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Analysis of kink boundaries in deformed synchronized long-period stacking ordered magnesium alloys

Hongye Gao [a,*], Ken-ichi Ikeda [b], Tatsuya Morikawa [a], Kenji Higashida [a], Hideharu Nakashima [b]

[a] Department of Materials Science and Engineering, Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[b] Department of Engineering Sciences for Electronics and Materials, Faculty of Engineering Sciences, Kyushu University, 6-1 Kasuga-koen, Kasuga-shi, Fukuoka 816-8580, Japan

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ABSTRACT

Microstructures of kink boundaries in a magnesium–zinc–yttrium (Mg–Zn–Y) alloy were observed by transmission electron microscopy. Wedge-shaped kinks with high angle kink boundaries have been found in Mg–Zn–Y alloys due to deformation of the long-period stacking ordered (LPSO) phase. It has been found that wedge-shaped kinks have several Zn/Y-rich sub-kink boundaries, since more dislocations are introduced in both *hcp* and *fcc* structures of the LPSO phase due to further compression.

1. Introduction

Mg alloys, which are lightweight structural materials, are being used for automotive structural components to improve fuel efficiency. However, in spite of their advantages, which include their low density and relatively high specific strength and specific elastic modulus, their strength is lower than that of aluminum alloys. Thus, the main challenge with regard to the development of Mg alloys is to increase their strength as well as their ductility, since Mg has a hexagonal close packing (*hcp*) phase and does not have a sufficient number of slip systems. In 2001, a Mg–Zn–Y alloy was found to have excellent mechanical properties, including a maximum tensile yield strength of ~600 MPa and an elongation of ~5% at room temperature, when subjected to rapid solidification [1,2]. Rare earth (RE) additions have been reported to improve the material properties of Mg alloys as well as their creep resistance at high temperatures [3,4]. Moreover, a study suggested that a novel precipitate with a long-period stacking ordered (LPSO) structure could be an important factor affecting the mechanical properties of Mg alloys [5–8]. In Mg–Zn–RE alloys, LPSO phases are long-period stacking derivatives of the *hcp* Mg structure, and the Zn/RE atoms are enriched at the stacking fault layers, resulting in the formation of local face-centered cubic (*fcc*) stacking [9–11]. Later studies showed that, in these LPSO phases, deformation twins were suppressed, and kink bands were observed instead within the LPSO structure in Mg–Zn–RE alloys [12,13]. Those kink bands developed when a compressive stress was loaded parallel to the (0001) plane, that is, when the Schmid factor for basal slipping was negligible [13]. It was reported that kink deformation is an essential mechanism for generating homogeneous strain in crystals and that it contributes to some extent to the ductility. However, the mechanism of kink formation within the LPSO phases in Mg alloys is still unclear.

Kink formation is an important deformation mechanism of LPSO phases when basal slippage is inhibited, and the mechanical behavior is controlled by the microstructures of the kinks of the LPSO phases. Therefore, it is important to elucidate the microstructures of the kink boundaries in the LPSO phases of Mg alloys.

In this study, the microstructures of the kink boundaries of the deformed LPSO phase were investigated by transmission electron microscopy (TEM). In addition, the elemental distribution around the kink boundaries was determined by high-angle annular dark-field (HAADF) scanning transmission electron microscopy (STEM) combined with energy dispersive X-ray spectroscopy (EDS). We also discuss how the inner structures of the kink bands in the LPSO phases can be dramatically influenced by the extended dislocations introduced by the deformation of the LPSO phases.

2. Experimental

Mg–5 at% Zn–7 at% Y (Mg–11 wt% Zn–20 wt% Y) was prepared by high-frequency induction, melted, and then cast in a preheated mold coated with graphite. The as-cast ingots were all extruded

* Corresponding author. Tel./fax: +81 92 583 7546.
E-mail address: gao.hongye.129@m.kyushu-u.ac.jp (H. Gao).

