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Analysis of Twin in Mg Alloys Using Electron Backscatter Diffraction Technique

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Electron backscatter diffraction (EBSD) is widely used for quantitative microstructural analysis of the crystallographic nature of variety of materials such as metals, minerals, and ceramics. EBSD can provide a wide range of information on materials including grain size, grain orientation, texture, and phase identity. In the case of metallic alloys, EBSD now has become an essential technique to analyze the texture, particularly when severe deformation is applied to the alloys. In addition, EBSD can be one of the very useful tools in identification of twin, particularly in Mg alloys. In Mg alloys different type of twin can occur depending on the c/a ratio and stacking fault energy on the twinning plane. Such an occurrence of different type of twin can be most effectively analyzed using EBSD technique. In this article, the recent development of Mg alloys and occurrence of twin in Mg are reviewed. Then, recently published example for identification of tension and compression twins in AZ31 and ZX31 is introduced to explain how EBSD can be used for identification of twin in Mg.

Key Words: Electron backscatter diffraction, Twin, Texture, Mg alloy

INTRODUCTION

Nowadays "electron backscatter diffraction (EBSD)" is widely used for quantitative microstructural analysis of the crystallographic nature of variety of materials such as metals, minerals, and ceramics. EBSD can provide a wide range of information on materials including grain size, grain orientation, texture, and phase identity. In the case of metallic alloys, EBSD now has become an essential technique to analyze the texture, particularly when severe deformation is applied to the alloys.

One of the recent critical issues in the metallurgical society is to develop the light-weight alloys with high specific strength. This issue is emerging as one of the solutions which can solve the environmental problems threatening the safety of the modern society. Particularly, the automobile industry is very keen in weight reduction of the cars to enhance the fuel efficiency. Among the metallic alloys, Mg alloys are considered to be the lightest alloys. Therefore, Mg alloys recently receives a great attention as possible candidate to replace the metallic alloys which are currently used for automobiles. Through the active research activities, Mg alloys with reasonably high strength and better high temperature properties have been developed. However, critical problems for Mg alloys are corrosion resistance and formability. The corrosion problem is inherent for Mg alloys, since very small amount of impurity can enormously affect the corrosion resistance. There have been a lot of efforts to solve the problem by proper selection of surface treatment or coating.

The formability is also an inherent problem for Mg alloys, since the pure Mg has a hexagonally close packed (HCP) structure. If each atom is assumed to be a rigid sphere, the

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axial ratio (c/a) in an ideal HCP unit cell is 1.633. Since the axial ratio of Mg, 1.623 is close to that of the ideal HCP unit cell, slip occurs predominantly on the basal plane. Therefore, there are only two independent slip systems for deformation of Mg. Generally, in order to allow substantial plastic deformation, the condition for grain boundary compatibility during deformation should be satisfied, therefore five independent slip systems are required to meet the condition. Without these five independent slip systems such as in Mg, polycrystalline materials are brittle. Therefore, it is inevitable that a strong basal texture develops during forming process such as rolling or extrusion, and thereby critically limits the formability which is required for the secondary forming process. In order to improve the formability of wrought Mg alloys, it is well understood that weakening of strong basal texture is strongly required by proper selection of alloy compositions or processing routes. So far, various new processing routes such as differential speed rolling (Xia et al., 2009), cross-rolling (Lim et al., 2009), and torsion extrusion (Chino et al., 2008) have been developed for fabrication of highly formable Mg alloys. There have been also many studies focusing on weakening of basal texture by modification of the alloy chemistry (Chino et al., 2006; Huang et al., 2008). In particular, there have been many studies on modification of texture and grain size in conjunction with dynamic recrystallization during rolling (Sun et al., 2009; Agnew & Nie, 2010; Wang et al., 2011; Zhang et al., 2012). Moreover, it has been shown that depending on the alloy compositions, strong basal texture developed in rolled sheets can be significantly weakened by recrystallization during post annealing treatment (Mackenzie & Pekguleryuz, 2008). As mentioned above, EBSD has become a critical tool in analysis of the texture. In addition, EBSD can be one of the very useful tools in identification of twin, particularly in Mg alloys.

