Materials Characterization 118 (2016) 481–485

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Investigation of the crystallographic orientations of the β-$Mg_{17}Al_{12}$ precipitates in an Mg-Al-Zn-Sn alloy

Yu Liu [a,b,*], Jixue Zhou [a,b], Dongqing Zhao [a,b], Shouqiu Tang [a,c]

[a] *Advanced Materials Institute, Shandong, Academy of Sciences, Jinan, China*
[b] *Shandong Key Laboratory for High Strength Lightweight Metallic Materials, Jinan, China*
[c] *Shandong Engineering Research Center for Lightweight Automobiles Magnesium Alloy, Jinan, China*

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 26 May 2016
Accepted 19 June 2016
Available online 21 June 2016

Keywords:
Mg-Al based alloys
β-$Mg_{17}Al_{12}$ precipitates
Crystallographic orientation relationship
Stereographic projection
Interfaces

ABSTRACT

The crystallographic orientation relationships between β-$Mg_{17}Al_{12}$ precipitates and α-Mg matrix were investigated in the Mg-Al-Zn-Sn alloy. New orientation relationships were observed and the growth direction of the particles with new orientation relationships was along the $[0002]_\alpha$ direction of the magnesium matrix. One of the orientation relationships was analyzed and identified as $[1\bar{2}10]_\alpha//[11\bar{1}]_\beta, (0001)_\alpha//(1\overline{21})_\beta$. The stereographic projection of the newly observed orientation relationship was calculated and discussed. Moreover, the interfaces between the β-$Mg_{17}Al_{12}$ precipitates and α-Mg matrix and two β-$Mg_{17}Al_{12}$ particles were studied.

1. Introduction

For their best combination of castability, mechanical strength and ductility [1–4], the Mg-Al based alloys have been investigated widely. The main precipitated phase in Mg—Al based alloys is the intermetallic phase β-$Mg_{17}Al_{12}$ phase with a complex body centred cubic (bcc) structure (a α-Mn type cubic structure, $a_\beta = 1.05438$ nm, space group$I\bar{4}3m$) [5,6], while the α-Mg matrix has a hexagonal close packed (hcp) structure ($a_\alpha = 0.31694$ nm and $c_\alpha = 0.51582$ nm according to Vegard's law) [7]. During the aging process of an Mg-Al based alloy, β phase precipitates in two ways: discontinuous precipitation or/and continuous precipitation. Discontinuous precipitation occurs on grain boundaries and reveals the lamellar eutectic α/β structure with Burgers orientation relationship (Burgers OR), i.e. $[1\bar{2}10]_\alpha//[11\bar{1}]_\beta, (0001)_\alpha//(101)_\beta$, $(10\bar{1}0)_\alpha//(\bar{1}21)_\beta$ and ceases relatively early in precipitation process [2,3,8,9]. Continuous precipitation takes place in the remaining areas of the matrix, revealing more complicated morphologies and orientation relationships than those of discontinuous precipitation as listed in Table 1 in references [2–4,8–14]. The predominant fraction of continuous precipitates are thin-lath shaped with their primary habit plane parallel to the $(0001)_\alpha$basal plane of the matrix and possess the Burgers OR with the matrix [2–4,8–14]. It was reported that the age-hardening response of Mg-Al-based alloys is poor compared with many age-hardenable aluminum alloys, and this is due to the orientations and morphologies (particle size, shape, etc.) of the continuous precipitates [2,11]. Since slips in the matrix of Mg-Al-based alloys occur mostly on the close-packed basal planes $(0001)_\alpha$ i.e. basal slip system, and the majority of the continuous precipitates are in thin plates (Burgers OR) parallel to the basal plane. Therefore, the basal slip system can still be activated. Only the minor fraction of the continuous precipitates have the Crawley OR and Porter OR which act as barriers for dislocations to glide on the basal planes. The continuous precipitates with Crawley OR have the primary growth direction perpendicular to the basal plane $(0001)_\alpha$ and have a morphology of a hexagonal prism-shaped rod [15,16,17]. The Porter OR precipitates with even less minor fraction have the primary growth direction lying at an angle of about 16°to the normal of $(0001)_\alpha$. There have been many kinds of crystallographic ORs observed in the Mg-Al based system, as listed in the table below. However, increasing the β-$Mg_{17}Al_{12}$ precipitates with the ORs beneficial to the performances of the alloys is the main target.

