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Effects of minor Sr additions on the as-cast microstructure, fluidity and mechanical properties of Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca (wt%) alloy

Yu Fu, Han Wang, Chen Zhang, Hai Hao*

Key Laboratory of Solidification Control and Digital Preparation Technology (Liaoning Province), School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, PR China

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ABSTRACT

Microstructure, fluidity and mechanical properties of Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca (wt%) alloy with minor Sr contents have been investigated. All the alloys exhibited the homogeneous microstructure with equiaxed α-Mg matrix and eutectic compounds distributing along grain boundaries. The as-cast alloys are mainly composed of α-Mg phase, $Mg_{51}Zn_{20}$ phase and T-phase. The fluidity of the Sr-containing Mg alloys was examined by means of the three concentric spirals mould. It was found that the fluidity of Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.2 Sr alloy was effectively increased by 122.8% as compared to the quaternary alloy. This could be attributed to grain refinement as well as the reductions of oxides and melt viscosity. The Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.2 Sr alloy exhibits the optimum tensile properties with ultimate tensile strength, yield strength and elongation of 144.1 MPa, 114.4 MPa and 4.9%, respectively, which is ascribed to refinement strengthening and dislocation pinning effect of T-phase. Furthermore, the fracture characteristic of Sr-containing alloys is mainly quasi-cleavage.

1. Introduction

A strong demand to reduce the emission of greenhouse gases has motivated the development of eco-friendly and energy saving engineering materials [1]. Magnesium (Mg) alloys, as the lightest structural metallic materials, are currently the subject of intensive research for structural applications requiring high specific strength and stiffness, excellent castability and good weldability, these requirements being particularly relevant for aerospace industries [2]. However, poor corrosion resistance, ductility and formability are roadblocks hampering their widespread applications [3]. A broad tunability of microstructure and mechanical properties has been demonstrated by adjusting the alloy composition with the addition of alloying elements [4]. For example, alloying Mg with Zinc (Zn) and rare earth (RE) improves strength and creep resistance through solid solution strengthening and precipitation hardening [5]. Alloying Mg with Zirconium (Zr) and/or Calcium (Ca) induces grain refinement that enhances strength and castability [6]. In the past few decades, Mg-Zn-RE-Zr based alloys have been supposed to be the popular aerospace alloys for producing thin-wall and complex-shape casting products such as compressor casings and accessory gearboxes [7]. Hence, special attention has to be taken to improve the mechanical properties and fluidity of the alloys.

The fluidity of Mg alloys is influenced by a number of factors. The metallurgical aspects include alloy composition, latent heat, superheat, surface tension, viscosity and mould of solidification. The mould/casting factors are geometric structure of castings, interface heat transfer coefficient, mould temperature, mould material and its surface characteristics [8,9]. In addition, refining grain size and decreasing oxide inclusions offer an effective strategy for improving the fluidity of alloys [10,11]. Being a relatively inexpensive alloying element, Ca addition alone does not only increase the ignition temperature of Mg alloys, but also bring significant grain refinement [12]. In a recent article, we have studied the role of Ca addition on the casting fluidity of the Mg-Zn-Ce-Zr alloy, indicating that 0.2 wt% Ca addition contributes to improve the fluidity of the alloy, but the higher Ca content brings about ultimate tensile strength loss and fluidity reduction [6]. At present, many research efforts indicate that the synergistic effects of the multiple alloying elements are favored to improve the properties of alloys [2,13,14]. Strontium (Sr), an alkaline-earth alloying element, has been used as a minor addition to Mg-Al alloys in combination with Ca [15]. In the presence of Ca, the addition of Sr has been shown to inhibits the tendency of the divorce eutectic and lowers the temperature of Al_2Ca phase formation, contributing to improve the hot-crack resistance of Ca-containing AZ91D alloys [16]. Moreover, creep resistance of Mg-4Al-(1 − 3)Sr alloys that stems from the present of thermally stable interphases can be improved by adding 1.0 wt% Ca

* Correspondence to: School of Materials Science and Engineering, Dalian University of Technology, No.2 Linggong Road, High Technology Zone, Dalian City, Liaoning Province, PR China.

