Results in Physics 11 (2018) 152–157

Contents lists available at ScienceDirect

Results in Physics

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

Evolution of phase morphologies, compositions, structures of Mg-Y-Nd system with Sm addition

Guilong Jia, Erjun Guo*, Liping Wang, Yicheng Feng, Yanhong Chen

School of Materials Science and Engineering, Harbin University of Science and Technology, Harbin 150040, China

ARTICLE INFO

Keywords:
Mg-Y-Nd-Sm-Zr
Phase evolution
TEM

ABSTRACT

In this study, the evolution of phase morphologies, compositions, structures of Mg-Y-Nd system with Sm addition were investigated. The microstructure of the as-cast alloy consists of a Mg-matrix, $Mg_{24}Y_5$ (bcc structure, a = 1.1250 nm), and $Mg_5(Y_{0.7}Nd_{0.1}Sm_{0.2})$ (fcc structure, a = 2.2472 nm) phases. After a solution treatment, the eutectic phases are substantially dissolved into the Mg-matrix. A large amount of β′ precipitates are dispersed and precipitated in the grain after a T6 heat treatment, and the orientation relationships between β′ precipitates and Mg-matrix are $(0\,0\,1)_{\beta'} \parallel (0\,0\,0\,1)_{Mg}$, $(0\,2\,0)_{\beta'} \parallel (1\,0\,\bar{1}\,0)_{Mg}$, $[1\,0\,0]_{\beta'} \parallel [0\,1\,\bar{1}\,0]_{Mg}$. Furthermore, the quadrate phases indexed as $Mg_6Y_3(Nd_{0.8}Sm_{0.2})_1$, $Mg_6Y_3(Nd_{0.2}Sm_{0.8})_1$, and $Mg_{10}Y_5(Nd_{0.2}Sm_{0.8})_1$ are observed in various heat treatment states, which are fcc structures and their lattice parameters are a = 0.5318 nm, a = 0.5319 nm, a = 0.9894 nm, respectively.

Introduction

The research of low-cost high-strength magnesium rare earth (Mg-RE) alloys have attracted significant interest, and are developing rapidly at an amazing speed [1–3]. Mg-RE alloys, which contain two rare earths and especially the two rare earths belong to different groups, show higher strength [4–7], therefore, the current designs of which conform to the concept of pluralistic development [8–10].

WE series alloys were typical pluralistic aging strengthening Mg-RE alloys based on Mg-Y-Nd system. The aging precipitation sequence ($\beta'' \rightarrow \beta' \rightarrow \beta_1 \rightarrow \beta$) and the evolution of crystal structures of precipitated phases in WE series alloys had been investigated detailedly [11–15]. Furthermore, in the phase diagram of Mg-Y-Nd system, $Mg_{24}Y_5$ and $Mg_{41}Nd_5$ were the only two phases existing with Mg solid solution in the Mg-rich region [16], but a new β phase ($Mg_{14}Nd_2Y$) with face-centered cubic (fcc) structure (a = 2.23 nm) was discovered in the as-cast Mg-4Y-2.5Nd-0.7Zr alloy [17].

Mg-4Y-4Sm-0.5Zr [18] alloy based on Mg-Y-Sm system had better mechanical properties than WE43 and WE54 alloys, owing to the maximum solid solubility of Sm (5.8%) higher than that of Nd (3.6%). The aging precipitation sequence ($\beta' \rightarrow \beta_1 \rightarrow \beta$) and the orientation relationships between precipitated phases and Mg-matrix were reported with detail [19]. In addition, the phases of the alloy in different heat treatments states were characterized. $Mg_5(Sm_{0.6}Y_{0.4})$ with fcc structure (a = 2.326 nm) was the only eutectic phase in the as-cast alloy [20], which was different from what was shown in the phase diagram of Mg-Y-Sm system; $Mg_{6.2}(Sm,Y)$ and $Mg_{24}(Y,Sm)_5$ were the only two phases existing with Mg solid solution in the Mg-rich region [21]. Therefore, there is a difference between the actual phases in the alloys and the phases in the phase diagram, whether in Mg-Y-Nd system or in Mg-Y-Sm system.

