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Effects of minor Ca addition on as-cast microstructure and mechanical properties of Mg–4Y–1.2Mn–1Zn (wt.%) magnesium alloy

Mingbo Yang [a,b,c,d,*], Chengyu Duan [b], Hongliang Li [b], Tingzhang Guo [b], Jia Zhang [b]

[a] Key Laboratory of Manufacture and Test Techniques for Automobile Parts, Chongqing University of Technology, Ministry of Education, Chongqing 400054, China
[b] Materials Science & Engineering College, Chongqing University of Technology, Chongqing 400054, China
[c] Chongqing Academy of Science and Technology, Chongqing 401123, China
[d] National Engineering Research Center for Magnesium Alloys, Chongqing University, Chongqing 400030, China

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ABSTRACT

The effects of minor Ca addition on the as-cast microstructure and mechanical properties of the Mg–4Y–1.2Mn–1Zn (wt.%) alloy were investigated by using optical and electron microscopies, differential scanning calorimetry (DSC) analysis, and tensile and creep tests. The results indicate that adding 0.3–0.9 wt.%Ca to the Mg–4Y–1.2Mn–1Zn alloy does not cause an obvious change in the morphology and distribution for the $Mg_{12}YZn$ phase in the alloy. However, the grains of the Ca-containing alloys are effectively refined, and an increase in Ca amount from 0.3 wt.% to 0.9 wt.% causes the grain size to gradually decrease. In addition, adding 0.3–0.9 wt.%Ca to the Mg–4Y–1.2Mn–1Zn alloy can effectively improve the tensile and creep properties. Among the Ca-containing alloys, the alloys with the additions of 0.6 and 0.9 wt.%Ca exhibit the relatively optimum tensile and creep properties. The improvement in the tensile and creep properties for the Ca-containing alloys is possibly related to the grain refinement and higher thermal stability of the Ca-containing $Mg_{12}YZn$ phases in the alloys, respectively.

1. Introduction

Magnesium alloys are the lightest structural alloys commercially available and have great potential for applications in automotive, aerospace and other industries. At present, the development of new magnesium alloys is becoming increasingly important due to the potential saving in weight when compared to aluminum based alloys. However, the creep properties of magnesium alloys are limited by their low melting point which can vary depending on the alloying content [1]. Therefore, the development of elevated temperature magnesium alloys is necessary in order to compete with other light constructional materials such as aluminum alloys and in order to improve the temperature range of application of magnesium components. Previous investigations indicated that Mg–Y–Mn–Sc alloys are considerably superior to WE alloys and exhibit high creep resistance at high temperatures over 300 °C [2–6]. However, due to the expensive Sc, the application of Mg–Y–Mn–Sc alloys is limited. Since Zn can form intermetallic phases with Mg and/or RE as plates on basal planes of α-Mg matrix [7], the research of replacing expensive Sc by cheap Zn for Mg–Y–Mn–Sc alloys has been carried out, and the results indicated that Mg–Y–Mn–Zn alloys have similar mechanical properties at room temperature and 300 °C as compared with Mg–Y–Mn–Sc alloys [7,8]. However, it is further reported that, similar to the quaternary Mg–Y–Mn–Sc alloys, the grains of the quaternary Mg–Y–Mn–Zn alloys also are relatively coarse, leading to the relatively poor mechanical properties [8,9]. Therefore, further enhancement in the mechanical properties for the quaternary Mg–Y–Mn–Zn alloys by grain refinement needs to be considered. But up to now, the investigations about the effects of alloying and/or microalloying on the grain refinement and mechanical properties of Mg–Y–Mn–Zn alloys are very rare. Although in the previous investigations [9] the authors of this paper found that minor Zr and/or Sr additions to Mg–Y–Mn–Zn alloys can refine the grains thus leads to enhance the properties, it is not clear whether other additions such as Ca to Mg–Y–Mn–Zn alloys have similar effects on the microstructure and properties as Zr and Sr additions. It is well known that Ca can behave as a grain refiner of magnesium alloys [10]. In addition, Jun et al. [11] found that 0.5–1.0 wt.%Ca addition to the Mg–4RE–3Zn (wt.%) alloy not only can refine the primary α-Mg phases but also increase the thermal stability of the Mg–RE phases in the alloy. Therefore, it is expected that Ca addition possibly plays a beneficial role in the grain refinement and mechanical properties for Mg–Y–Mn–Zn alloys. Based on the above mentioned-reasons, the present work investigates the effects of minor Ca addition on the as-cast microstructure and mechanical properties of the Mg–4Y–1.2Mn–1Zn (wt.%) alloy (previously reported by Smola and Yang et al. [7–9]).