MECHANICAL TWINNING IN Mg

Mechanical twinning occurs when the number of slip systems is not enough for the plastic deformation, therefore it is one of the plastic deformation modes. During twinning, the crystal structure does not change, only orientation of the some part of the grain changes. In the case of slip, the shear is localized on the specific slip plane during slip, while in the case of twinning, the shear is uniformly distributed over the twinned area. During twinning, the atoms only move small distance, less than the interatomic spacing, therefore, total shear by twinning is not large. Therefore, twinning is important for shear deformation only in metallic alloys where deformation by slip is limited. Since the c/a ratio of Zn is larger than the ideal HCP structure, and that of Mg is smaller than the ideal HCP structure, the angle between the basal plane and the twinning plane $(10\bar{1}2)$ is ~47° in Zn and ~43° in Mg, indicating that twinning in Zn increases the length of the crystal, while shortened in Mg. The tensile stress parallel to the basal plane favors twinning in Zn, whereas the compressive stress favors twinning in Mg.

Such an occurrence of twins depending on the magnitude of c/a ratio has a significant effect on the texture development in wrought Mg alloys. In HCP metals such as Mg and Zn, the critical resolved shear stress for slip is much lower than that for twinning. Fig. 1 explains how $(10\bar{1}2)$ tension twin occurs in Mg alloys during rolling process. Rolling orients the {0001} planes parallel to the surface of the sheet and the <10$\bar{1}$0> directions in the rolling direction. At this stage, further occurrence of basal slip becomes difficult because the Schmid factor for basal slip becomes very low. To accommodate the stress continuously loaded during rolling, tensile twin occurs by which the basal plane rotates ~86° from the original position (parallel to the surface). Due to the high mobility of the tensile twin boundary, twin plate becomes wider accommodating the stress continuously loaded during rolling. Finally, the twin appears as "extension twin" as shown in Fig. 1. Since the Schmid factor for basal slip is low, occurrence of slip is still difficult, therefore, very strong basal texture is developed. Because tension twinning in Mg occurs in compression when the basal plane is parallel to the stress axis, wrought Mg alloys have lower longitudinal yield strength in compression than in tension. Consequently, the conventional wrought magnesium alloys such as Mg-3Al-1Zn (wt%, AZ31) exhibit very low level of formability. As a result,

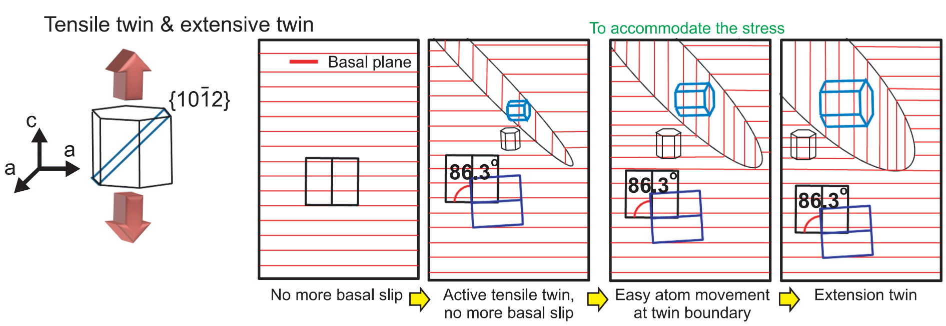

Fig. 1. Schematic diagram showing the occurrence of tensile twin in Mg.

the application of wrought Mg alloys for automobile has been limited.