A new low-cost high-strength Mg-Y-Nd-Sm-Zr alloy was prepared by using Mg-Y-Nd and Mg-Y-Sm systems for reference [22], the mechanical properties of which were better than those of WE43 and WE54 alloys [23]. Up to today, there is no detailed report on the phase diagram of Mg-Y-Nd-Sm system, and the phases existing with Mg solid solution in the Mg-rich region are unknown. In addition, there are still some differences in the characterization of the phases in the as-cast Mg-Y-Nd and Mg-Y-Sm alloys at present, and these differences are mainly concentrated on the characterization of another phase besides $Mg_{24}Y_5$ phase, which is marked as Mg_5RE or β phases. Therefore, it is very necessary to study the evolution of phase morphologies, compositions, structures in the Mg-Y-Nd-Sm-Zr alloy, which is of reference value for the study of the Mg-Y-Nd-Sm system phase diagram and the characterization of the phases in the Mg-RE alloys in the future.

In this work, the evolution of phase morphologies, compositions, structures in Mg-Y-Nd-Sm-Zr alloy in various heat treatment states are discussed emphatically.

* Corresponding author.
E-mail address: guoerjun@126.com (E. Guo).

https://doi.org/10.1016/j.rinp.2018.08.042
Received 15 July 2018; Received in revised form 22 August 2018; Accepted 22 August 2018
Available online 28 August 2018

Experimental materials and method

The alloy was prepared from pure Mg and Mg-30%Zr, Mg-30%RE master alloys, and melted in a pit-type resistance furnace at a melting temperature of 780 °C. After the raw materials were completely melted, the melt was cast into a steel permanent mold at a pouring temperature of 760 °C. The whole melting process was under protection gas consisting of SF_6 (1 vol%) and CO_2 (99 vol%).

The solution treatment was performed in a box-type resistance furnace, at 525 °C for 8 h, followed by quenching in hot water. After solution treatment, the aging treatment was performed isothermally at 200 °C for 16 h in a drying oven, followed by cooling in air.

The microstructures of the studied alloy were observed by scanning electron microscope (SEM). The morphologies, chemical compositions, and crystal structures of phases were analyzed and identified by transmission electron microscope (TEM) equipped with an energy dispersive X-ray spectrometer (EDXS) at 200 kV. TEM specimens were cut to 2 mm in thickness by wire electrical discharge machining (WEDM), mechanically grounded to 30–50 µm, and punched to 3 mm in diameter, followed by ion milling at an ion-gun energy of ~3.6 kV and milling angle of ~4° [24].

Experimental results and discussion

Phases in the as-cast state

The SEM micrograph of the as-cast state is presented in Fig. 1. The microstructure of the as-cast state is composed of α-Mg matrix and eutectic phases, most of the discontinuous eutectic phases tend to cluster at the grain boundaries, especially at the triple junction of the grain boundaries, as shown in Fig. 1(a). The triple junction of the grain boundaries is enlarged to further observe the morphology of the eutectic phases, as shown in Fig. 1(b). The morphology of the eutectic phases are lamellae shape and connected into network.

In order to characterize the crystal structure of the eutectic phases with detail, TEM observation is performed. TEM micrographs and corresponding selected area electron diffraction (SAED) patterns of the typical eutectic phases are shown in Fig. 2. The SAED pattern, as shown in Fig. 2(b), indicates a body-centered cubic (bcc) structure with a = 1.1250 nm for A eutectic phase, and this eutectic phase is $Mg_{24}Y_5$ [25]. The SAED pattern, as shown in Fig. 2(d), indicates a fcc structure with a = 2.2472 nm for B eutectic phase, this fcc structure and lattice parameter are isomorphous and approximate with that of Mg_5Sm [21]. In addition, the calibrations of the Mg_5RE phases by combining SAED patterns and EDXS results are reported in the Mg-Y-Sm-Zr and Mg-Gd-Sm-Zr alloys, only the lattice parameters of the Mg_5RE phases are different [7,20].

Furthermore, a quadrate phase is observed in the as-cast state, the TEM micrograph and corresponding SAED pattern of which are shown in Fig. 3. The SAED pattern indicates that the quadrate phase has a fcc structure with a = 0.5318 nm, and the quadrate phase is 240 ± 10 nm in length approximately.