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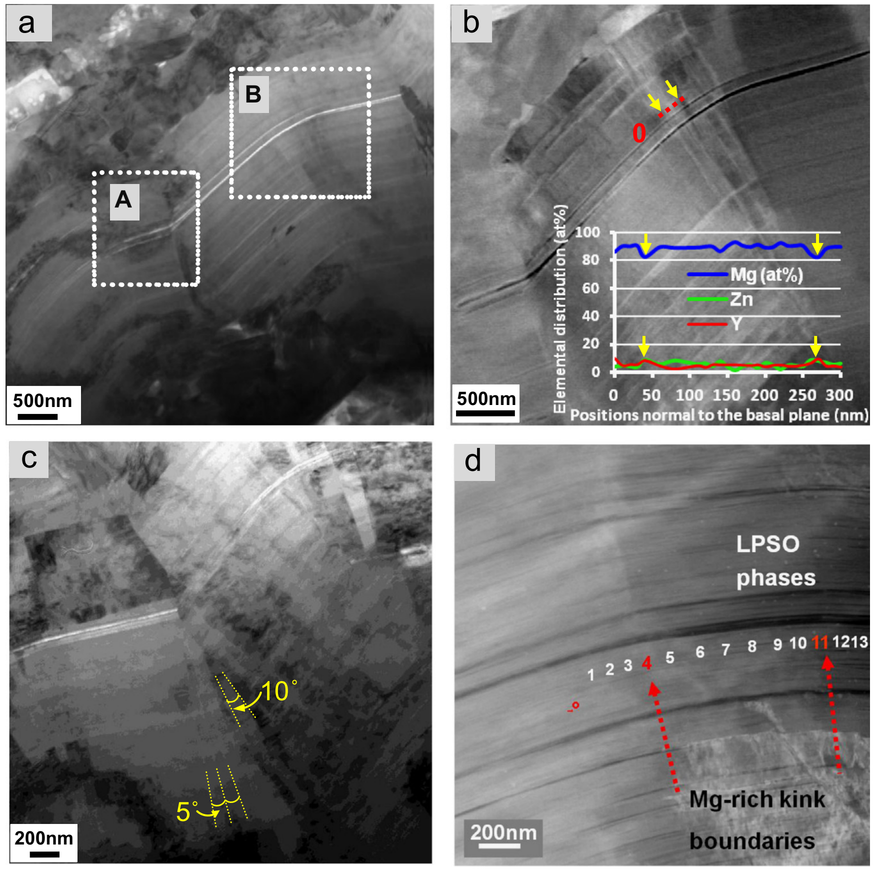

Fig. 1. (a) TEM bright-field image of kink bands and a schematic of the wedge-shape kink in the lower right corner, (b) the corresponding HAADF–STEM image of the same kink and a profile of the elemental distribution along the basal plane denoted by the red dotted line. (c) High-magnification TEM bright-field image of the kink bands in area A in (a). (d) HAADF–STEM image of the bending kink bands in LPSO phases as reported in a previous study [14].

under the same conditions: at 723 K under a ram speed of 2.5 mm/s in air, with the extrusion ratio being 10:1. One sample was compressed along the basal plane, and the compressive strain was 10%. The microstructures of the specimens were observed using an FEI Tecnai-F20 TEM (accelerating voltage: 200 kV). Samples of the Mg–Zn–Y alloy for obtaining high-resolution TEM images were prepared by the focused ion beam (FIB) microsampling technique. All the FIB processes were performed using a Hitachi FB-2000K FIB, and the maximum accelerating voltage was 30 kV.

3. Results and discussion

Fig. 1a shows the kink boundaries are just simple bending boundaries as plotted within the dotted rectangles A and B. However, the corresponding HAADF image (Fig. 1b) indicates that the kink boundaries are complex formations consisting of several sub-boundaries with a stepwise misorientation distribution. This STEM–EDS profile shows that the Zn/Y ratio increases at the positions along the lines with the bright contrast, which are indicated by the yellow arrows. Fig. 1c shows a high-magnification TEM bright-field image of the kink bands in the dotted area A in Fig. 1a; the kinks within area A have several sub-kink-boundaries in a fan-like shape with a uniform angle, and the angle between these sub-kink-boundaries is approximate 5–10°. Fig. 1d shows a HAADF–STEM image of the bending kink bands of the LPSO phases of $Mg_{97}Zn_1Y_2$ as reported in a previous paper [14]. The kink boundaries are indicated by the red dotted arrows. STEM–EDS analyses were performed at 13 positions (labeled 1–13 in Fig. 1d). The atomic concentrations of Mg, Zn, and Y were determined at each position. At positions 4 and 11, the Mg atomic concentration was high, while those of Zn and Y were low. This indicates that the kink boundaries in the LPSO phase are accompanied by a shortage of elemental Zn and Y, which results in an increase in Mg. This shows that the degree of misorientation of the wedge-shaped kink boundaries (Fig. 1c) is greater than that of the kink boundaries shown in Fig. 1d. The concentration of Mg increases along the kink boundaries of the LPSO phase, as reported in a previous paper [14].

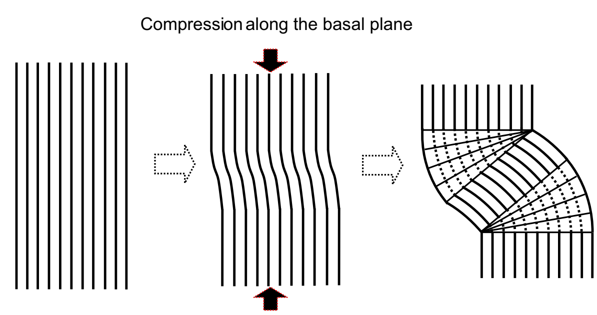

Fig. 2. Schematic illustration of wedge-shaped kinks attributable to the formation of disorientated wedge-shaped kink boundaries. Before distinct wedge-shaped boundaries were observed owing to further compression, dislocations had already concentrated around the kinks of the LPSO phase.

Fig. 2 shows a schematic illustration of the formation process of the wedge-shaped kinks due to compression along the basal plane of the LPSO phase. This illustration of the wedge-shaped kinks was suggested by Romanov et al. [15], who stated that misorientation