E-mail address: haohai@dlut.edu.cn (H. Hao).

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Table 1
Nomenclatures and chemical compositions of the as-cast experimental alloys (wt%).

Alloy	Nominal alloys	Actual composition					
		Mg	Zn	RE	Zr	Ca	Sr
1#	Mg-4.2Zn-1.7RE-0.8Zr	Bal.	4.11	1.62	0.71	–	–
2#	Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca	Bal.	4.17	1.61	0.74	0.16	–
3#	Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.1Sr	Bal.	4.03	1.67	0.67	0.19	0.11
4#	Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.2Sr	Bal.	4.13	1.62	0.69	0.22	0.21
5#	Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.4Sr	Bal.	4.11	1.64	0.75	0.17	0.38

[17]. However, little is known about the interactive effects of Sr and Ca additions on the Mg-Zn-RE-Zr alloys. Our previous study shows that the Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca (all the alloy compositions in wt% except otherwise stated) alloy exhibits a fairly fluidity at the cost of ultimate tensile strength. To overcome this problem, we will present a study on the microstructure, fluidity and mechanical properties of the as-cast Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca alloy with minor Sr additions, aiming to provide the optimal Sr content for the Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca alloy as well as the related fluidity mechanism.

2. Experiments

Alloys with nominal compositions of Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-xSr (x = 0, 0.1, 0.2, 0.4) were cast from high-purity Mg, Zn, Ce-rich mischmetal, Mg-30Zr, Mg-20Ca and Mg-20 Sr by melting in a mild steel crucible under a protected argon atmosphere at 730 °C, and pouring into a spiral sand mould and cylindrical ingots of 50 mm diameter and 130 mm height. The mould was preheated to 200 °C. For comparison, the Mg-4.2Zn-1.7RE-0.8Zr alloy was prepared by the same preparation procedure. The chemical compositions of the samples were determined by the X-ray fluorescence (XRF) method and the results were summarized in Table 1.

Intermetallic phases were identified by means of X-ray diffraction (XRD) with Cu Kα radiation at the scan rate of 2°/min. Microstructural examinations were conducted by optical microscope (OM), scanning electron microscope (SEM), electron probe micro-analysis (EPMA) and energy dispersive X-ray spectroscopy (EDS). The specimens in as-cast condition for OM and SEM observations were etched in a solution of 2.1 g picric acid, 5 ml acetic acid, 5 ml H_2O and 35 ml ethanol. Grain size measurements were performed using the linear intercept method described in ASTM standard E 112-88. Differential scanning calorimetry (DSC) was conducted for analyzing the phase transition under argon atmosphere. The heating rate was 10 °C/min and the scanned temperature interval went from 25° to 650°C. Tensile tests were carried out for the as-cast samples using a fully computerized universal testing machine with a strain rate of 2 mm/min at room temperature. Samples for tensile test were machined out of the bars with a gauge dimension of 30 mm and 6 mm in diameter. Each test condition was repeated at least three times for repeatability and accuracy.

Fluidity, in the casting field, is defined as the ability of molten metal to flow before it is stopped by solidification [18]. The length of fluidity spiral is taken as indicative of the fluidity of the molten alloy. An improved equipment for gravity casting of fluidity spirals in a precoated sand mould is described in Fig. 1(a), which consists of a pouring basin, a tapered sprue, a upper die (a flat sand mould) and a bottom die (three concentric Archimedian spiral cavities). The Archimedian spiral, with a cross section of (3 + 5)× 2.5 mm^2, gives a maximum running length of 750 mm and each spiral end is vented, as depicted in Fig. 1(b) and (c). In the spiral fluidity test, the melt was poured to the pouring basin at the constant pouring temperature, which gave a constant melt superheat. In addition, since the molten metal was poured into the spiral sand mould from the same height, the equipment gave a constant