Micro-alloying of element in Mg matrix can induce the change in c/a axial ratio or stacking fault energy along the twinning plane. In such cases, different type of twinning can occur in Mg during deformation. Fig. 2 explains how (10$\bar{1}$1) compression twin occurs in Mg alloys during rolling process. During rolling process, the basal plane in the most grains becomes parallel to the surface of the rolled plate. At this stage, if the conditions are met for the occurrence of compression twin, it will occur as indicated in Fig. 2. The compressive twin can be generated by ~56° rotation of basal plane, and generally has narrow width due to immobile mature of twin boundary. Since the basal plane is aligned ~56° from the surface, basal slip can occur rather easily in the compression twinned region due to high value of Schmid factor. If basal slip occurs inside the compression twinned region, high stress is accumulated at the twin boundary. Such high stress can be relieved by the formation of secondary twin (tensile twin in the compression twinned region), which corresponds to rotation of basal plane by ~38° from the orientation parallel to the surface. If the accumulated stress is still very high inside the twinned region, static recrystallization can occur easily during post annealing treatment. Therefore, such an occurrence of compression twin in Mg can weaken the basal texture, otherwise which will be strongly developed if tension twin occurs. It has been shown that compression twin can occur easily in Mg-3Zn-1Ca (wt%, XZ31) alloy (Lee et al., 2014). The occurrence of twins in AZ31 and ZX31 will be compared in the following section.

IDENTIFICATION OF TENSILE AND COMPRESSION TWINS IN AZ31 AND ZX31

Fig. 3A shows an inverse pole figure map obtained from rolling direction (RD)-transverse direction (TD) plane of AZ31 sheet with thickness of 8 mm (i.e., after 1st rolling pass), and Fig. 3D shows the corresponding (0002) pole figure extracted from the EBSD image of Fig. 3A. EBSD analysis shows that the twins observed in AZ31 mostly corresponded to (10$\bar{1}$2) tensile twins, corresponding to 86.3° rotation of basal plane, and (10$\bar{1}$1) compression twin was rarely observed. Fig. 3C shows the misorientation angle measured along the white arrow in Fig. 3B, and clearly indicates the occurrence of tensile twins. Due to the high mobility of the tensile twin boundary, wide twin plate formed as can be noticed in the white circled areas (1~3) in Fig. 3A. It was difficult to observe nucleation of re-crystallized grains in the twinned area in AZ31, as can be seen in Fig. 3B. It was confirmed that the intensity of the basal plane perpendicular to the normal