In this paper, the aged Mg-9.0wt.%Al-1.0wt.%Zn-4.0wt.%Sn alloy was prepared and studied. The addition of the alloying element Sn can further improve the performance of the alloy, especially the mechanical properties at high temperatures. One reason is the precipitation of the thermal stable Mg_2Sn phase. Meanwhile, the addition of Sn affects the precipitation of the β-$Mg_{17}Al_{12}$ phase, including the number density, morphologies, crystallographic orientations and so on. This work mainly focuses on the crystallographic characteristics of the β-$Mg_{17}Al_{12}$ phase.

---

* Corresponding author at: Advanced Materials Institute, Shandong Academy of Sciences, Jinan, China.
E-mail address: liuyu@sdas.org (Y. Liu).

http://dx.doi.org/10.1016/j.matchar.2016.06.024
1044-5803/© 2016 Elsevier Inc. All rights reserved.

Table 1
Reported crystallographic ORs in Mg-Al based system.

Name	Crystallography orientation relationship	Morphology	References
OR1 (Burgers OR)	$(1\,0\,1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[1\,1\,-1]_{\beta}//[1\,-2\,1\,0]_{\alpha}$	Lath shaped	[1,8–14,16,17]
OR2 (Pitsch-Schrader OR)	$(1\,0\,1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[0\,1\,0]_{\beta}//[2\,-1\,-1\,0]_{\alpha}$	Lath shaped	[13,14,18]
OR3 (Gjönnes-östmoe OR)	$(1\,0\,1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[1\,2\,-1]_{\beta}//[2\,-1\,-1\,0]_{\alpha}$	–	[1,19]
OR4 (Potter OR)	$(1\,0\,1)_{\beta}$ 2° from $(0\,0\,0\,1)_{\alpha}$, $[1\,1\,-1]_{\beta}//[1\,-2\,1\,0]_{\alpha}$	Platelets/rod shaped	[13,14,19]
OR5 (Crawley OR)	$(1\,1\,1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[-2\,1\,1]_{\beta}//[1\,1\,-2\,0]_{\alpha}$	Rod/prism shaped	[1,8,10,16,20]
OR6 (Porter OR)	$(1\,-5\,1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[-1\,0\,1]_{\beta}//[0\,1\,-1\,0]_{\alpha}$	Short rod shaped	[1,8,10,16,17,20]
OR7	$(1\,0\,1)_{\beta}//(1\,1\,-20)_{\alpha}$, $[-1\,-3\,1]_{\beta}//[0\,0\,0\,1]_{\alpha}$	–	[21]
OR8	$(4\,-4\,-1)_{\beta}//(0\,0\,0\,1)_{\alpha}$, $[1\,1\,0]_{\beta}//[2\,-1\,-1\,0]_{\alpha}$	–	[8]

2. Experimental procedures

The nominal composition of the cast ingot in our experiment was: 9.0wt.%Al, 1.0wt.%Zn, 4.0wt.%Sn, balance Mg. In order to dissolve the β-$Mg_{17}Al_{12}$ phase and achieve homogeneous aluminum distribution, slices (2 mm × 10 mm × 10 mm) were cut from the ingot and heat-treated at 673 K for 24 h under the protection of Ar flow, then quenched in water at room temperature. Next, the slices were aged at 523 K for 48 h in a Muffle furnace. The slices were mechanically thinned to about 60 μm, and then disks of 3 mm in diameter were punched and electro-chemically polished. Finally, the specimens were ion-milled by a Gatan precision ion polishing system under the condition of 3.0 kV. The TEM observations were conducted on the JEM-2010(HT) and JEM-2010(FEF) transmission electron microscope (TEM) operated at a voltage of 200 kV.

3. Results and discussion

3.1. Crystallographic orientation relationships between the β-$Mg_{17}Al_{12}$ particles and the α-Mg matrix

After aging process, the β-$Mg_{17}Al_{12}$ particles precipitated from the α-Mg matrix of the Mg-9.0wt.%Al-1.0wt.%Zn-4.0wt.%Sn alloy. Then, the crystallographic ORs between the continuously precipitated β phase and the α-Mg matrix were investigated using TEM. The results showed that most of the β particles exhibited Burgers OR ($[1\bar{2}10]_{\alpha}//[11\bar{1}]_{\beta}$, $(0001)_{\alpha}//(101)_{\beta}$, $(10\bar{1}0)_{\alpha}//(\bar{1}21)_{\beta}$). Only minor fraction of the β particles exhibited Crawley OR ($[1\bar{2}10]_{\alpha}//[11\bar{2}]_{\beta}$, $(0001)_{\alpha}//(111)_{\beta}$, $(10\bar{1}0)_{\alpha}//(\bar{1}10)_{\beta}$).