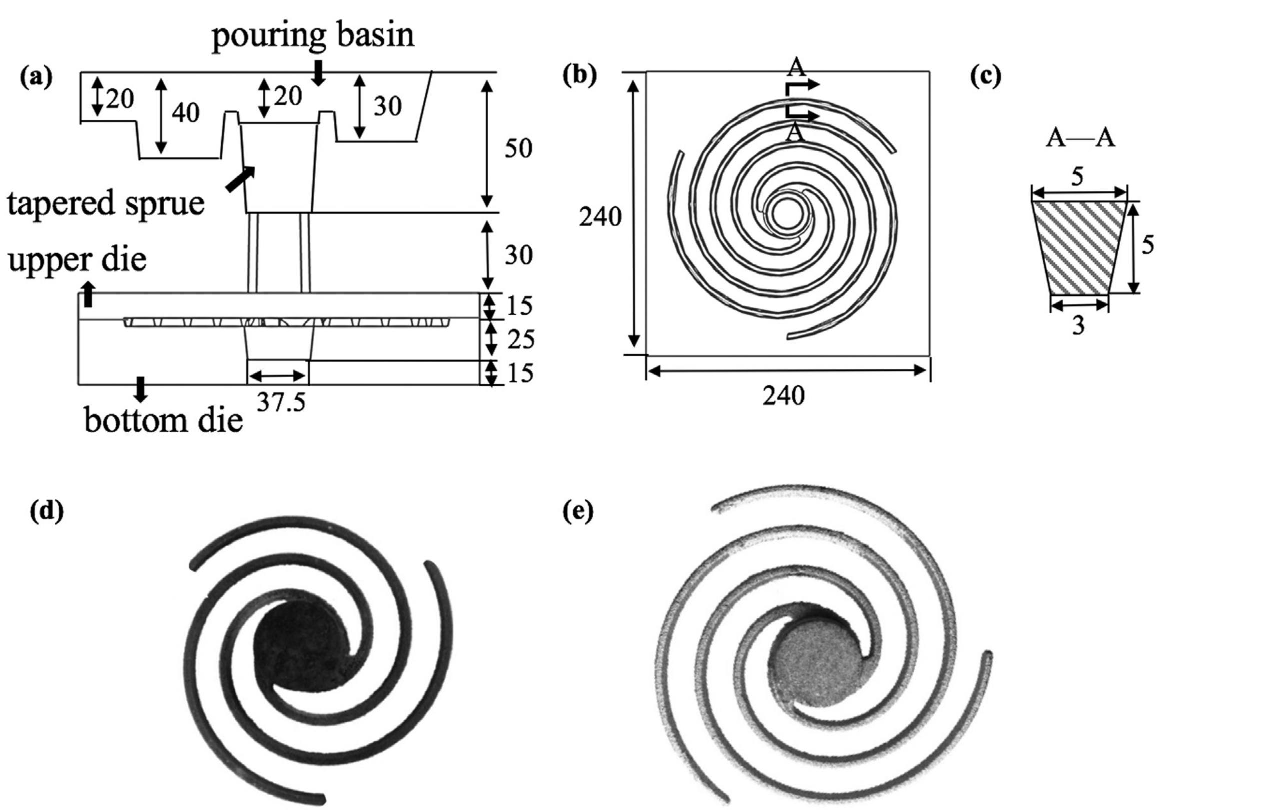

Fig. 1. The illustration of the equipment showing (a) front view of the mould, (b) top view of the bottom die, (c) cross-section of the spiral, (d) the fluidity specimen of the Mg-4.2Zn-1.7RE-0.8Zr alloy and (e) the fluidity specimen of the Mg-4.2Zn-1.7RE-0.8Zr-0.2Ca-0.2 Sr alloy. (all dimensions are in mm).