(c)) are much scattered than the matrix outside of twin bands. Although no clear regions with OR of $\{0\overline{1}1\}$ twins were found, orientations of tension twins can be found along the orientation line of matrix M and compression twin $T_2$ as shown in Fig. 4(c).

Several orientation maps were made and all manifest the dominant $\gamma/40^-\langle 11\overline{2}0 \rangle$ relationship. As the initial texture was a TD-rotated basal texture, it is concluded that double twinning will occur easily in basal oriented matrix with more scattering in orientation.

### 3.3 Dependence of twinning on grain orientation and the condition of double twinning

Similar to the case in single crystals, there is a close orientation dependence of deformation twinning on grain orientation in polycrystalline magnesium. Figure 5(a) and (b) show the Schmid factor distribution with different deformation mechanisms in the condition of plane strain compression. Boundaries are determined by assuming equal CRSSs for each deformation mechanism. Here only two sections of Euler angle $\varphi_2 = 0^\circ$ and $30^\circ$ are given. It can be seen that compression twins mainly occur in the region C around basal orientation and tension twin in region A around prismatic orientation region. The regions B, D and E favor basal slip, prismatic slip and pyramid slip respectively. Figure 5(c) shows the experimentally determined matrix orientations of tension twins and compression twins in $\{0002\}$ pole figure which are in accordance with results of Schmid factor calculation. This close dependence of deformation mechanisms on grain orientations causes strong anisotropies in properties of magnesium alloys.

Let us analyze the condition for double twinning. In Fig. 5(a), the orientations of two variants of compression twin are displayed (see the two arrows), which were calculated from the matrix orientation with exact basal orientation (Euler angle $(0, 0, 0)$). The twin orientations are
Fig. 4 EBSD orientation mapping on compression twin. (a) Micrograph, the blue square refers to the orientation-mapped region; (b) Orientation map with colors corresponding to the poles in Fig. 4(c); (c) (0002) pole figure and (d) Orientation relationship.

Fig. 5 Schmid factor calculation of different deformation mechanisms and its comparison with experimentally detected orientations, assuming equal CRSS for different mechanisms. (a) Active regions for different deformation mechanisms. A: tension twinning; B: basal slip; C: compression twinning; D: prism slip; E: pyramid slip. $\varphi_2 = 0^\circ$; (b) Regions for different deformation mechanisms at $\varphi_2 = 30^\circ$; (c) Detected matrix orientations of compression twins (circles) and tension twins (square), [0002] pole figure; (d) Analysis of the condition of basal slip and tension twinning within compression twins, $\varphi_2 = 0^\circ$; (e) The conditions of basal slip and tension twinning at $\varphi_2 = 30^\circ$. 

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located in the region favoring basal slip. Thus, the decrease in misorientation angle of twins with respect to their matrix should be resulted from simply basal slip, at least at early stage. If the matrix orientation is strongly scattered like the case of orientation M in Fig. 3(e), the orientation of compression twin will situate at the region A of tension twinning. Through tension twinning, the final orientation approaches closer to the exact basal orientation, i.e. becomes more stable. Figure 5(d) and (e) show the boundaries between basal/prismatic slips and tension twinning within compression twins (region C). The calculation proceeds as follows: the orientations of 6 variants of a compression twin whose matrix orientation locates in region C were computed and the orientational position of the one with maximum Schmid factor determines the deformation type. It can be seen that a basal orientation with spread around TD has a high tendency of double twinning (region C-T), whereas the basal orientation with spread around RD may be related more to the basal slip after compression twinning (region C-B). This is only a rough analysis on sections of $\varphi_2 = 0^\circ$ and 30$^\circ$. It is note that it never means that tension twinning can not operate in the region C-B (the region favoring basal slip) of Fig. 5(d) within compression twins. Since compression twins are very thin, dislocations for basal slip have relative short distance to operate and may easily cause pile-up at twin boundaries which leads to either tension twinning or cracks as suggested in.$^{5,6}$

4. Conclusions

We studied the compression twins in magnesium and concluded as follows:

(1) A clear morphological difference was observed between the tension twins and the compression twins which should be resulted from the boundary mobility and the orientation stability of twins on further deformation.

(2) [1011] twins and double twinning were confirmed through orientation relationship determination. Unlike the tension twin, whose exact OR can be easily detected, the exact misorientation angle of compression twin is generally hard to be obtained due to the unstable twin orientation and the immobility of twin grain boundaries. The shear bands evolved from a group parallel compression twins contain matrix orientations with higher misorientation angles than those outside twins/shear bands.

(3) Schmid factor calculation and matrix orientation determination indicate a close dependence of twinning type on grain orientations in polycrystalline magnesium. Basal orientations with spreads around TD and RD can favor basal slip and tension twinning respectively after compression twinning based on the Schmid factor analysis.

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REFERENCES