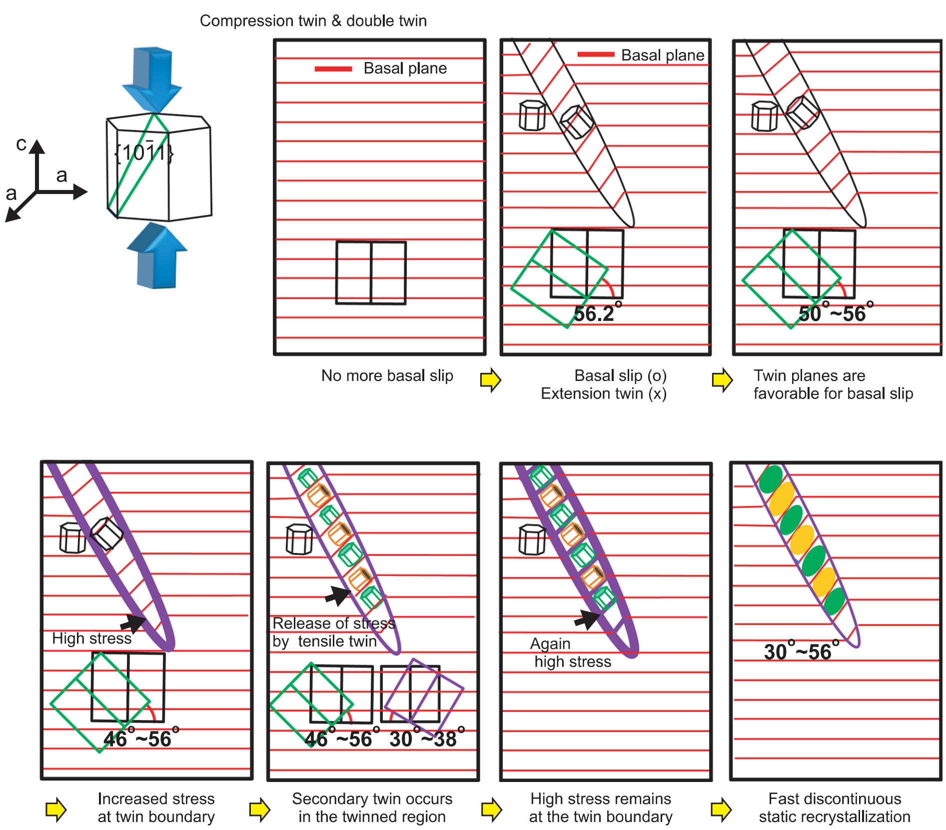

Fig. 2. Schematic diagram showing the occurrence of compression twin in Mg.

