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Secondary phases in quasicrystal-reinforced Mg–3.5Zn–0.6Gd Mg alloy

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ABSTRACT

The secondary phases in quasicrystal-reinforced Mg–Zn–Gd alloys are investigated by transmission electron microscopy. The orientation relationships between the dendritic I-phase and the Mg matrix are identified to be $[11\bar{2}0]_{Mg}\parallel[2\text{-fold}]_{I\text{-phase}}$ and $(0001)_{Mg}\parallel(5\text{-fold})_{I\text{-phase}}$. We also find that the dendritic I-phase is brittle along 2-fold, 5-fold, and 3-fold atomic planes during hot extrusion. Moreover, new orientation relations $[\bar{1}101]_{Mg}\parallel[\text{mirror 2-fold}]_{I\text{-phase}}$ and $(0\bar{1}11)_{Mg}\parallel(5\text{-fold})_{I\text{-phase}}$ are found between nanoscale I-phase and Mg matrix. The findings have implications for our understanding of excellent mechanical properties of the I-phase-strengthened Mg alloys.

1. Introduction

Quasicrystal is a quasi-periodic solid with a rotational symmetry and is incompatible with conventional periodic lattice [1,2]. It shows many outstanding intrinsic properties, such as high strength and hardness at elevated temperatures, low friction coefficients, and low surface energy [3]. In view of these merits, Sainfort and Dubost first applied it as a strengthening phase for structural materials [4]. It has been reported that the mechanical properties of an Al–Li–Cu–Mg alloy are enhanced greatly by introducing quasicrystalline precipitates. Afterwards, much effort has been devoted to introduction of quasicrystals to Mg-based alloys as a strengthening phase in order to take full advantage of the excellent intrinsic properties of quasicrystal. For instance, it has been reported that there forms a stable icosahedral quasicrystalline phase (I-phase) in Mg–Zn–RE (RE: rare-earth element) alloys [5]. Such formation of I-phase stimulates intensive interest in probing mechanical properties of the Mg alloys containing I-phase, such as Mg–Zn–Y [6,7], Mg–Zn–Gd [8,9], Mg–Zn–Ho [10] and Mg–Li–Zn–Y [11] alloys. Structurally, such I-phase often forms in the extruded alloys as microscale or nanoscale ellipsoidal particles, which are suggested to be crucial to strengthening Mg alloys. However, a systematical investigation of the I-phase in Mg alloys remains scarce, especially at the atomic scale. Here, we investigate the orientation relationship between the I-phase and Mg matrix in quasicrystal-reinforced Mg–3.5Zn–0.6Gd (at.%) Mg alloy and the deformation and fracture behaviors of the I-phase during hot extrusion by transmission electron microscopy (TEM) [12–14].

2. Experimental details

The as-cast Mg–3.5Zn–0.6Gd (at.%) Mg alloy was fabricated by melting Mg, Zn (purity: 99.9%) and Mg-90% Gd (wt.%) master metals at mixed gas atmosphere of SF_6 (1 vol.%) and CO_2 (99 vol.%). The alloys were then subject to homogenized heat treatment at 673 K for 10 h, followed by an extrusion at 523 K at a ratio of ~25:1. Specimens for TEM and high-resolution TEM (HRTEM) imaging were prepared by cutting, grinding, and dimpling down to ~20 μm. To make electron transparent, the dimpled slices were finally thinned by argon-ion sputter beam using PIPS 691 (Gatan Co., Ltd.). A gun voltage of 1–4 kV and in incident beam angle of 4 − 6° were used to avoid, to maximum extent, radiation damage. Selected-area diffraction patterns (SADPs), TEM, and HRTEM images were obtained using JEOL JEM-2010F transmission electron microscope.

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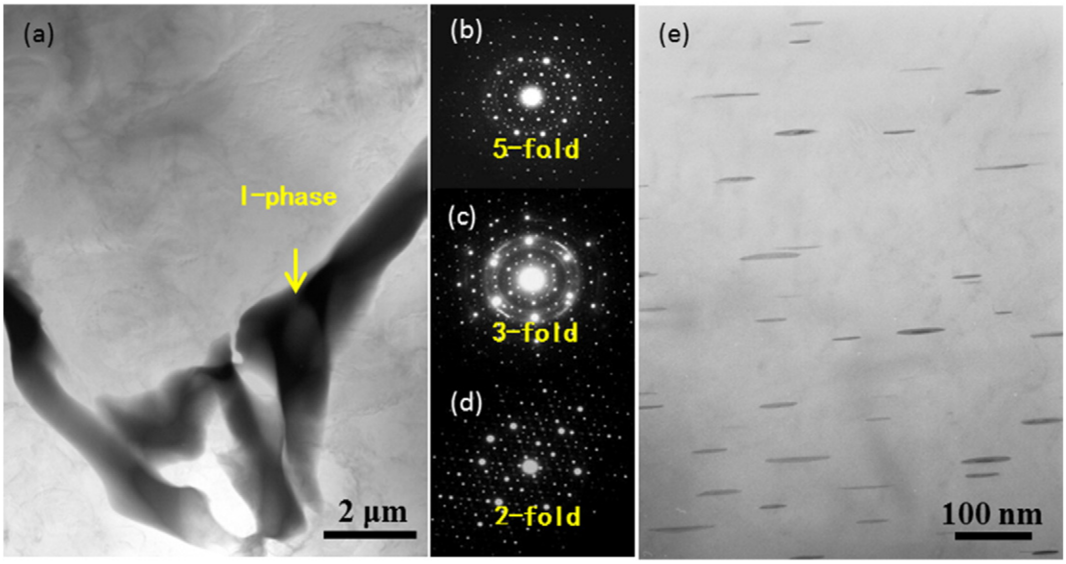

