



Full length article

Effect of Zr modification on solidification behavior and mechanical properties of Mg–Y–RE (WE54) alloy

Jilin Li, Rongshi Chen*, Yuequn Ma, Wei Ke

State Key Laboratory for Corrosion and Protection, Institute of Metal Research, Chinese Academy of Sciences, 62 Wencui Road, Shenyang 110016, China

Received 11 November 2013; revised 26 November 2013; accepted 3 December 2013

Abstract

Magnesium alloys containing rare earth elements (RE) have received considerable attention in recent years due to their high mechanical strength and good heat-resisting performance. Among them, Mg–5%Y–4%RE (WE54) magnesium alloy is a high strength sand casting magnesium alloy for use at temperatures up to 300 °C, which is of great interest to engineers in the aerospace industry. In the present work, the solidification behavior of Zr-containing WE54 alloy and Zr-free alloy was investigated by computer-aided cooling curve analysis (CA-CCA) technique. And the solidification microstructure and mechanical properties of them were also investigated comparatively. It is found from the cooling curves and as-cast microstructure of WE54 alloy that the nucleation temperature of α -Mg in WE54 alloy increases after Zr addition, and the as-cast microstructure of the alloy is significantly refined by Zr. While the phase constitution of WE54 alloy is not changed after Zr addition. These phenomena indicate that Zr acts as heterogeneous nuclei during the solidification of WE54 alloy. Due to refined microstructure, the mechanical properties of Zr-containing WE54 alloy is much higher than Zr-free WE54 alloy.

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Keywords: WE54 alloy; Zr modification; Solidification behavior; Mechanical properties

1. Introduction

Magnesium alloys have the advantageous properties such as low density, high specific strength, good castability, and excellent machinability. And rare earth elements have been used as alloying elements to improve the mechanical properties of magnesium alloys since the 1920s. While the application of Mg–RE alloys have been obsessed by the coarse microstructure of these alloys until Sauerwald et al. found the

grain-refining effect of zirconium on Mg–RE alloys such as Mg–Th alloy [1] and Mg–Ce alloy [2] in 1940s. It was found that the grain size of Mg–RE alloys were refined from millimeter scale to about 50 μ m by Zr addition under normal cooling rate [3].

In recent years, magnesium alloys containing heavy rare earth elements (HRE) such as Gd, Y, Nd have received considerable attention due to their high mechanical strength and good heat-resisting performance [4–7]. Among them, Mg–5%Y–4%HRE–Zr (WE54) magnesium alloy is a high strength sand casting magnesium alloy, whose high temperature mechanical strength is the top of existing commercial magnesium alloys [8–10]. As a powerful grain-refiner in these alloys, zirconium is broadly believed to improve the mechanical property and corrosion resistance of these alloys [11], and lots of work have been carried out on the grain refining mechanism of Zr in magnesium alloys [12–14]. While these works were mainly carried out in Mg–Zr alloys, which are quite different in solidification behavior and microstructure

* Corresponding author.

E-mail addresses: jlli@imr.ac.cn (J. Li), rschen@imr.ac.cn (R. Chen), yqma@imr.ac.cn (Y. Ma), wke@imr.ac.cn (W. Ke).

Peer review under responsibility of National Engineering Research Center for Magnesium Alloys of China, Chongqing University



with Mg–RE–Zr alloys. So far, no detailed research has been carried out on exactly how Zr addition affects the solidification behavior and mechanical properties of these alloys to the author's knowledge, and the influence mechanism of Zr on solidification microstructure and mechanical properties of these alloys remain unclear.

In the present research, the solidification behavior of Zr-free and Zr-containing WE54 alloy were investigated by a computer aided cooling curve analysis (CA-CCA) technology and microstructure observation in order to study the effects of Zr addition on the solidification behavior of WE54 alloy. And the mechanical properties of Zr-free and Zr-containing WE54 alloy were studied comparatively, aiming at revealing the influence mechanism of Zr on solidification microstructure and mechanical properties of WE54 alloy.