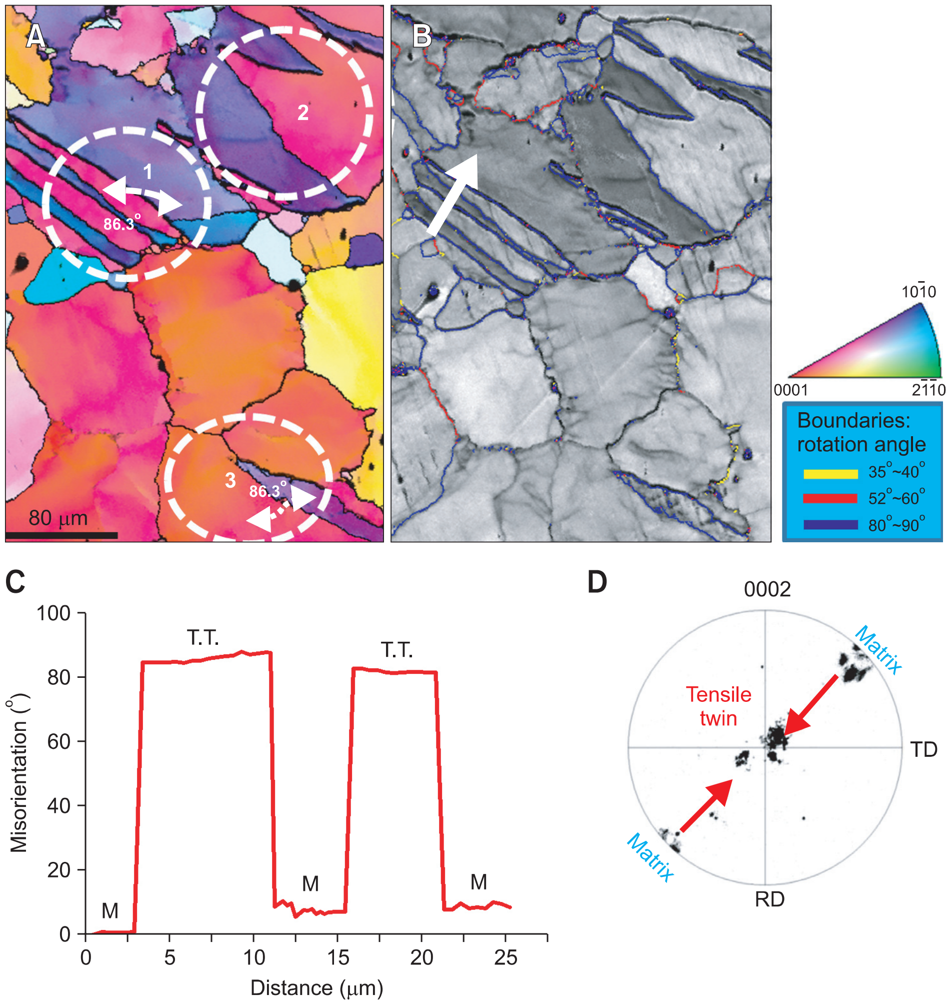

Fig. 3. (A) Inverse pole figure map obtained from the rolled AZ31 sheet (thickness: 8 mm, after one roll pass) after annealing at 350°C for 30 seconds. (B) Kikuchi band quality map. (C) Line profile of misorientation along the white arrow in (B). (D) Pole figure corresponding to (A). Reused from the article of Lee et al. (*J. Alloys Compd*. 2014;589:240-246) with original copyright holder's permission. M, matrix; T.T., tensile twin; TD, transverse direction; RD, rolling direction.

direction becomes strong in AZ31 through the generation of tensile twins, as shown in Fig. 3D (Lee et al., 2014).

ZX31 shows different tendency in twin distribution from AZ31. While mostly tensile twins are observed in AZ31, not only tensile twins but also compressive twins are often observed in ZX31. Fig. 4A shows an inverse pole figure map obtained from RD-TD plane of ZX31 sheet with thickness of 8 mm (i.e., after 1st rolling pass), and Fig. 4E shows the corresponding (0002) pole figure extracted from the EBSD image of Fig. 4A. As can be seen in Fig. 4A and B compressive twins having narrow width are frequently observed. The compressive twins are generated by 56° rotation of basal plane as shown in Fig. 4B and E. In the compressive-twinned region, generation of basal slip becomes favorable due to high value of Schmid factor. In addition to compressive twins, (10$\bar{1}$1)-(10$\bar{1}$2) secondary twins are observed frequently in ZX31 (in Fig. 4B and E). Moreover, fresh annealing for 30s before EBSD analysis caused nucleation of recrystallized grains, which can be seen clearly in Fig. 4B. Fig. 4C shows an enlarged view of corresponding circled areas in Fig. 4A. Fig. 4D shows the misorientation angle measured along the recrystallized grains in Fig. 4C, and clearly indicates the occurrence of compression and secondary twins. Orientations of each grains nucleated in the compressive-twined region were carefully examined. Most of the newly nucleated grains exhibit twin orientation relationship with the surrounding matrix. Therefore, such recrystallized grains effectively lead to weakening of the basal texture (Lee et al., 2014).

SUMMARY

EBSD is widely used for quantitative microstructural analysis of the crystallographic nature of variety of materials such as metals, minerals, and ceramics. EBSD can provide a wide range of information on materials including grain size, grain orientation, texture, and phase identity. In the case of metallic alloys, EBSD now has become an essential technique to analyze the texture, particularly when severe deformation is applied to the alloys. In addition, EBSD can be one of the very useful tools in identification of twin, particularly