Fig. 1. Microstructure of dendritic I-phase in as-cast Mg–3.5Zn–0.6Gd (at.%) alloys. (a) Low-magnification bright-field TEM image. SADPs of the secondary phase along the (b) 5-fold, (c) 3-fold, and (d) 2-fold zone axis. (e) Magnified bright-field TEM image, highlighting the needle-like Mg_4Zn_7 precipitates.

3. Results and discussion

Fig. 1 shows bright-field TEM image and the corresponding SADPs of dendritic I-phase in the as-cast Mg–3.5Zn–0.6Gd alloy [15]. The zone axes in Fig. 1(b)—1(d) are 5-fold, 3-fold and 2-fold, respectively, and Fig. 1(b)—1(d) shows the typical SADPs for an icosahedral quasicrystal. Fig. 1(e) highlights needle-like Mg_4Zn_7 phase precipitates in Mg matrix [16,17]. To gain more insight into the dendritic I-phase, we further conduct HRTEM imaging of the dendritic I-phase (Fig. 2(a)) and take SADPs from the Mg matrix (Fig. 2(b)), the dendritic I-phase (Fig. 2(d)), and their combined area (Fig. 2(c)). The zone axis of Mg matrix is $[11\bar{2}0]$, while that of the dendritic I-phase is 2-fold, indicating that the $[11\bar{2}0]$ direction of Mg matrix is parallel to the 2-fold direction of I-phase (denoted as $[11\bar{2}0]_{Mg} \parallel [2\text{-fold}]_{I\text{-phase}}$). From Fig. 2, one can

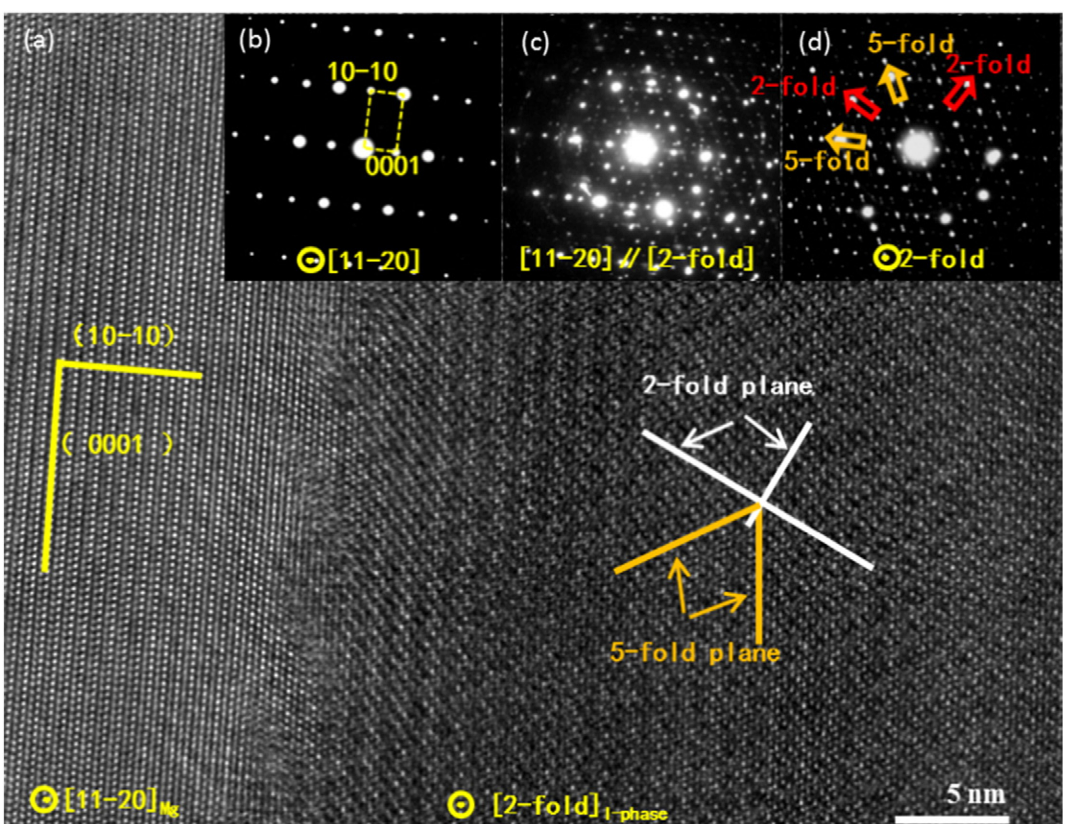

Fig. 2. HRTEM image of dendritic I-phase in as-cast Mg–3.5Zn–0.6Gd (at.%) alloys. (a) HRTEM image taken at the interface region. SADPs obtained at (b) Mg matrix, (c) interface regions, and (d) I-phase.