In order to verify the correctness of the TEM results further, the chemical compositions of the eutectic phases and the quadrate phase are performed by EDXS. The tested positions of the eutectic phases and the quadrate phase are marked at Figs. 2 and 3 in sequence, and the atomic percentage results of Mg, Y, Nd, and Sm for all points are provided in Table 1. The results show that point 1 (A eutectic phase) mainly contains Mg and Y, and the atomic percentage for Mg:Y is 81.94:17.14 approximately, therefore, A eutectic phase can be indexed as $Mg_{24}Y_5$. Point 2 (B eutectic phase) contains Mg, Y, Nd, and Sm, which indicates that B eutectic phase may be a Mg-Y-Nd-Sm phase; the atomic percentage for Mg:(Y,Nd,Sm) is 83.71:16.29 approximately, which indicates a stoichiometry of B eutectic phase near $Mg_5(Y_{0.7}Nd_{0.1}Sm_{0.2})$. Through examining the point of the quadrate phase, the result shows that the atomic percentage for Mg:Y:(Nd,Sm) is 6:3:1, therefore, the quadrate phase can be indexed as $Mg_6Y_3(Nd_{0.8}Sm_{0.2})_1$ [20].

Although a small amount of granular-like phases can be observed at the grain interior in the SEM image, as shown in Fig. 1, they are not observed in the TEM observation. After examining some eutectic phases, the results show that the SAED patterns obtained above are representative and no other eutectic phases with other structures exist in the as-cast state, as well as other quadrate phases.

Phases in the solutionized state

The SEM micrograph of the solutionized state is presented in Fig. 4. After solution treatment, the eutectic phases are almost completely dissolved into the Mg-matrix, as shown in Fig. 4(a); but there are still a small amount of quadrate phases remained at the triple junction of the grain boundaries, as shown in Fig. 4(b).

The TEM micrograph and corresponding SAED pattern of the quadrate phase in the solutionized state are shown in Fig. 5. The length of the quadrate phase is 490 ± 10 nm approximately, which is much larger than that of the quadrate phase in the as-cast state. However, the fcc structure with a = 0.5319 nm indicated by SAED pattern is the same as that of the quadrate phase in the as-cast alloy. Therefore, it can be deduced that the quadrate phases may be the same substance. The chemical composition of the quadrate phase is performed by EDXS further, and the result is provided in Table 2. The average atomic percentage for Mg:Y:(Nd,Sm) is equal to 6:3:1; therefore, the quadrate phase can be indexed as $Mg_6Y_3(Nd_{0.2}Sm_{0.8})_1$ [7,20,26].

After solution treatment, most of the residual phases are distributed at the triple junction of the grain boundaries, as shown in Fig. 4; and the quadrate phase is the typical morphology through investigating the area of the triple junction. The quadrate phases, which are indexed as $Mg_6Y_3(Nd_{0.8}Sm_{0.2})_1$ in the as-cast state and indexed as

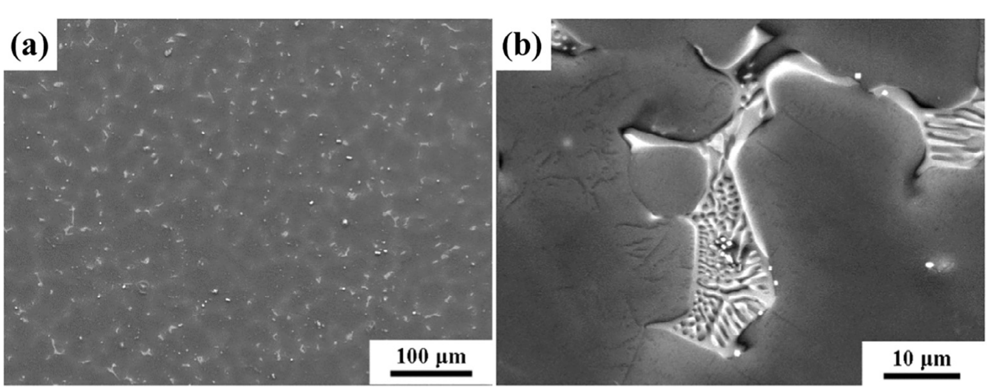

Fig. 1. SEM micrograph of the as-cast Mg-Y-Nd-Sm-Zr alloy.