* Corresponding author at: Materials Science & Engineering College, Chongqing University of Technology, Chongqing 400054, China. Tel./fax: +86 23 62563176.
E-mail address: yangmingbo@cqut.edu.cn (M. Yang).

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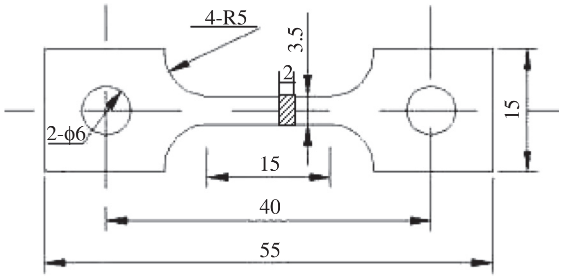

Fig. 1. Configuration of the samples used for the tensile and creep tests (unit: mm).

Table 1
Actual compositions of the experimental alloys, wt.%.

Experimental alloys	Y	Mn	Zn	Ca	Mg
1# (Mg–4Y–1.2Mn–1Zn)	3.69	1.11	0.92	–	Bal.
2# (Mg–4Y–1.2Mn–1Zn–0.3Ca)	3.74	1.05	0.89	0.21	Bal.
3# (Mg–4Y–1.2Mn–1Zn–0.6Ca)	3.68	1.07	0.93	0.55	Bal.
4# (Mg–4Y–1.2Mn–1Zn–0.9Ca)	3.81	1.03	0.91	0.79	Bal.

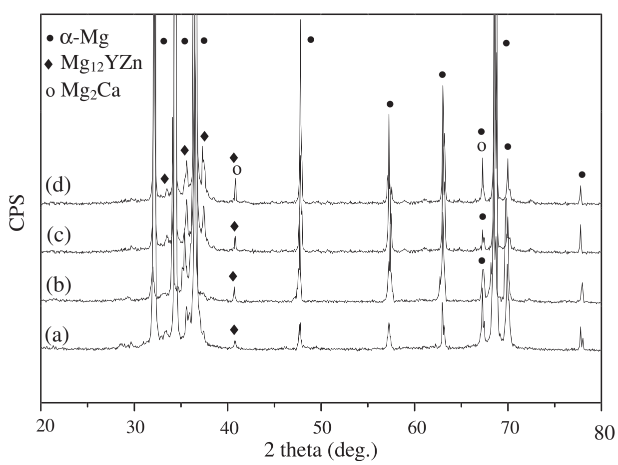

Fig. 2. XRD results of the as-cast experimental alloys: (a) 1# alloy; (b) 2# alloy; (c) 3# alloy; and (d) 4# alloy.

2. Experimental procedures

The Ca-containing Mg–4Y–1.2Mn–1Zn experimental alloys were prepared by adding pure Mg and Zn, Mg–17 wt.%Y, Mg–4.38 wt.%Mn, and Mg–19.7 wt.%Ca master alloys. In this work, three Ca contents, 0.3, 0.6 and 0.9 wt.%, were preliminarily selected due to the following considerations: (i) in the previous investigations about the effects of minor Ca on the microstructure and mechanical properties of the as-cast Mg–Al, Mg–Zn and Mg–RE based alloys [11–17], the Ca contents selected mainly focused on 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and/or 1.0 wt.% and (ii) although the chemical compositions of the Mg–4Y–1.2Mn–1Zn and the above mentioned Mg–Al, Mg–Zn and Mg–RE based alloys are different, the main aims for minor Ca addition to these alloys, such as microstructural refinement and properties improvement, are same. Therefore, a similar Ca content, 0.3–0.9 wt.%, is possibly suitable for the as-cast Mg–4Y–1.2Mn–1Zn alloy. The experimental alloys were melted in a crucible resistance furnace and protected by a flux addition. After being held at 740 °C for 20 min, the melts of the experimental alloys were respectively homogenized by mechanical stirring and then poured into a permanent mold which was coated and preheated to 200 °C in order to obtain a casting. The specimens as shown in Fig. 1 were fabricated from the castings for tensile and creep tests. Furthermore, the samples of the experimental alloys were subjected to a solution heat treatment (520 °C/12 h + water cooled) in order to reveal the grain boundaries and examine the microstructural stability at high temperatures. For comparison, the Mg–4Y–1.2Mn–1Zn alloy without Ca addition was also cast and machined into the same dimensions and tested under the same conditions as the above samples. Table 1 lists the actual chemical compositions of the experimental alloys, which were inspected by inductively coupled plasma spectroscopy.