However, some β particles with new ORs were observed, as shown in Fig. 1. Fig. 1(a) and (d) are the TEM bright field images of the aged specimen. It can be obviously observed that a large amount of particles continuously precipitated from the matrix. The selected area electron diffraction (SAED) patterns suggest that all the particles in this area are the β-$Mg_{17}Al_{12}$ particles. The SAED technique is also taken to analyze their crystallographic characteristics. From the morphologies of the particles, as we usually observed before, it can be deduced that most of these lath-shaped β particles have the Burgers OR with the α-Mg matrix. However, the SAED results are quite different. Unexpectedly, none of the β particles exhibits Burgers orientation. The β particles marked by P in Fig. 1(a) and (d) are the same one and it will be analyzed in detail individually (in Fig. 2) in the next part. The overlapped patterns (particle and the matrix) in Fig. 1(b), (c), (e), and (f) are taken from the particles marked by P1, P2 (in Fig. 1(a)), P3 and P4 (in Fig. 1(d)), respectively. The diffraction spots from the α-Mg matrix and the β particles are distinguished and pointed by short and long arrows, respectively. The direction of the electron beam is along the $[1\bar{2}10]_{\alpha}$ direction of the matrix. Obviously, the lath-shaped β particles P1 and P3 have the same crystallographic ORs with the matrix (Fig. 1(b) and (e)). Compared with the ORs observed in the Mg-Al based system (listed in

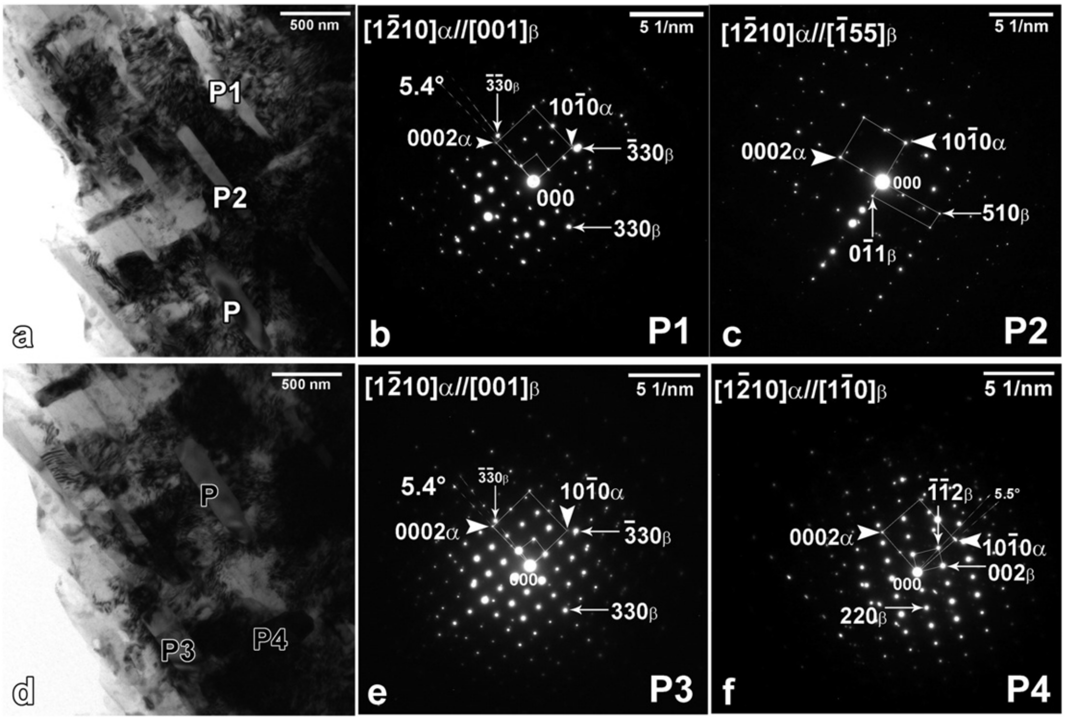

Fig. 1. (a) and (d) TEM bright-field image of the β-$Mg_{17}Al_{12}$ particles P, P1–P4 in Mg-9.0wt.%Al-1.0wt.%Zn-4.0wt.%Sn magnesium alloy aged at 523 K for 48 h, along the $[1\bar{2}10]_{\alpha}$ direction; (b), (c), (e) and (f) Overlapped SAED patterns of the particles P1–P4 together with the matrix.