2. Experimental procedures

2.1. Alloy casting and heat treatment

WE54 alloys with and without Zr addition were prepared from high purity Mg (99.95%), Gd (99%), Y (99%), Nd (99%) and/or Mg–30Zr (wt.%) master alloy by melting them in an electric resistance furnace under protection of an anti-oxidizing flux. The melt was poured into a steel mold preheated to 300 °C at about 780 °C to cast the alloy ingots. The actual chemical composition of the alloy was determined by using inductively coupled plasma atomic emission spectroscopy (ICP) and listed in Table 1. The solution treatment of the alloys was carried out at 525 °C for 6 h followed by water quenching, and the subsequent aging treatment was carried out at 250 °C for 16 h followed by air cooling.

2.2. Cooling curve analysis

Computer aided cooling curve analysis (CA-CCA) of the investigated alloys was performed by remelting and solidifying cylindrical samples of the alloys in a cylindrical graphite crucible placed in an electrical resistance furnace. The cylindrical samples with dimensions of Φ 30 mm $\times$ 60 mm were cut from the casting ingots using an electric discharge wire cutting machine, and burnished by sandpaper before remelting. After holding at 740–750 °C for 5 min, the graphite crucible was removed from the furnace, and the melt in the crucible began to solidify at a cooling rate of approximately 1 K/sec. During the melt solidification, the temperature variations of the melt were recorded continuously with a high speed data acquisition system at an acquisition frequency of 20 Hz. Then the temperature data were imported into Origin 8.5 data analysis software, and the cooling curve and its first

derivative curve were calculated with this software in order to determine the characteristic features of the alloy solidification. In order to ensure reproducibility of the testing results, each test was carried out at least twice.

2.3. Microstructure observation and tensile testing

Microstructure observations were conducted using optical microscope (OM) and scanning electron microscope (SEM) equipped with an energy disperse spectroscopy (EDS). Electron backscattered diffraction technology (EBSD) was used to measure the grain size of the investigated alloys. Samples for optical microscopy were etched in a solution of 4 vol.% HNO₃ in ethanol after mechanical polishing to reveal grain boundaries, no chemical etching was applied to specimens for SEM investigations, and the EBSD samples were electrochemical polished after grinding with sandpapers. The mean grain size, d , was determined by the linear intercept method using the equation $d = 1.74 L$, where L is the linear intercept grain size determined by analyzing the EBSD micrographs of the investigated alloys.

The tensile tests of the WE54 alloys with and without Zr content at different heat treatment states were performed on standard round tensile specimens with the gauge length of 25 mm and the gauge diameter of 4 mm. Tensile test was conducted at room temperature with an initial strain rate of 10^{−3}/s on a universal testing machine. Three specimens were tested for each test condition to ensure the reliability of data. And the fracture morphology of the alloys was observed by SEM.

3. Results and discussion

3.1. Solidification behavior

Fig. 1 shows the thermal analysis results for the investigated alloys and their microstructures in the as-cast condition. It is seen from the cooling curves and the first derivative curves of the alloys that Zr-free and Zr-containing WE54 alloys experiences similar phase transformations during their solidification procedure. Thus the as-cast microstructure and phase constitution of Zr-free and Zr-containing WE54 alloys are similar as shown in Fig. 1(b) and (d). While the α -Mg phase nucleated at 637.5 °C in Zr-free WE54 alloy, which was lower than the nucleation temperature of 646 °C in Zr-containing WE54 alloy, as seen clearly on first derivative curves. So a higher supercooling degree is necessary for α -Mg nucleation in Zr-free WE54 alloy than in Zr-containing WE54 alloy, indicating that a transformation of nucleation mode occurs after Zr addition in WE54 alloy.

Fig. 2 shows the as-cast microstructure of WE54 alloy obtained by OM and EBSD techniques. It is found from the EBSD images shown in Fig. 2(a) and (c) that the as-cast microstructure of WE54 alloy is significantly refined after Zr addition. By linear intercept method, the average grain size of Zr-free and Zr-containing WE54 alloy is determined to be 295 μ m and 83 μ m, respectively. And the OM images show

Table 1
Chemical composition of the experimental alloy (wt.%).

Element	Y	Nd	Gd	Zr	Mg
Zr-containing WE54 alloy	5.02	1.92	2.13	0.45	Balance
Zr-free WE54 alloy	5.10	1.91	2.03	—	Balance

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