In order to analyze the solidification behavior of the experimental alloys, the differential scanning calorimetry (DSC) was carried out by using a NETZSCH STA 449C system equipped with platinum–rhodium crucibles. Samples weighing around 30 mg were heated in a flowing argon atmosphere from 30 to 700 °C for 5 min before being cooled down to 100 °C. The heating and cooling curves were recorded at a controlling speed of 15 °C/min.

The as-cast and solutionized samples of the experimental alloys were respectively etched in an 8% nitric acid solution in distilled water and a solution of 1.5 g picric, 25 ml ethanol, 5 ml acetic acid and 10 ml distilled water, and then examined by an Olympus optical microscope and/or JEOL JSM-6460LV type scanning electron microscope equipped with Oxford energy dispersive X-ray spectrometer (EDS) with an operating voltage of 20 kV. The phases in the experimental alloys were analyzed by D/Max-1200X type X-ray diffraction (XRD) operated at 40 kV and 30 mA with Cu Ka radiation, a step scanning 2θ from 20° to 80°, a step size of 0.03° and a count time of 3 s. The phases in the experimental alloys were determined by using a PDF2 database. The grain size was analyzed by the standard linear intercept method using an Olympus stereomicroscope. The tensile tests were performed by CMT5105 type electromechanical universal testing machine of M/s MTS System (China) Co., Ltd. The as-cast tensile properties at room temperature and 300 °C for the experimental alloys were determined from a complete stress–strain curve. In a bisected resistance furnace with the temperature controlled to within ±2 °C and protected by CO_2 atmosphere, the tensile specimens tested at 300 °C were heated at a heating rate of 12 °C/min. The ultimate tensile strength (UTS), 0.2% yield strength (YS), and elongation to failure (Elong.) were obtained based on the average value of three

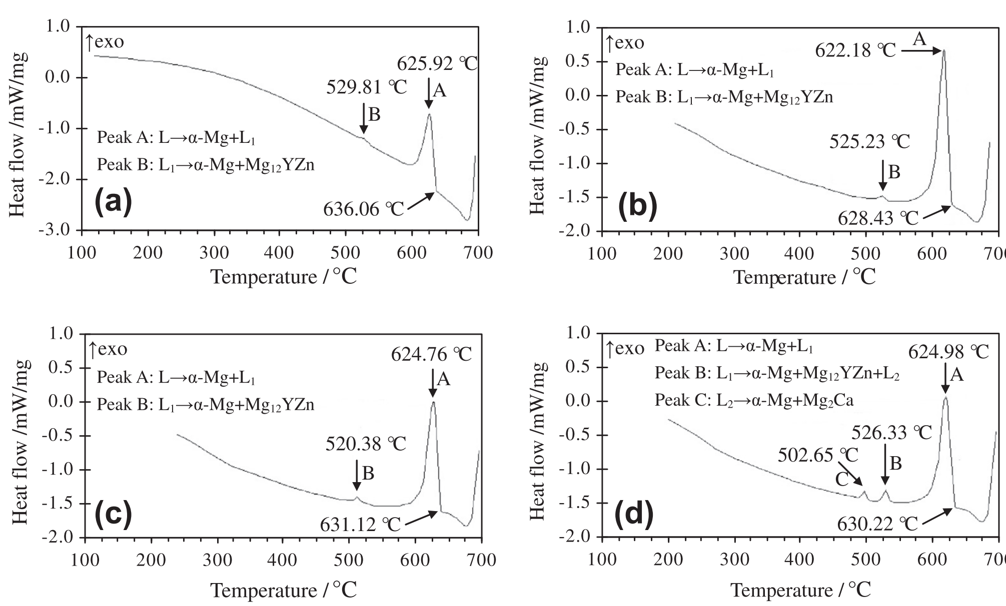

Fig. 3. DSC cooling curves of the as-cast experimental alloys: (a) 1# alloy; (b) 2# alloy; (c) 3# alloy; and (d) 4# alloy.