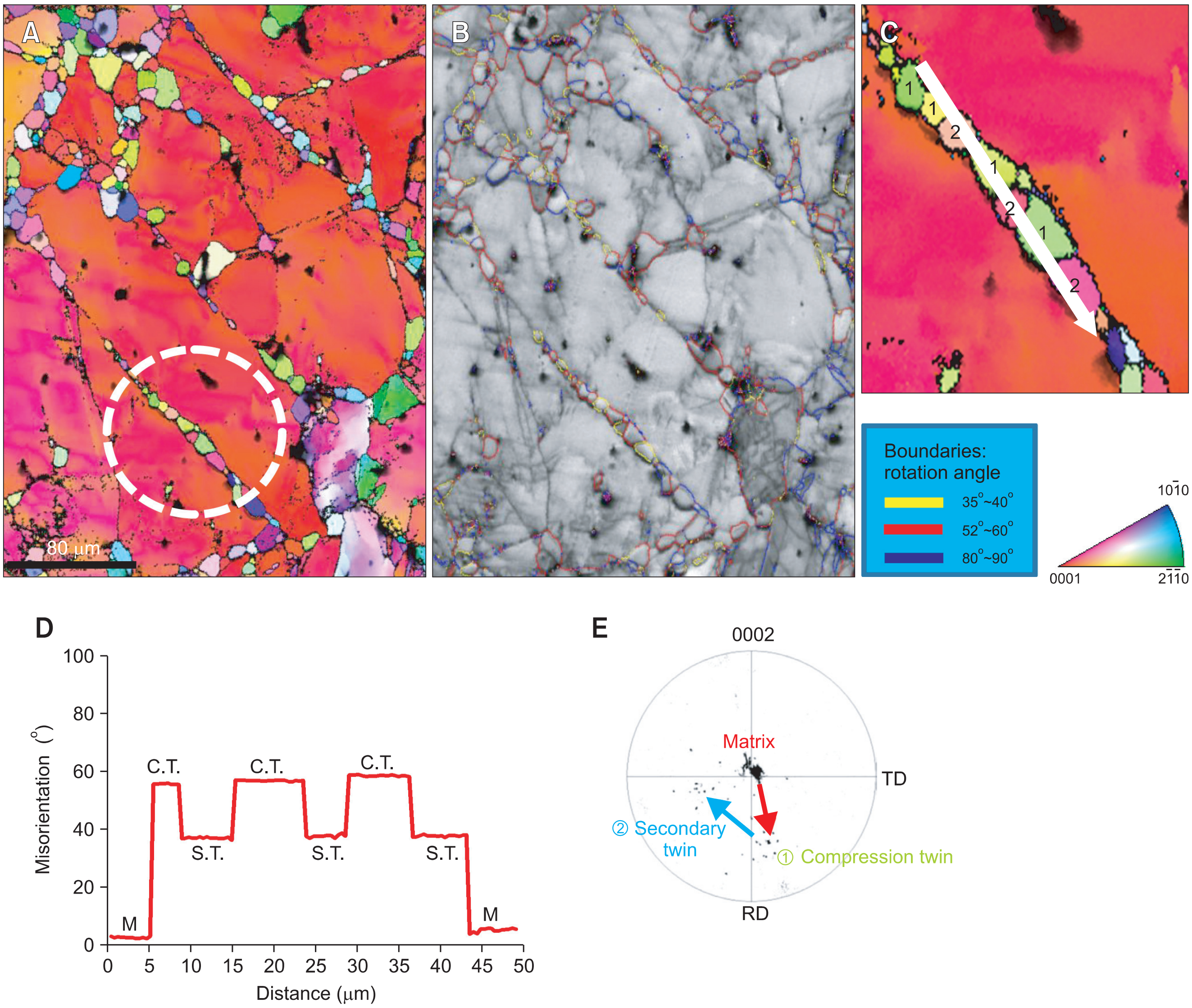

Fig. 4. (A) Inverse pole figure map obtained from the rolled ZX31 sheet (thickness: 8 mm, after one roll pass) after annealing at 350°C for 30 seconds. (B) Kikuchi band quality map. (C) Magnified view of the area marked in (A). (D) Line profile of misorientation along the recrystallized grains in (C). (E) Pole figure corresponding to (A). Reused from the article of Lee et al. (*J. Alloys Compd*. 2014;589:240-246) with original copyright holder's permission. M, matrix; C.T., compression twin; S.T., secondary twin; TD, transverse direction; RD, rolling direction.

in Mg alloys. In Mg alloys, different type of twin can occur depending on the c/a ratio and stacking fault energy on the twinning plane. Such an occurrence of different types of twin can be most effectively analyzed using EBSD technique. Recently published example for identification of tension and compression twins in AZ31 and ZX31 is introduced to explain how EBSD can be used for identification of twin in Mg. While the twins observed in the AZ31 sheet are mostly tensile twins, not only tensile twins but also compressive and secondary twins are frequently observed in the ZX31 sheet. A weaker basal texture evolution in the ZX31 sheet is related to the mode of twins generated during rolling process, i.e. the deformation bands consisted of compression and secondary twins induces nucleation of recrystallized grains during static recrystallization, leading to a weaker basal texture evolution in the ZX31 sheet.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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